

Principles of AI Planning

17. Strong cyclic planning

Albert-Ludwigs-Universität Freiburg



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1 Strong cyclic plans



- Motivation
- Nested Fixpoint Algorithm
- Incremental Planning Algorithm

Strong cyclic plans

Motivation

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Incremental Planning Algorithm

Maintenance

Summary

- The simplest objective for nondeterministic planning is the one we have considered in the previous lecture: reach a goal state with certainty.
- With this objective the nondeterminism can also be understood as **an opponent** like in 2-player games. The plan guarantees reaching a goal state no matter what the opponent does: plans are **winning strategies**.

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- In strong plans, goal states can be reached without visiting any state twice.
- This property guarantees that the length of executions is bounded by some constant (which is smaller than the number of states.)
- Some solvable problems are not solvable this way.
 - 1 Action may fail to have any effect.
Hit a coconut to break it.
 - 2 Action may fail and take us away from the goals.
Build a house of cards.

Consequences:

- 1 It is impossible to avoid visiting some states several times.
- 2 There is no finite upper bound on execution length.

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Fairness assumption

For any nondeterministic operator $\langle \chi, \{e_1, \dots, e_n\} \rangle$, the “probability” of every effect e_i , $i = 1, \dots, n$, is greater than 0.

Alternatively: For each $s' \in \text{img}_o(s)$ the “probability” of reaching s' from s by o is greater than 0.

This assumption guarantees that a strong cyclic plan reaches the goal **almost certainly** (with probability 1).

This is **not compatible** with viewing nondeterminism as an opponent in a 2-player game: the opponent’s strategy might rule out some of the choices e_1, \dots, e_n .

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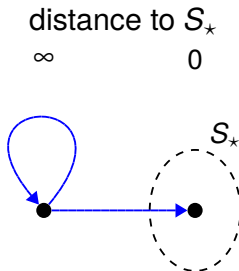
Need for strong cyclic plans

Example

Example (Breaking a coconut)

- Initial state: coconut is intact.
- Goal state: coconut is broken.
- On every hit the coconut may or may not break.
- There is no finite upper bound on the number of hits.

This is equivalent to coin tossing.



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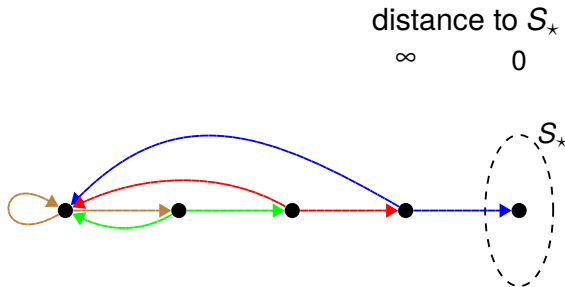
Need for strong cyclic plans

Example



Example (Build a house of cards)

- Initial state: all cards lie on the table.
- Goal state: house of cards is complete.
- At every construction step the house may collapse.



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We present two algorithms for strong cyclic planning:

- The **nested fixpoint algorithm** is conceptually simpler, but typically very costly, especially if not implemented symbolically.
 - Historically older
 - **Uninformed**
 - **Considers entire state space**
- The **determinization-based incremental planning algorithm** is a bit more complicated, but typically more efficient.
 - Historically newer, **state of the art**
 - Can use **informed** classical planner as sub-procedure
 - Often only **considers small portion of state space**

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- Finds plans that may loop (strong cyclic plans).
- The algorithm is rather tricky in comparison to the algorithm for strong plans.
- Every state covered by a plan satisfies two properties:
 - 1 The state is **good**: there is at least one execution (= path in the graph defined by the plan) leading to a goal state.
 - 2 Every successor state is either a goal state or good.
- The algorithm repeatedly eliminates states that are not good.

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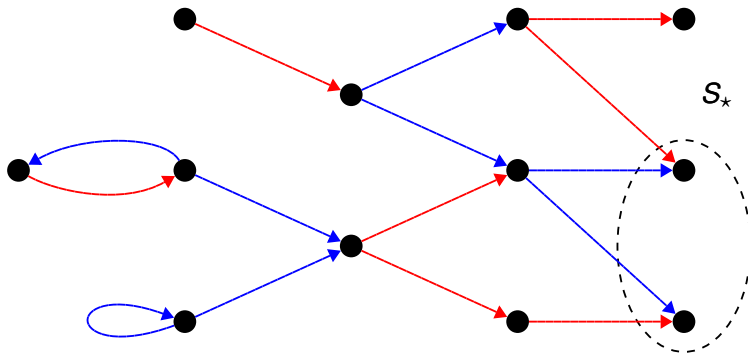
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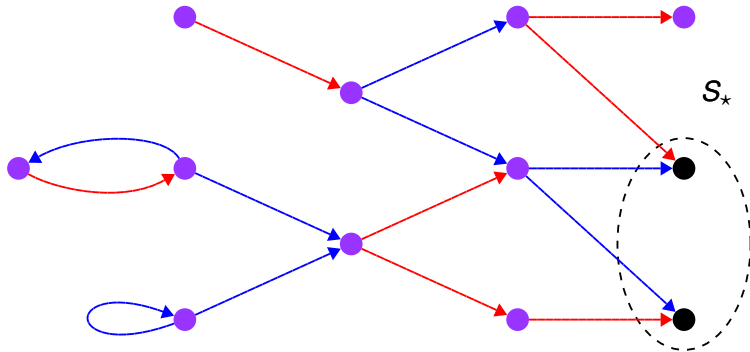


Nested Fixpoint Algorithm

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All states are candidates for being good.



