

Foundations of Artificial Intelligence

10. Action Planning

Solving Logically Specified Problems using a General Problem Solver

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- 2 Planning Formalisms
- 3 Basic Planning Algorithms
- 4 Computational Complexity
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- 6 Current Trends in Planning
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Lecture Overview

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- Planning is the art and practice of thinking before acting [Haslum]
- Planning is the process of generating (possibly partial) representations of **future behavior** prior to the use of such plans to constrain or control that behavior.
- The outcome is usually a **set of actions**, with temporal and other constraints on them, for **execution** by some agent or agents.

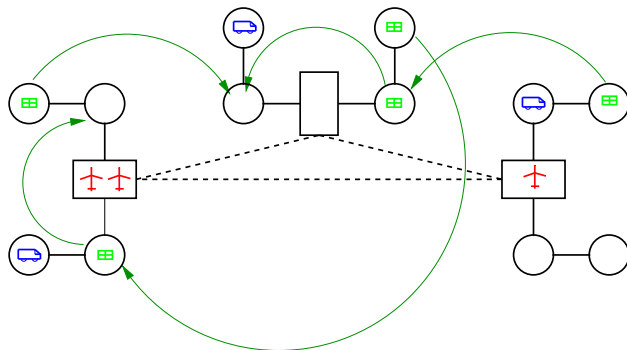
Planning Tasks

Given a **current state**, a set of possible **actions**, a specification of the **goal conditions**, which **plan** transforms the **current state** into a **goal state**?



Another Planning Task: *Logistics*

Given a road map, and a number of trucks and airplanes, make a plan to transport objects from their start to their goal destinations.



Action Planning is not ...

- **Problem solving by search**, where we describe a problem by a state space and then implement a program to search through this space
 - in action planning, we specify the problem declaratively (using logic) and then solve it by a general planning algorithm
- **Program synthesis**, where we generate programs from specifications or examples
 - in action planning we want to solve just one instance and we have only very simple action composition (i.e., sequencing, perhaps conditional and iteration)
- **Scheduling**, where all jobs are known in advance and we only have to fix time intervals and machines
 - instead we have to find the right actions and to sequence them
- Of course, there is **interaction** with these areas!

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Domain-Independent Action Planning

- Start with a **declarative specification** of the planning problem
- Use a **domain-independent planning** system to solve the planning problem
- Domain-independent planners are **generic problem solvers**
- Issues:
 - Good for evolving systems and those where performance is not critical
 - Running time should be comparable to specialized solvers
 - Solution quality should be acceptable
 - ... at least for all the problems we care about

Planning as Logical Inference

Planning can be elegantly formalized with the help of the *situation calculus*.

Initial state:

$At(truck1, loc1, s_0) \wedge At(package1, loc3, s_0)$

Operators (successor-state axioms):

$\forall a, s, l, p, t \quad At(t, p, Do(a, s)) \Leftrightarrow \{a = Drive(t, l, p) \wedge Poss(Drive(t, l, p), s) \\ \vee At(t, p, s) \wedge (a \neq Drive(t, p, l, s) \vee \neg Poss(Drive(t, p, l, s)))\}$

Goal conditions (query):

$\exists s \quad At(package1, loc2, s)$

The **constructive** proof of the existential query (computed by a automatic theorem prover) delivers a plan that does what is desired.
Can be quite **inefficient**!

