

Principles of AI Planning

13. Nondeterministic planning

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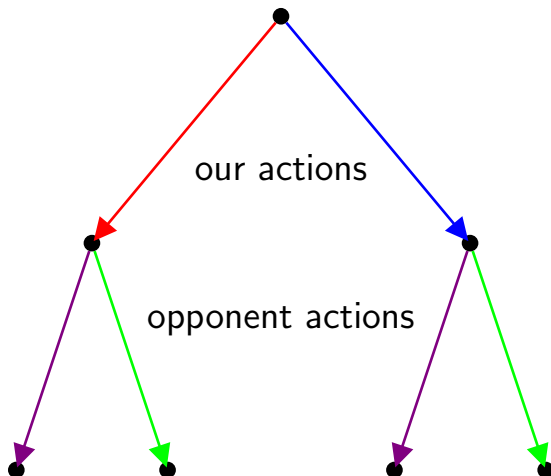
1 Motivation

Nondeterministic planning

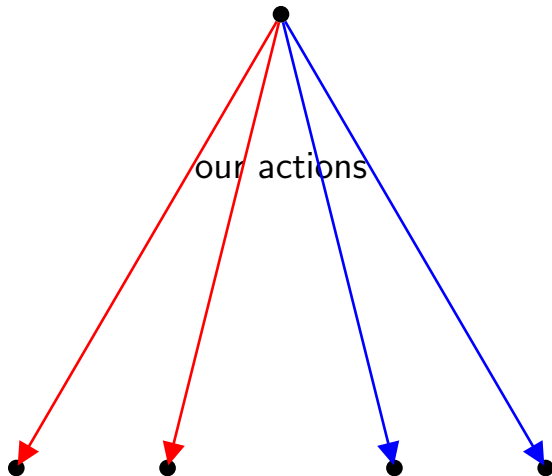
- ▶ The world is not predictable.
- ▶ AI robotics:
 - ▶ imprecise movement of the robot
 - ▶ other robots
 - ▶ human beings, animals
 - ▶ machines (cars, trains, airplanes, lawn-mowers, ...)
 - ▶ natural phenomena (wind, water, snow, temperature, ...)
- ▶ Games: other players are outside our control.
 - ▶ To win a game (reaching a goal state) with certainty, all possible actions by the other players have to be anticipated (a **winning strategy** of a game).
 - ▶ The world is not predictable because it is unknown: we cannot **observe** everything.

In this lecture, we will only deal with uncertain operator outcomes, not with partial observability.

Nondeterminism in games



Nondeterminism in games



Nondeterministic planning

- ▶ In **deterministic planning** we have assumed that the only changes taking place in the world are those caused by us and that we can **exactly predict** the results of our actions.
- ▶ **Other agents** and processes, beyond our control, are formalized as **nondeterminism**.
- ▶ Implications:
 1. The future state of the world cannot be predicted.
 2. We cannot reliably plan ahead: no single operator sequence achieves the goals.
 3. In some cases it is not possible to achieve the goals with certainty no matter which outcomes the actions have, but only under certain fairness assumptions.

2 Transition systems and planning tasks

- Transition systems
- Operators
- Planning tasks

Transition systems with nondeterminism (cf. Chapter 2)

Definition (transition system)

A **nondeterministic transition system** is a 5-tuple $\mathcal{T} = \langle S, L, T, s_0, S_\star \rangle$ where

- ▶ S is a finite set of **states**,
- ▶ L is a finite set of (transition) **labels**,
- ▶ $T \subseteq S \times L \times S$ is the **transition relation**,
- ▶ $s_0 \in S$ is the **initial state**, and
- ▶ $S_\star \subseteq S$ is the set of **goal states**.

Note: $T \subseteq S \times L \times S$ allows **nondeterministic operators** with more than one possible outcome.

Nondeterministic operators

Definition (nondeterministic operator)

Let V be a set of finite-domain state variables. A nondeterministic operator in unary nondeterminism normal form with conjunctive precondition and unconditional effects, or **nondeterministic operator** for short, is a pair $o = \langle \chi, E \rangle$, where

- ▶ χ is a conjunction of atoms over V (the **precondition**), and
- ▶ $E = \{e_1, \dots, e_n\}$ is a finite set of possible **effects** of o , each e_i being a conjunction of atomic finite-domain effects over V .

Nondeterministic operators

Definition (nondeterministic operator application)

Let $o = \langle \chi, E \rangle$ be a nondeterministic operator and s a state.

Applicability of o in s is defined as in the deterministic case, i.e., o is **applicable** in s iff $s \models \chi$ and the change set of each effect $e \in E$ is consistent.

If o is applicable in s , then the **application** of o in s leads to one of the states in the set $app_o(s) := \{app_{\langle \chi, e \rangle}(s) \mid e \in E\}$ nondeterministically.

Nondeterministic operators

Example

$put\text{-on-block}(A, B) = \langle \chi, \{e_1, e_2\} \rangle$ where

- ▶ $\chi = \{handempty \mapsto false, clear\text{-}B \mapsto true, pos\text{-}A \mapsto hand\}$,
- ▶ $e_1 = \{handempty \mapsto true, clear\text{-}B \mapsto false, pos\text{-}A \mapsto on\text{-}B\}$,
- ▶ $e_2 = \{handempty \mapsto true, posn\text{-}A \mapsto table\}$.

Applied to a state where the agent is holding block A and block B is clear, this operator leads to one of two possible successor states. Either A gets stacked on B successfully, or A is dropped to the table.