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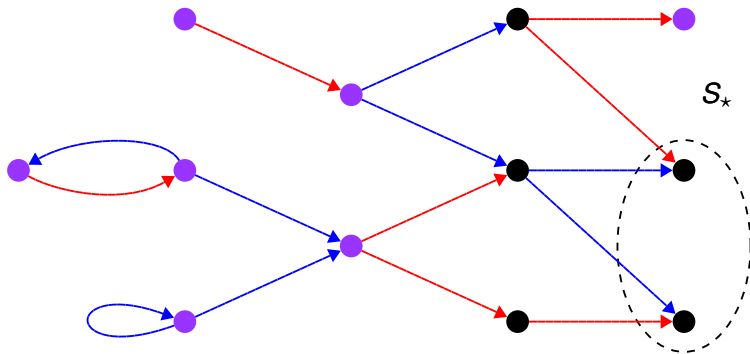
Summary

Nested Fixpoint Algorithm

Example



States from which goals are reachable in ≤ 1 steps so that all immediate successors are possibly good.



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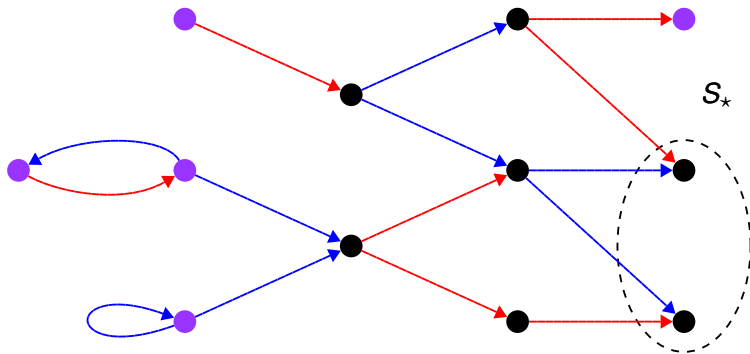
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States from which goals are reachable in ≤ 2 steps so that all immediate successors are possibly good.



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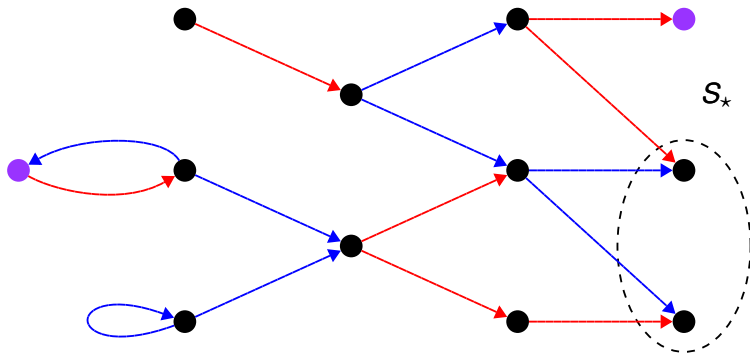
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States from which goals are reachable in ≤ 3 steps so that all immediate successors are possibly good.



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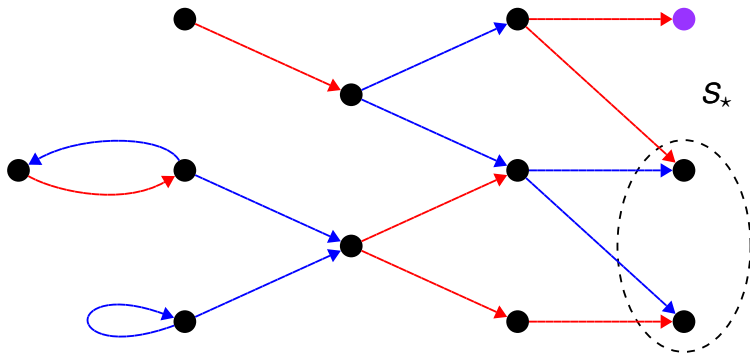
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States from which goals are reachable in ≤ 4 steps so that all immediate successors are possibly good.



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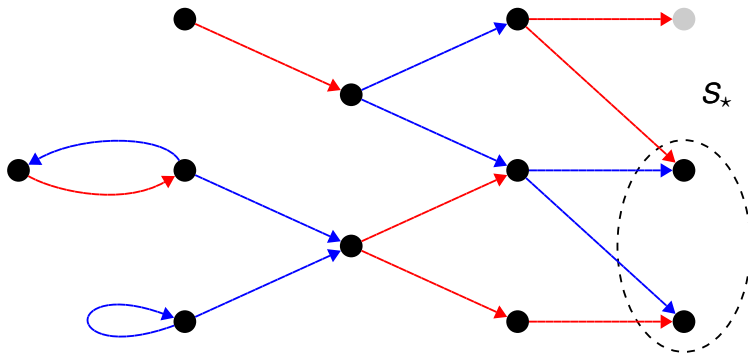
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Example



Eliminate states that turned out not to be good.



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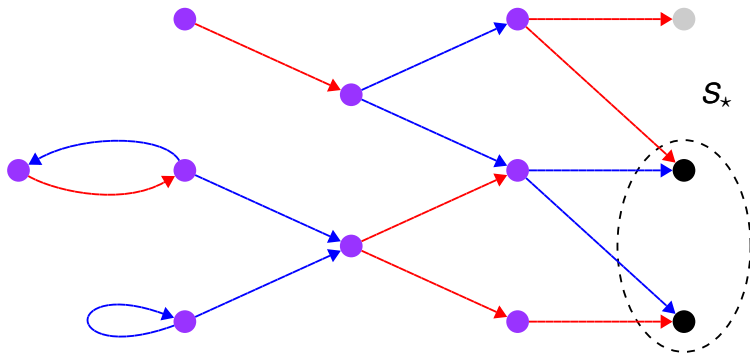
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Example



The set of possibly good states is now smaller.



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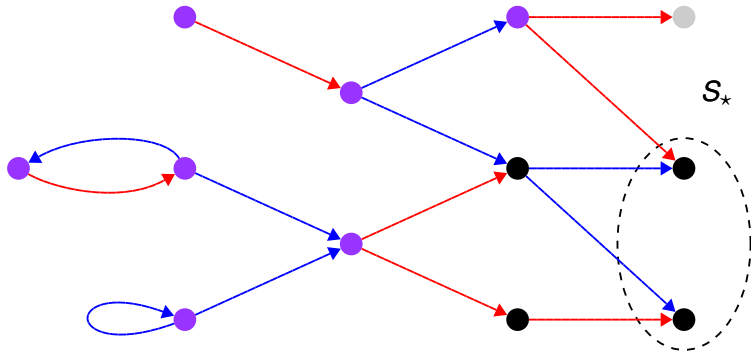
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States from which goals are reachable in ≤ 1 steps so that all immediate successors are possibly good.