The Basic STRIPS Formalism

STRIPS: STanford Research Institute Problem Solver

- \mathcal{S} is a *first-order vocabulary* (predicate and function symbols) and $\Sigma_{\mathcal{S}}$ denotes the set of *ground atoms* over the signature (also called **facts** or **fluents**).
- $\Sigma_{\mathcal{S}, \mathbf{V}}$ is the set of atoms over \mathcal{S} using variable symbols from the set of variables \mathbf{V} .
- A **first-order STRIPS state** S is a subset of $\Sigma_{\mathcal{S}}$ denoting a *complete theory* or *model* (using CWA).
- A **planning task** (or **planning instance**) is a 4-tuple $\Pi = \langle \mathcal{S}, \mathbf{O}, \mathbf{I}, \mathbf{G} \rangle$, where
 - \mathbf{O} is a set of **operator** (or *action types*)
 - $\mathbf{I} \subseteq \Sigma_{\mathcal{S}}$ is the **initial state**
 - $\mathbf{G} \subseteq \Sigma_{\mathcal{S}}$ is the **goal specification**
- **No domain constraints** (although present in original formalism)

Operators, Actions & State Change

- **Operator:**

$$o = \langle para, pre, eff \rangle,$$

with $para \subseteq \mathbf{V}$, $pre \subseteq \Sigma_{\mathcal{S}, \mathbf{V}}$, $eff \subseteq \Sigma_{\mathcal{S}, \mathbf{V}} \cup \neg \Sigma_{\mathcal{S}, \mathbf{V}}$ (element-wise negation) and all variables in pre and eff are listed in $para$.

Also: $pre(o)$, $eff(o)$.

$eff^+ =$ positive effect literals

$eff^- =$ negative effect literals

- **Operator instance** or **action**: Operator with empty parameter list (*instantiated schema!*)
- **State change** induced by action:

$$App(S, o) = \begin{cases} S \cup eff^+(o) - \neg eff^-(o) & \text{if } pre(o) \subseteq S \text{ \& } eff(o) \text{ is cons.} \\ \text{undefined} & \text{otherwise} \end{cases}$$

Example Formalization: *Logistics*

- Logical atoms: $at(O, L)$, $in(O, V)$, $airconn(L1, L2)$, $street(L1, L2)$, $plane(V)$, $truck(V)$
- Load into truck: *load*
Parameter list: (O, V, L)
Precondition: $at(O, L), at(V, L), truck(V)$
Effects: $\neg at(O, L), in(O, V)$
- Drive operation: *drive*
Parameter list: $(V, L1, L2)$
Precondition: $at(V, L1), truck(V), street(L1, L2)$
Effects: $\neg at(V, L1), at(V, L2)$
- ...
- Some constant symbols: $v1, s, t$ with $truck(v1)$ and $street(s, t)$
- Action: $drive(v1, s, t)$

- A **plan** Δ is a sequence of actions
- State resulting from **executing a plan**:

$$\begin{aligned} Res(S, \langle \rangle) &= S \\ Res(S, (o; \Delta)) &= \begin{cases} Res(App(S, o), \Delta) & \text{if } App(S, o) \\ & \text{is defined} \\ \text{undefined} & \text{otherwise} \end{cases} \end{aligned}$$

- **Plan Δ is successful** or **solves** a planning task if $Res(\mathbf{I}, \Delta)$ is defined and $\mathbf{G} \subseteq Res(\mathbf{I}, \Delta)$.

A Small Logistics Example

Initial state: $S = \left\{ \begin{array}{l} at(p1, c), at(p2, s), at(t1, c), \\ at(t2, c), street(c, s), street(s, c) \end{array} \right\}$

Goal: $G = \{ at(p1, s), at(p2, c) \}$

Successful plan: $\Delta = \langle load(p1, t1, c), drive(t1, c, s), \\ unload(p1, t1, s), load(p2, t1, s), \\ drive(t1, s, c), unload(p2, t1, c) \rangle$

Other successful plans are, of course, possible

Simplifications: DATALOG- and Propositional STRIPS

- STRIPS as described above allows for unrestricted **first-order terms**, i.e., arbitrarily nested **function terms**
- **Infinite state space**
- Simplification: No function terms (only 0-ary = constants)
- **DATALOG-STRIPS**
- Simplification: No variables in operators (= actions)
- **Propositional STRIPS**
- Propositional STRIPS used in planning algorithms nowadays (but specification is done using DATALOG-STRIPS)

Beyond STRIPS

Even when keeping all the restrictions of classical planning, one can think of a number of **extensions** of the planning language.