Nondeterministic planning task

Definition (nondeterministic planning task)

A (fully observable) **nondeterministic planning task** is a 4-tuple

$\Pi = \langle V, I, O, \gamma \rangle$ where

- ▶ V is a finite set of **finite-domain state variables**,
- ▶ I is an **initial state** over V ,
- ▶ O is a finite set of **nondeterministic operators** over V , and
- ▶ γ is a conjunctions of atoms over V describing the **goal states**.

Remark: In the following, we will always assume that our nondeterministic planning tasks are fully observable and omit the qualification.

Mapping planning tasks to transition systems

Definition (induced transition system)

Every nondeterministic planning task $\Pi = \langle V, I, O, \gamma \rangle$ induces a corresponding nondeterministic transition system $\mathcal{T}(\Pi) = \langle S, L, T, s_0, S_\star \rangle$:

- ▶ S is the set of all states over V ,
- ▶ L is the set of operators O ,
- ▶ $T = \{ \langle s, o, s' \rangle \mid s \in S, o \text{ applicable in } s, s' \in \text{app}_o(s) \}$,
- ▶ $s_0 = I$, and
- ▶ $S_\star = \{ s \in S \mid s \models \gamma \}$

3 Plans

- Motivation
- Definition

What is a plan?

In nondeterministic planning, plans are more complicated objects than in the deterministic case:

The best action to take may **depend** on nondeterministic effects of previous operators.

Nondeterministic plans thus often require **branching**. Sometimes, they even require **looping** (we will likely only cover branching in this course).

What is a plan?

Example (Branching)

(Part of) a plan for winning the game **Connect Four** can be described as follows:

- ▶ Place a tile in the 4th column.
 - ▶ If opponent places a tile in the 1st, 4th or 7th column, place a tile in the 4th column.
 - ▶ If opponent places a tile in the 2nd or 5th column, place a tile in the 2nd column.
 - ▶ If opponent places a tile in the 3rd or 6th column, place a tile in the 6th column.

There is no **non-branching** plan that solves the task
(= is guaranteed to win the game).

What is a plan?

Example (Looping)

A plan for building a card house can be described as follows:

1. Build a wall with two cards.
If the structure falls apart, redo from start.
2. Build a second wall with two cards.
If the structure falls apart, redo from start.
3. Build a ceiling on top of the walls with a fifth card.
If the structure falls apart, redo from start.
4. Build a wall on top of the ceiling with two cards.
If the structure falls apart, redo from start.

There is no **non-looping** plan that solves the task (unless the planning agent is very dextrous).

What is a plan?

- ▶ Plans should be allowed to **branch**. Otherwise, most interesting nondeterministic planning tasks cannot be solved.
- ▶ We may or may not allow plans to **loop**.
 - ▶ Non-looping plans are preferable because they **guarantee** that the goal is reached within a bounded number of steps.
 - ▶ Where non-looping plans are not possible, looping plans may be adequate because they at least guarantee that the goal will be reached **eventually** unless nature is **unfair**.

We will now introduce the formal concepts necessary to define branching (and looping) plans.

Nondeterministic plans: formal definition

Definition (strategy)

Let $\Pi = \langle V, I, O, \gamma \rangle$ be a nondeterministic planning task with state set S and goal states S_* .

A **strategy** for Π is a function $\pi : S_\pi \rightarrow O$ for some subset $S_\pi \subseteq S$ such that $\pi(s)$ is applicable in s for all $s \in S_\pi$.

The set of states reachable in $\mathcal{T}(\Pi)$ starting in state s and following π is denoted by $S_\pi(s)$.

Nondeterministic plans: formal definition

Definition (weak, closed, proper, and acyclic strategies)

Let $\Pi = \langle V, I, O, \gamma \rangle$ be a nondeterministic planning task with state set S and goal states S_* , and let π be a strategy for Π .

Then π is called

- ▶ **weak** iff $S_\pi(s_0) \cap S_* \neq \emptyset$,
- ▶ **closed** iff $S_\pi(s_0) \subseteq S_\pi \cup S_*$,
- ▶ **proper** iff $S_\pi(s') \cap S_* \neq \emptyset$ for all $s' \in S_\pi(s_0)$, and
- ▶ **acyclic** iff there is no state $s' \in S_\pi(s_0)$ such that s' is reachable from s' following π in a strictly positive number of steps.

Nondeterministic plans: formal definition

- ▶ **Strategies** in nondeterministic planning correspond to **applicable operator sequences** in deterministic planning.
- ▶ In deterministic planning, a **plan** is an applicable operator sequence that results in a goal state.
- ▶ In nondeterministic planning, we define different notions of “resulting in a goal state”.

Nondeterministic plans: formal definition

Definition

Let $\Pi = \langle V, I, O, \gamma \rangle$ be a nondeterministic planning task with state set S and goal states S_* .

- ▶ A strategy for Π is called a **weak plan** for Π iff it is weak.
- ▶ A strategy for Π is called a **strong cyclic plan** for Π iff it is closed and proper.
- ▶ A strong cyclic plan for Π is called a **strong plan** for Π iff it is acyclic.

Summary and outlook

We extended the deterministic (**classical**) planning formalism:

- ▶ **operators** can be nondeterministic

Remark: We could also introduce nondeterminism in the initial situation by allowing more than one initial state, but this can be easily compiled into our formalism.

As a consequence, **plans** can contain

- ▶ **branches** and
- ▶ **loops**.

In the following chapter, we consider the **strong planning** problem (and maybe strong cyclic planning, if time permits) and discuss some algorithms.