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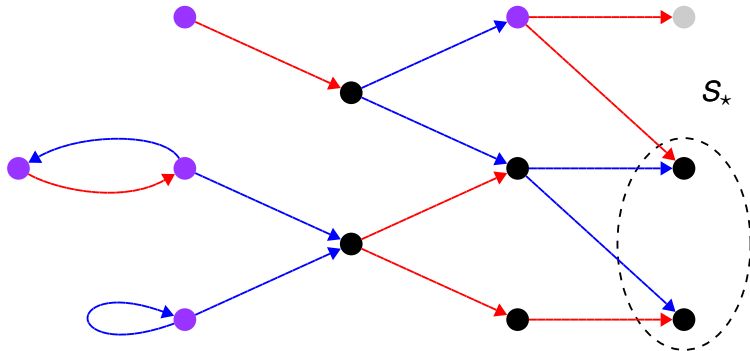
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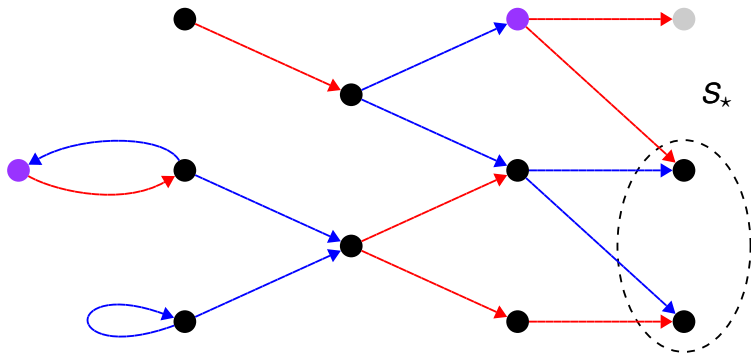
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States from which goals are reachable in ≤ 3 steps so that all immediate successors are possibly good.



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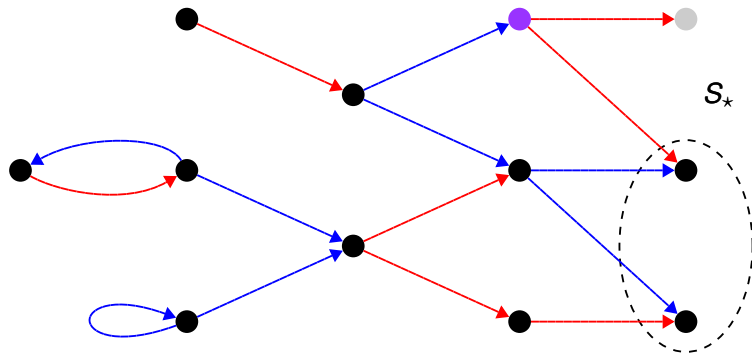
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States from which goals are reachable in ≤ 4 steps so that all immediate successors are possibly good.



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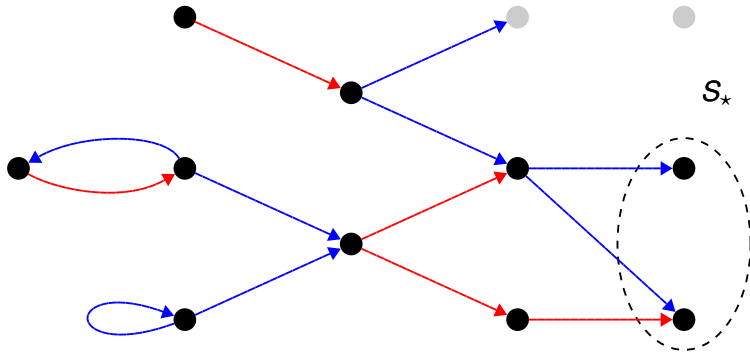
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Eliminate states that turned out not to be good.



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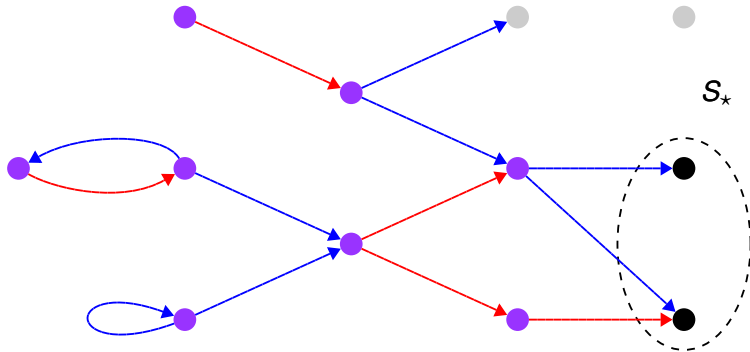
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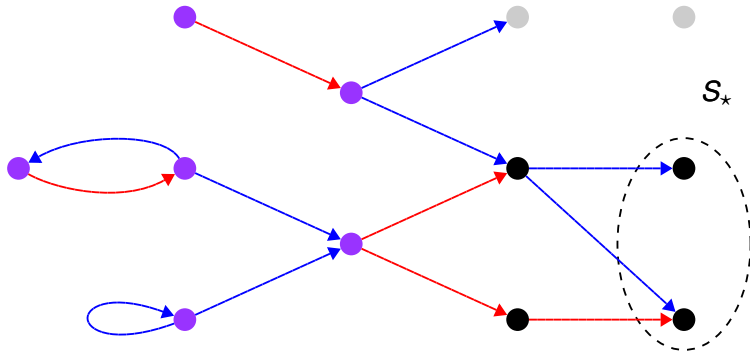
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States from which goals are reachable in ≤ 1 steps so that all immediate successors are possibly good.