- **General logical formulas as preconditions**: Allow all Boolean connectors and quantification
- **Conditional effects**: Effects that happen only if some additional conditions are true. For example, when **pressing the accelerator pedal**, the effects depends on which gear has been selected (no, reverse, forward).
- **Multi-valued state variables**: Instead of 2-valued Boolean variables, multi-valued variables could be used
- **Numerical resources**: Resources (such as fuel or time) can be effected and be used in preconditions
- **Durative actions**: Actions can have duration and can be executed concurrently
- **Axioms/Constraints**: The domain is not only described by operators, but also by additional laws

PDDL: The Planning Domain Description Language

- Since 1998, there exists a bi-annual **scientific competition** for action planning systems.
- In order to have a common language for this competition, **PDDL** has been created (originally by Drew McDermott)
- Meanwhile, version 3.1 (IPC-2011) with most of the features mentioned – and many sub-dialects and extensions.
- Sort of “standard” by now.

PDDL Logistics Example

```
(define (domain logistics)
  (:types truck airplane - vehicle
    package vehicle - physobj
    airport location - place
    city place physobj - object)

  (:predicates (in-city ?loc - place ?city - city)
    (at ?obj - physobj ?loc - place)
    (in ?pkg - package ?veh - vehicle))

  (:action LOAD-TRUCK
    :parameters (?pkg - package ?truck - truck ?loc - place)
    :precondition (and (at ?truck ?loc) (at ?pkg ?loc))
    :effect (and (not (at ?pkg ?loc)) (in ?pkg ?truck)))
    ...)
```

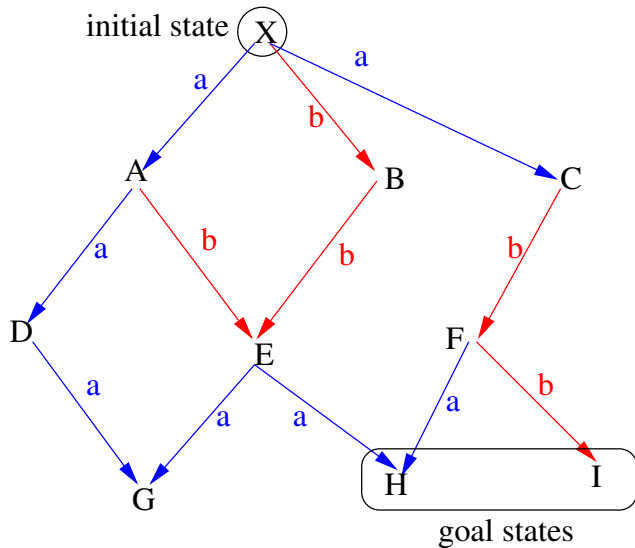
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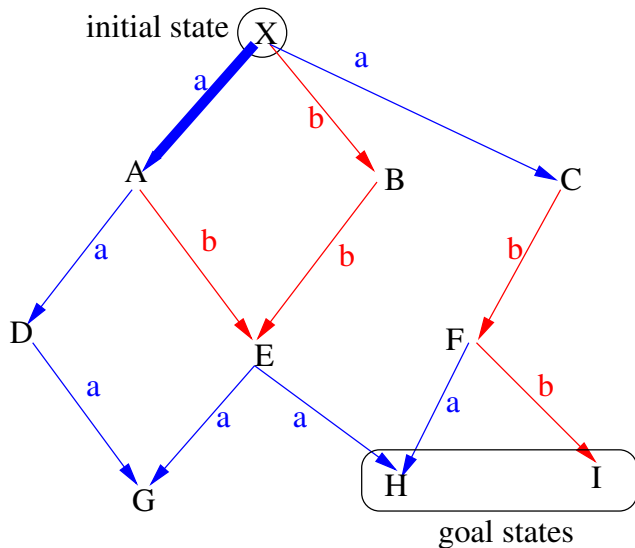
Planning Problems as Transition Systems