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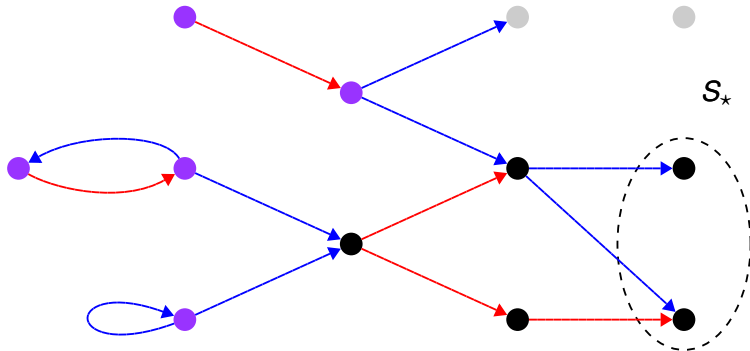
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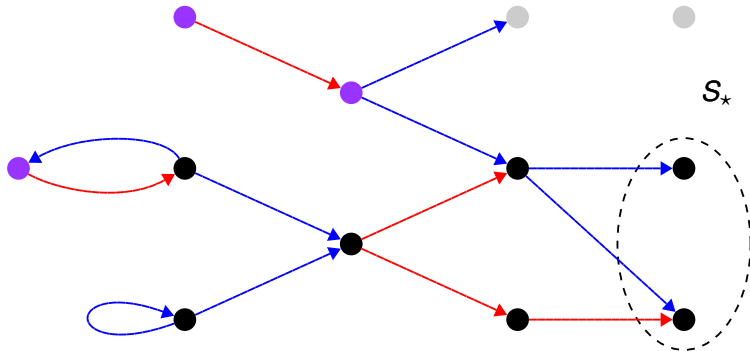
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States from which goals are reachable in ≤ 3 steps so that all immediate successors are possibly good.



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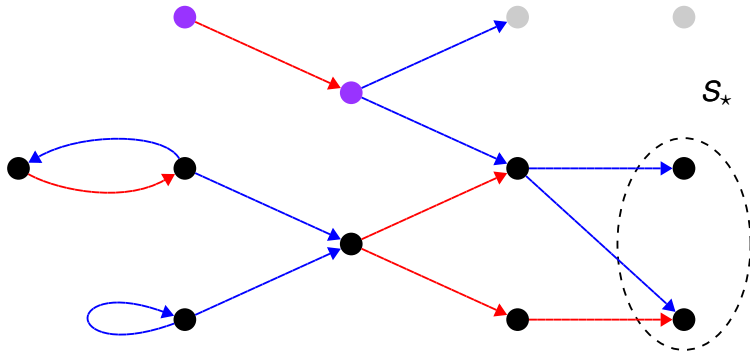
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States from which goals are reachable in ≤ 4 steps so that all immediate successors are possibly good.



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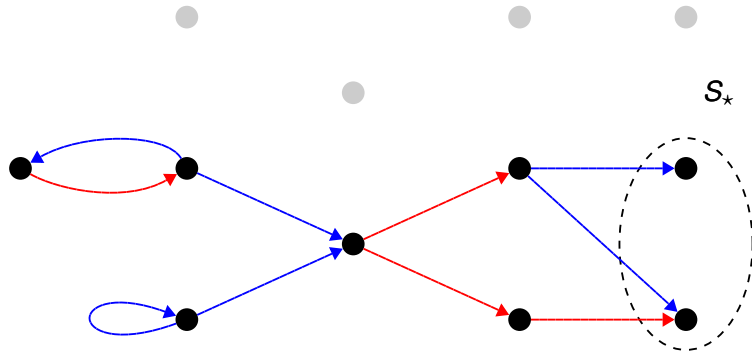
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Remaining states are all good.

A further iteration would not eliminate more states.



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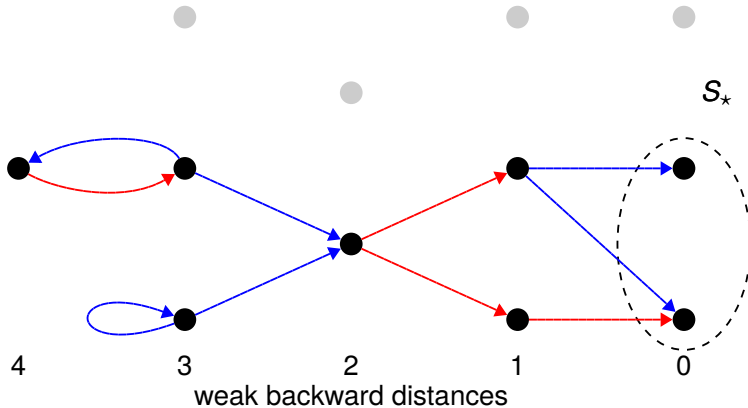
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Assign each state an operator so that the successor states are goal states or good, and some of them are closer to goal states. Use **weak distances** computed with **weak preimages**. For this example this is trivial.



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Recall the definition of cyclic strong plans:

Definition (strong cyclic plan)

Let S be the set of states of a planning task Π . Then a **strong cyclic plan** 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 $s \in S_\pi$,
- $S_\pi(s_0) \subseteq S_\pi \cup S_\star$ (π is closed), and
- $S_\pi(s') \cap S_\star \neq \emptyset$ for all $s' \in S_\pi(s_0)$ (π is proper).

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- The procedure **prune** finds a maximal set of states for which reaching goals with looping is possible.
- It consists of two nested loops:
 - 1 The outer loop iterates through $i = 0, 1, 2, \dots$ and produces a **shrinking** sequence of candidate good state sets C_0, C_1, \dots, C_n until $C_i = C_{i+1}$.
 - 2 The inner loop identifies **growing** sets W_j of states from which a goal state can be reached with j steps without leaving the current set of candidate good states C_i . The union of all W_0, W_1, \dots will be C_{i+1} .

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Procedure *prune*

def *prune*(S, O, S_*):

$C_0 := S$

for each $i \in \mathbb{N}_1$:

$W_0 := S_*$

for each $j \in \mathbb{N}_1$:

$W_j := W_{j-1} \cup \bigcup_{o \in O} (\text{wpreimg}_o(W_{j-1}) \cap \text{spreimg}_o(C_{i-1}))$

if $W_j = W_{j-1}$:

break

$C_i := W_j$

if $C_i = C_{i-1}$:

return $\langle C_i, \langle W_0, \dots, W_{j-1} \rangle \rangle$

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Lemma (Procedure *prune*)

Let S and $S_\star \subseteq S$ be sets of states and O a set of operators. Then $\text{prune}(S, O, S_\star)$ terminates after a finite number of steps and returns $C \subseteq S$ such that there is a strategy $\pi : C \setminus S_\star \rightarrow O$ that is a strong cyclic plan (for the states for which it is defined) and maximal in the sense that there is no set $C' \supsetneq C$ and a strong cyclic plan $\pi' : C' \setminus S_\star \rightarrow O$.

- The sets W_j also returned by *prune* encode weak distances and can be used to define the strong cyclic plan π .

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The planning algorithm

def strong-cyclic-plan($\langle V, I, O, \gamma \rangle$):

$S :=$ set of states over V

$S_\star := \{s \in S \mid s \models \gamma\}$

$\langle C, (W_j)_{j=0,1,2,\dots} \rangle = \text{prune}(S, O, S_\star)$

if $I \notin C$:

return no solution

for each $s \in C$:

$\delta(s) := \min\{j \in \mathbb{N}_0 \mid s \in W_j\}$

for each $s \in C \setminus S_\star$:

$\pi(s) :=$ some operator $o \in O$ with $\text{img}_o(s) \subseteq C$
and $\min\{\delta(s') \mid s' \in \text{img}_o(s)\} < \delta(s)$

return π

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- The procedure *prune* runs in polynomial time in the number of states because the number of iterations of each loop is at most n – hence there are $O(n^2)$ iterations – and computation on each iteration takes polynomial time in the number of states.
- Finding strong cyclic plans for full observability is in the complexity class EXPTIME.
- The problem is also EXPTIME-hard.
- Similar to strong planning, we can speed up the algorithm in many practical cases by using a symbolic implementation (e. g. with BDDs).

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Idea [Kuter/Nau/Reisner/Goldman, 2008; Fu/Ng/Bastiani/Yen, 2011]:

1. Pretend the planning task was deterministic: Turn each action $o = \langle \chi, E \rangle$ with $E = \{e_1, \dots, e_n\}$ into n actions $o_i = \langle \chi, e_i \rangle$ for $i = 1, \dots, n$. Obtain classical problem Π' .
2. Find classical plan P in Π' . Add state-action mapping corresponding to P to π .
3. For each operator o_i used in P (in state s), identify original nondeterministic operator o and states $S' = \text{img}_o(s)$.
4. For each “open” state $s' \in S'$, go to 2.

Remark: May require backtracking, if some state used in a classical plan turns out not to admit a strong cyclic plan.

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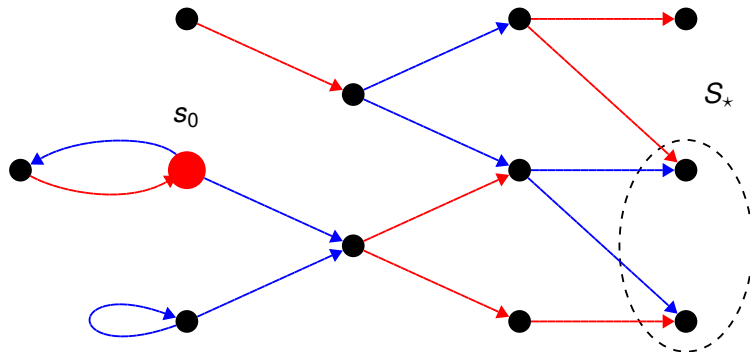
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Summary

Definition (all-outcomes determinization)

Let $\Pi = \langle V, I, O, \gamma \rangle$ be a nondeterministic planning task. The **all-outcomes determinization** of Π is the deterministic planning task $\Pi_{\text{det}} = \langle V, I, O_{\text{det}}, \gamma \rangle$, where $O_{\text{det}} = \bigcup_{o \in O} o_{\text{det}}$, and $\langle \chi, E \rangle_{\text{det}} = \{ \langle \chi, e \rangle \mid e \in E \}$.

List of states to solve: $\{s_0\}$



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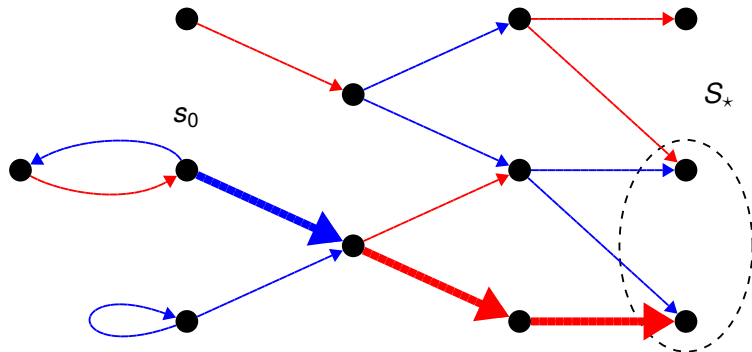
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Summary

Plan for s_0 in determinization: *blue₂, red₂, red*



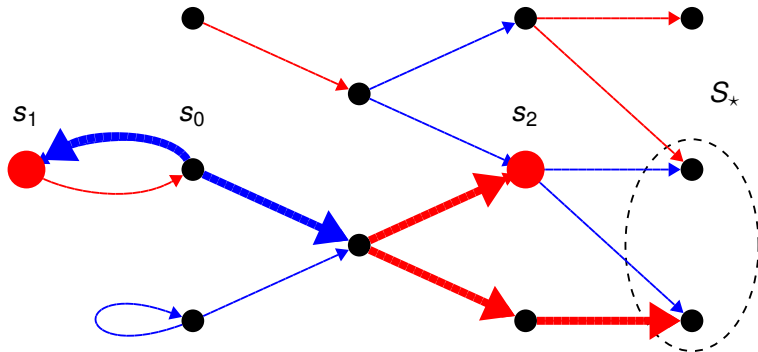
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“Undesired” outcomes of $blue_1$ and red_1 lead to new list of states to solve: $\{s_1, s_2\}$