- We can view planning problems as searching for goal nodes in a large **labeled graph** (**transition system**)
 - **Nodes** are defined by the value assignment to the fluents = **states**
 - **Labeled edges** are defined by actions that change the appropriate fluents
 - Use graph search techniques to find a (shortest) path in this graph!
 - **Note:** The graph can become **huge**: 50 Boolean variables lead to $2^{50} = 10^{15}$ **states**
- **Create the transition system on the fly and visit only the parts that are *necessary***

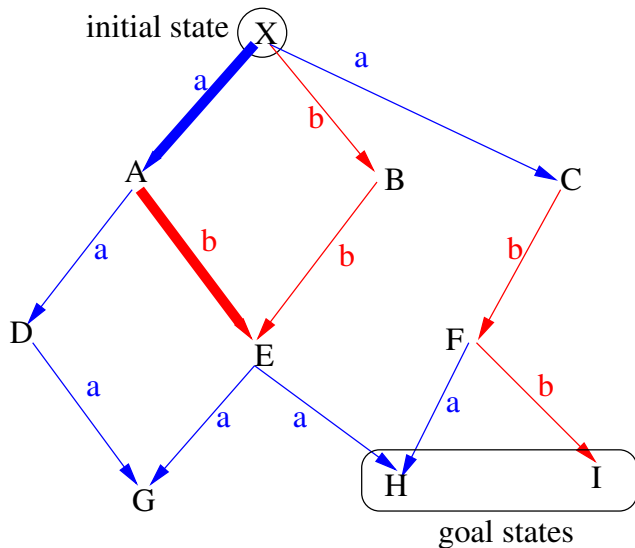
Transition System: Searching Through the State Space



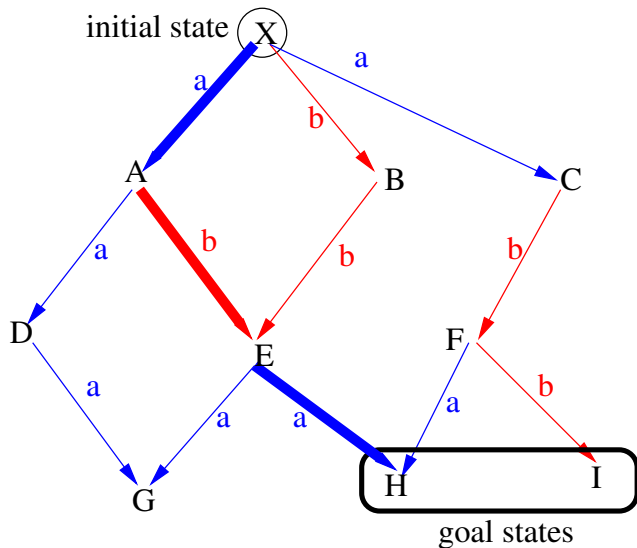
Transition System: Searching Through the State Space



Transition System: Searching Through the State Space



Transition System: Searching Through the State Space



Progression Planning: Forward Search

Search through transition system starting at **initial state**

- 1 Initialize partial plan $\Delta := \langle \rangle$ and **start** at the unique **initial state** I and make it the current state S
- 2 **Test** whether we have reached a **goal state** already: $G \subseteq S$? If so, return plan Δ .
- 3 **Select one applicable action** o_i **non-deterministically** and
 - compute successor state $S := App(S, o_i)$,
 - extend plan $\Delta := \langle \Delta, o_i \rangle$, and continue with step 2.

Instead of non-deterministic choice use some **search strategy**.