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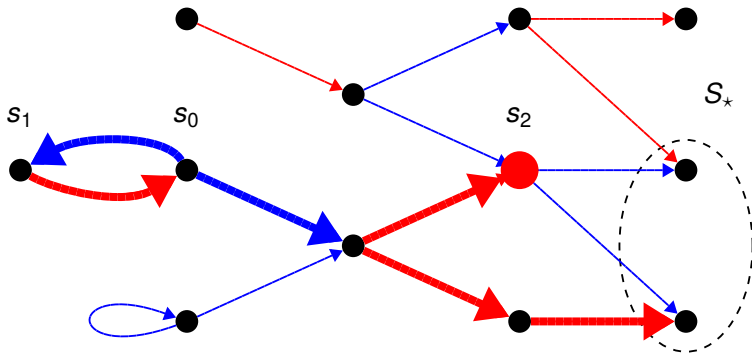
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Plan for s_1 in determinization: *red, blue₂, red₂, red*



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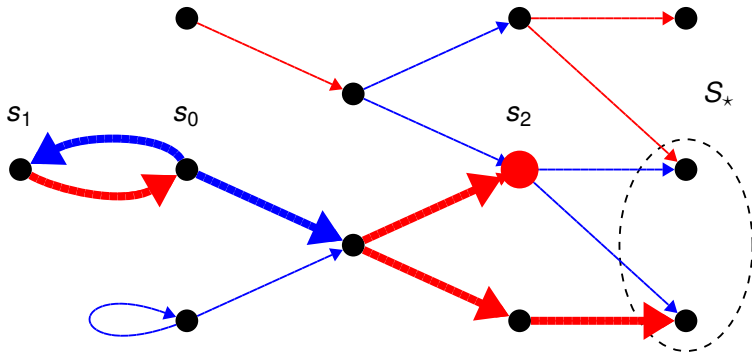
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Summary

No new “undesired” outcomes.

List of states to solve: $\{s_2\}$



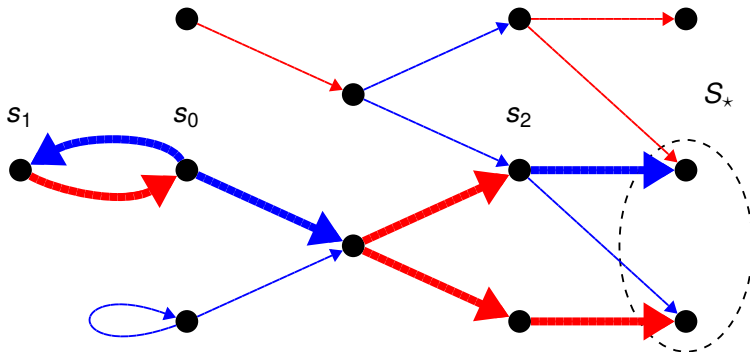
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Plan for s_2 in determinization: *blue₁*



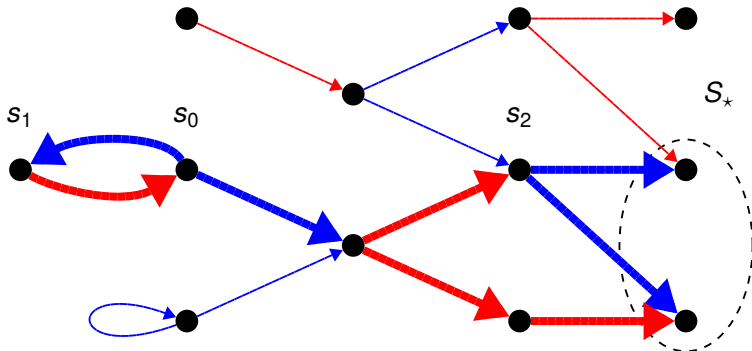
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Summary

“Undesired” outcome of *blue*₂ in *s*₂ leads to goal state, too.
List of states to solve: \emptyset . Strong cyclic plan found.



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Procedure incremental-strong-cyclic-plan

def incremental-strong-cyclic-plan($\langle V, I, O, \gamma \rangle$):

$\pi \leftarrow \emptyset$; *fail* $\leftarrow \{I\}$

while *fail* $\neq \emptyset$:

$s \leftarrow \text{SELECTANDREMOVEFROM}(\textit{fail})$

$\pi' \leftarrow \text{DETSEARCH}(\langle V, s, O_{\text{det}}, \gamma \rangle)$

if $\pi' = \text{FAILURE}$:

if $s = I$: **return** FAILURE

else: $\text{BACKTRACK}(s, \pi, \langle V, I, O, \gamma \rangle)$

else:

$\pi \leftarrow \pi \cup \pi'$

fail $\leftarrow \{s \in S \mid s \text{ nongoal state reachable from } I$
following π , but $\pi(s)$ undefined}

return π

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Summary

If a deterministic search fails, the state s from which it started cannot be part of a strong cyclic plan.

- If $s = l$, the whole given planning problem is unsolvable and the algorithm returns FAILURE.
- Otherwise, state s , which has already been added to the constructed policy π , has to be removed from π , and the algorithm has to ensure that s will never be reconsidered again. This is accomplished by the procedure BACKTRACK.

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Procedure backtrack

def backtrack($s, \pi, \langle V, I, O, \gamma \rangle$):

update π by deleting all entries that would immediately

lead to s , i.e. $\pi \leftarrow \pi \setminus \{(s', \pi(s')) \mid s \in \text{img}_{\pi(s')}(s')\}$

add all states s' removed from π to the set of fail-states *fail*

permanently mark all formerly assigned actions $\pi(s')$

removed from π at s' as inapplicable in s' to avoid
running into the same dead end again.

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Summary



- Iteratively solves all-outcomes determinizations of Π with “fail-states” as initial states.
- Planner can choose desired outcome of each action.
- Deterministic plans are added to policy under construction.
- Corresponding undesired outcomes have to be added to the set of “fail-states” *fail*.
- Deterministic plans for “fail-states” are constructed until no more “fail-states” remain.
- Eventually, the algorithm either returns a strong cyclic plan or FAILURE if no such plan exists.

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Theorem

Procedure incremental-strong-cyclic-plan, called with task Π , returns a strong cyclic plan for Π iff such a plan exists, and FAILURE, otherwise.

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Summary

Determinization-based Incremental Alg.

Underlying classical planner



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- Can use any classical planner for deterministic searches.
- Can benefit from heuristics etc. used there.
- Classical planner can be configured to prefer short solutions or solutions using deterministic actions induced by nondeterministic actions with few different outcomes (likely fewer new “fail-states”).

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Summary

- When to terminate a deterministic sub-search?
 - At goal states?
 - At states currently part of the partial solution?
 - At parent of currently solved “fail-state”?

This can make a huge difference.

- Similarly: Where should the heuristic guide the classical planner? Goals, partial solution, parent node?
- Additional marking of nodes as definitely solved if this can be detected.
- State reuse between subsequent classical planner calls.
- Generalization of solved states by regression search from goal along weak (deterministic) plan (cf. [Muise/McIlraith/Beck, 2012]).

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2 Maintenance goals

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Summary



- In this lecture, we usually limit ourselves to the problem of finding plans that **reach a goal state**.
- In practice, planning is often about more general goals, where execution cannot be terminated.
 - 1 An animal: find food, eat, sleep, find food, eat, sleep, ...
 - 2 Cleaning robot: keep the building clean.
- These problems cannot be directly formalized in terms of reachability because infinite (unbounded) plan execution is needed.
- We do not discuss this topic in full detail. However, to give at least a little impression of **planning for temporally extended goals**, we will discuss the simplest objective with infinite plan executions: **maintenance**.

Strong cyclic plans

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Definition

Let $\mathcal{T} = \langle V, I, O, \gamma \rangle$ be a planning task with state set S and set of goal states $S_{\star} = \{s \in S \mid s \models \gamma\}$.

A strategy π for \mathcal{T} is called a **plan for maintenance** for \mathcal{T} iff

- $\pi(s)$ is applicable in s for all $s \in S_{\pi}$,
- $S_{\pi}(s_0) \subseteq S_{\pi}$, and
- $S_{\pi}(s_0) \subseteq S_{\star}$.

- The state of an animal is determined by three state values: hunger (0, 1, 2), thirst (0, 1, 2) and location (river, pasture, desert). There is also a special state called **death**.
- Thirst grows when not at river; at river it is 0.
- Hunger grows when not on pasture; on pasture it is 0.
- If hunger or thirst exceeds 2, the animal dies.
- The goal of the animal is to avoid death.

Strong cyclic plans

Maintenance

Definition

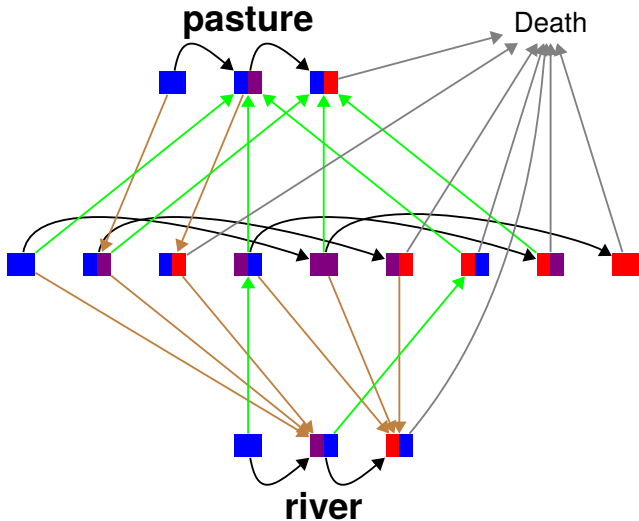
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Maintenance goals

Transition system for the example 0-safe states 1-safe states i -safe states for all $i \geq 2$



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We can infer rules backwards starting from the death condition.

- 1 If in desert and **thirst = 2**, must go to river.
- 2 If in desert and **hunger = 2**, must go to pasture.
- 3 If on pasture and **thirst = 1**, must go to desert.
- 4 If at river and **hunger = 1**, must go to desert.

If the above rules conflict, the animal will die.

Strong cyclic plans

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Summary of the algorithm idea

Repeatedly eliminate from consideration those states that in one or more steps unavoidably lead to a non-goal state.

- A state is *i-safe* iff there is a plan that guarantees “survival” for the next i actions.
- A state is *safe* (or ∞ -safe) iff it is i -safe for all $i \in \mathbb{N}_0$.
- The *0-safe* states are exactly the goal states: maintenance objective is satisfied for the current state.
- Given all i -safe states, compute all $i + 1$ -safe states by using strong preimages.
- For some $i \in \mathbb{N}_0$, i -safe states equal $i + 1$ -safe states because there are only finitely many states and at each step and $i + 1$ -safe states are a subset of i -safe states. Then i -safe states are also ∞ -safe.