Progression planning can be **easily extended** to more expressive planning languages

Progression Planning: Example

$$\mathcal{S} = \{a, b, c, d\},$$

$$\begin{aligned}\mathbf{O} = \{ & o_1 = \langle \emptyset, \{a, b\}, \{\neg b, c\} \rangle, \\ & o_2 = \langle \emptyset, \{a, b\}, \{\neg a, \neg b, d\} \rangle, \\ & o_3 = \langle \emptyset, \{c\}, \{b, d\} \rangle,\end{aligned}$$

$$\mathbf{I} = \{a, b\}$$

$$\mathbf{G} = \{b, d\}$$

{a,b}



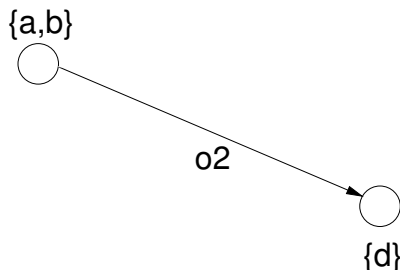
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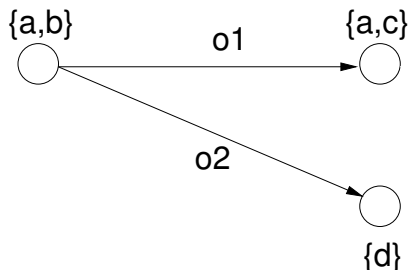
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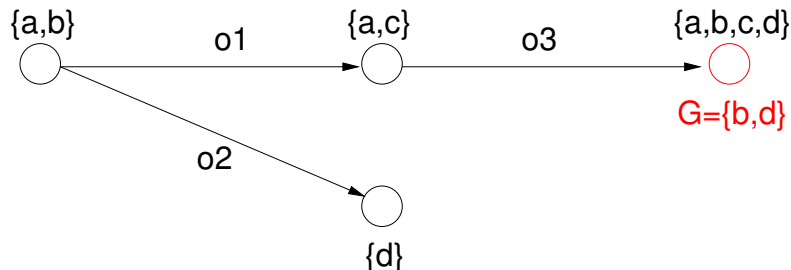
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$$\mathbf{I} = \{a, b\}$$

$$\mathbf{G} = \{b, d\}$$



Regression Planning: Backward Search

Search through transition system starting at **goal states**. Consider **sets of states**, which are **described** by the atoms that are **necessarily true** in them

- 1 Initialize partial plan $\Delta := \langle \rangle$ and set $S := G$
- 2 **Test** whether we have reached the unique **initial state** already: $I \supseteq S$? If so, return plan Δ .
- 3 **Select one action** o_i **non-deterministically** which does not make (sub-)goals false ($S \cap \neg \text{eff}^-(o_i) = \emptyset$) and
 - compute the **regression** of the description S through o_i :

$$S := S - \text{eff}^+(o_i) \cup \text{pre}(o_i)$$

- extend plan $\Delta := \langle o_i, \Delta \rangle$, and continue with step 2.

Instead of non-deterministic choice use some **search strategy**

Regression becomes much more complicated, if e.g. **conditional effects** are allowed. Then the result of a regression can be a general Boolean formula

Regression Planning: Example

$$\mathcal{S} = \{a, b, c, d, e\},$$

$$\begin{aligned}\mathbf{O} = \{ & o_1 = \langle \emptyset, \{b\}, \{\neg b, c\} \rangle, \\ & o_2 = \langle \emptyset, \{e\}, \{b\} \rangle, \\ & o_3 = \langle \emptyset, \{c\}, \{b, d, \neg e\} \rangle,\end{aligned}$$

$$\mathbf{I} = \{a, b\}$$

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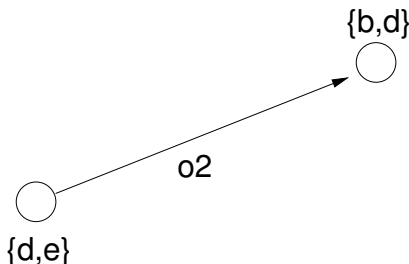
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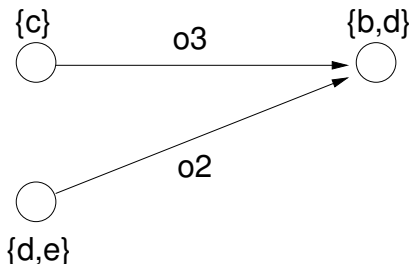
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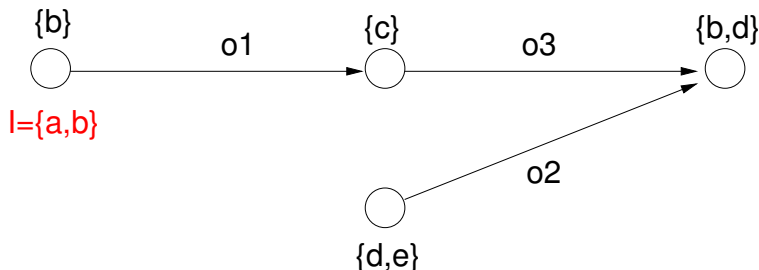
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$$\mathbf{I} = \{a, b\}$$

$$\mathbf{G} = \{b, d\}$$



Other Types of Search

- Of course, other types of search are possible.
- Change perspective: Do not consider the **transition system** as the space we have to explore, but consider the search through the space of (incomplete) plans:
 - **Progression search**: Search through the space of plan **prefixes**
 - **Regression search**: Search through **plan suffixes**
- **Partial order planning**:
 - Search through partially ordered plans by starting with the empty plan and trying to satisfy (sub-)goals by introducing new actions (or using old ones)
 - Make ordering choices only when necessary to resolve conflicts

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The Planning Problem – Formally

Definition (Plan existence problem (PLANEX))

Instance: $\Pi = \langle \mathcal{S}, \mathbf{O}, \mathbf{I}, \mathbf{G} \rangle$.

Question: Does there exist a plan Δ that solves Π , i.e., $\text{Res}(\mathbf{I}, \Delta) \supseteq \mathbf{G}$?

Definition (Bounded plan existence problem (PLANLEN))

Instance: $\Pi = \langle \mathcal{S}, \mathbf{O}, \mathbf{I}, \mathbf{G} \rangle$ and a positive integer n .

Question: Does there exist a plan Δ of length n or less that solves Π ?

From a practical point of view, also **PLANGEN** (*generating* a plan that solves Π) and **PLANLENGEN** (*generating* a plan of length n that solves Π) and **PLANOPT** (generating an optimal plan) are interesting (but at least as hard as the decision problems).

Basic STRIPS with First-Order Terms

- The state space for STRIPS with general first-order terms is **infinite**
- We can use function terms to describe (the index of) **tape cells of a Turing machine**
- We can use operators to describe the **Turing machine control**
- The existence of a plan is then equivalent to the existence of a **successful computation** on the Turing machine
- PLANEX for STRIPS with first-order terms can be used to decide the **Halting problem**

Theorem

*PLANEX for STRIPS with first-order terms is **undecidable**.*

Theorem

*PLANEX is **PSPACE-complete** for propositional STRIPS.*

- Membership follows because we can successively guess operators and compute the resulting states (needs only polynomial space)
- Hardness follows using again a **generic reduction** from TM acceptance. Instantiate polynomially many tape cells with no possibility to extend the tape (only poly. space, can all be generated in poly. time)
- PLANLEN is also PSPACE-complete (membership is easy, hardness follows by setting $k = 2^{|\Sigma|}$)

Restrictions on Plans

- If we restrict the length of the plans to be **short**, i.e., only **polynomial** in the size of the planning task, **PLANEX** becomes **NP-complete**
- Similarly, if we use a **unary** representation of the natural number k , then **PLANLEN** becomes **NP-complete**
- Membership obvious (guess & check)
- Hardness by a straightforward reduction from SAT or by a generic reduction.
- One source of complexity in planning stems from the fact that plans can become **very long**
- We are only interested in short plans!
- We can use methods for NP-complete problems if we are only looking for “short” plans.