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Planning for maintenance goals

def maintenance-plan($\langle V, I, O, \gamma \rangle$):

$S :=$ set of states over V

$Safe_0 := \{s \in S \mid s \models \gamma\}$

for each $i \in \mathbb{N}_1$:

$Safe_i := Safe_{i-1} \cap \bigcup_{o \in O} spreimg_o(Safe_{i-1})$

if $Safe_i = Safe_{i-1}$:

break

if $I \notin Safe_i$:

return no solution

for each $s \in Safe_i$:

$\pi(s) :=$ some operator $o \in O$ with $img_o(s) \subseteq Safe_i$

return π

Strong cyclic
plans

Maintenance

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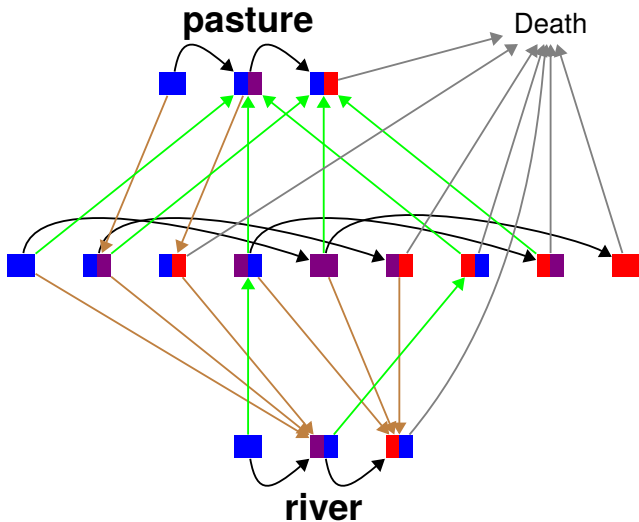
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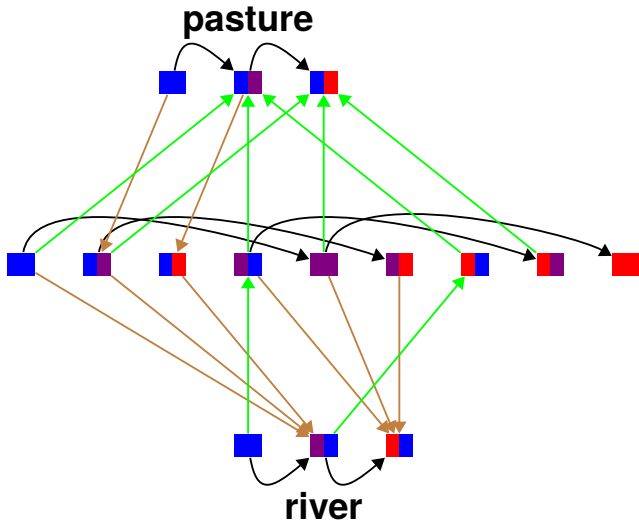
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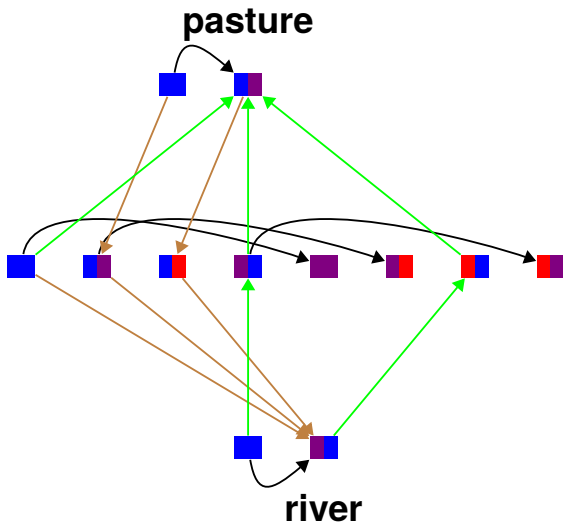
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Strong cyclic
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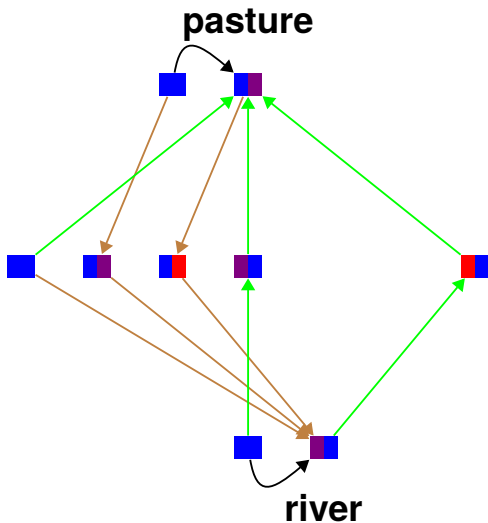
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3 Summary



Strong cyclic
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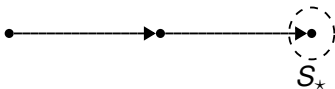
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Different planning objectives

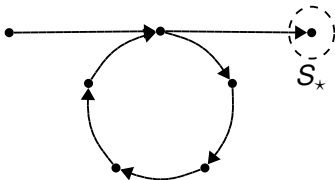


Strong planning



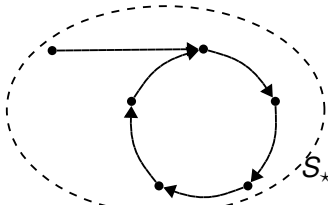
Strong cyclic plans

Strong cyclic planning



Maintenance

Maintenance



Summary



- We have considered different classes of solutions for planning tasks by defining **different planning problems**.
 - strong planning problem: find a strong plan
 - strong cyclic planning problem: find a strong cyclic plan
 - ...
- Alternatively, we could allow specifying goals in a **modal logic** like **computational tree logic** to directly express the type of plan we are interested in using **modalities** such as A (all), E (exists), G (globally), and F (finally).
 - Weak planning: $EF\varphi$
 - Strong planning: $AF\varphi$
 - Strong cyclic planning: $AGEF\varphi$
 - Maintenance: $AG\varphi$

Strong cyclic plans

Maintenance

Summary



- We have extended our earlier planning algorithm from **strong** plans to **strong cyclic** plans.
- The story does not end there: When considering infinitely executing plans, many more types of goals are feasible.
- We considered **maintenance** as a simple example of a **temporally extended goal**.
- In general, temporally extended goals be expressed in **modal logics** such as computational tree logic (CTL).
- We presented dynamic programming (backward search) algorithms for strong cyclic and maintenance planning.
- In practice, one might implement both algorithms by using binary decision diagrams (BDDs) as a data structure for state sets.

Strong cyclic
plans

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Summary