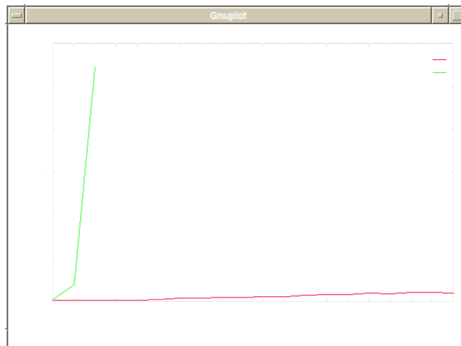
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- Planning as satisfiability: Iterative deepening.
- Planning with answer set programming.
- Symbolic planning with BDDs (finding many plans or non-det. plans)
- Heuristic forward-search planning (HSP, FF, FD)

Heuristic Search Planning

- Use an **automatically generated heuristic estimator** in order to select the next action or state
 - Depending on the **search scheme** and the **heuristic**, the plan might not be the shortest one
- It is often easier to go for **sub-optimal** solutions (remember *Logistics*)



Runtime of Heuristic search planner (red) vs. iterative deepening (green) on [Gripper](#)

Deriving Heuristics: Relaxations

- General principle for deriving heuristics:
 - Define a **simplification** (relaxation) of the problem and take the difficulty of a solution for the simplified problem as an **heuristic estimator**
- Example: **straight-line distance** on a map to estimate the travel distance
- Example: **decomposition** of a problem, where the components are solved ignoring the interactions between the components, which may incur additional costs
- In planning, one possibility is to ignore **negative effects**

Ignoring Negative Effects: Example

- In **Logistics**: The negative effects in *load* and *drive* are ignored:
 - **Simplified** load operation: $load(O, V, P)$
Precondition: $at(O, P), at(V, P), truck(V)$
Effects: $\neg at(O, P), in(O, V)$
 - After loading, the package is still at the place and also inside the truck
 - **Simplified** drive operation: $drive(V, P1, P2)$
Precondition: $at(V, P1), truck(V), street(P1, P2)$
Effects: $\neg at(V, P1), at(V, P2)$
 - After driving, the truck is in two places!
- We want the length of the shortest **relaxed** plan $\rightsquigarrow h^+(s)$
- How difficult is **monotonic planning**?

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Current Trends in AI Planning

- Developing and analyzing heuristics
- Developing and analyzing pruning techniques
- Developing new search techniques
- Extending the expressiveness of planning formalisms (and extending planning algorithms) in order to deal with
 - temporal planning,
 - planning with non-deterministic actions,
 - planning under partial observability,
 - planning with probabilistic effects,
 - multi-agent planning,
 - planning with epistemic goals,
- Reasoning about plans, e.g., diagnosing failures
- Judging morality of plans
- Applying/integrating planning technology
- Learning and planning
- ...

- Foundation / theory
- Extending planning technology in order to cope with **multi-agent scenarios and epistemic goals**
- Using **EVMDDs** in modelling state-dependent costs
- Using planning techniques and extending them for **robot control**
- Using planning methodology in **application** in general
- Exploring the **ethical dimension** of planning systems

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Summary

- Rational agents need to **plan** their course of action
- In order to describe planning tasks in a domain-independent, declarative way, one needs **planning formalisms**
- Basic **STRIPS** is a simple planning formalism, where actions are described by their preconditions in form of a conjunction of atoms and the effects are described by a list of literals that become true and false
- **PDDL** is the current “standard language” that has been developed in connection with the **international planning competition**
- Basic planning algorithms search through the space created by the **transition system** or through the **plan space**.
- Planning with **STRIPS** using **first-order** terms is **undecidable**
- Planning with **propositional STRIPS** is **PSPACE-complete**
- Since 1992, we have reasonably efficient planning method for **propositional, classical STRIPS planning**
- You can learn more about it in our **planning class** next term.