Principles of AI Planning

6. State-space search: search algorithms

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Our plan for the next lectures

Choices to make:

1. search direction: progression/regression/both
   ⇝ previous chapter
2. search space representation: states/sets of states
   ⇝ previous chapter
3. search algorithm: uninformed/heuristic; systematic/local
   ⇝ this chapter
4. search control: heuristics, pruning techniques
   ⇝ next chapters

Search

- Search algorithms are used to find solutions (plans) for transition systems in general, not just for planning tasks.
- Planning is one application of search among many.
- In this chapter, we describe some popular and/or representative search algorithms, and (the basics of) how they apply to planning.
- Most of this is review of material that should be known (details: Russell and Norvig's textbook).

Search states vs. search nodes

In search, one distinguishes:

- search states s $\rightsquigarrow$ states (vertices) of the transition system
- search nodes σ $\rightsquigarrow$ search states plus information on where/when/how they are encountered during search

What is in a search node?

Different search algorithms store different information in a search node σ, but typical information includes:

- $state(\sigma)$: associated search state
- $parent(\sigma)$: pointer to search node from which σ is reached
- $action(\sigma)$: an action/operator leading from $state(parent(\sigma))$ to $state(\sigma)$
- $g(\sigma)$: cost of σ (length of path from the root node)

For the root node, $parent(\sigma)$ and $action(\sigma)$ are undefined.

Search states vs. planning states

Search states $\neq$ (planning) states:

- Search states don't have to correspond to states in the planning sense.
  - progression: search states $\approx$ (planning) states
  - regression: search states $\approx$ sets of states (formulae)
- Search algorithms for planning where search states are planning states are called state-space search algorithms.
- Strictly speaking, regression is not an example of state-space search, although the term is often used loosely.
- However, we will put the emphasis on progression, which is almost always state-space search.

Required ingredients for search

A general search algorithm can be applied to any transition system for which we can define the following three operations:

- init(): generate the initial state
- is-goal(s): test if a given state is a goal state
- succ(s): generate the set of successor states of state s, along with the operators through which they are reached (represented as pairs $\langle o, s' \rangle$ of operators and states)

Together, these three functions form a search space (a very similar notion to a transition system).

Search for planning: progression

Let $\Pi = \langle A, I, O, G \rangle$ be a planning task.

Search space for progression search

states: all states of Π (assignments to A)

- init() $= I$
- succ(s) $= \{\langle o, s' \rangle \mid o \in O, s' = app_o(s)\}$
- is-goal(s) $= \begin{cases} \textbf{true} & \text{if } s \models G \\ \textbf{false} & \text{otherwise} \end{cases}$

Search for planning: regression

Let $\langle A, I, O, G\rangle$ be a planning task.

Search space for regression search

states: all formulae over A

- $\text{init}() = G$
- $\text{succ}(\phi) = \{\langle o, \phi'\rangle \mid o \in O, \phi' = \mathit{regr}_o(\phi), \phi' \text{ is satisfiable}\}$ (modified if splitting is used)
- $\text{is-goal}(\phi) = \begin{cases} \textbf{true} & \text{if } I \models \phi \\ \textbf{false} & \text{otherwise} \end{cases}$

Classification of search algorithms

uninformed search vs. heuristic search:

- uninformed search algorithms only use the basic ingredients for general search algorithms
- heuristic search algorithms additionally use heuristic functions which estimate how close a node is to the goal

systematic search vs. local search:

- systematic algorithms consider a large number of search nodes simultaneously
- local search algorithms work with one (or a few) candidate solutions (search nodes) at a time
- not a black-and-white distinction; there are crossbreeds (e. g., enforced hill-climbing)

Classification: what works where in planning?

uninformed vs. heuristic search:

- For satisficing planning, heuristic search vastly outperforms uninformed algorithms on most domains.
- For optimal planning, the difference is less pronounced. An efficiently implemented uninformed algorithm is not easy to beat in most domains.

systematic search vs. local search:

- For satisficing planning, the most successful algorithms are somewhere between the two extremes.
- For optimal planning, systematic algorithms are required.

Common procedures for search algorithms

Before we describe the different search algorithms, we introduce three procedures used by all of them:

- make-root-node: Create a search node without parent.
- make-node: Create a search node for a state generated as the successor of another state.
- extract-solution: Extract a solution from a search node representing a goal state.

Procedure make-root-node

make-root-node: Create a search node without parent.

Procedure make-root-node

def make-root-node(s):
  σ := **new** node
  state(σ) := s
  parent(σ) := undefined
  action(σ) := undefined
  $g(\sigma) := 0$
  return σ

Procedure make-node

make-node: Create a search node for a state generated as the successor of another state.

Procedure make-node

def make-node(σ, o, s):
  σ' := **new** node
  state(σ') := s
  parent(σ') := σ
  action(σ') := o
  $g(\sigma') := g(\sigma) + 1$
  return σ'

Procedure extract-solution

extract-solution: Extract a solution from a search node representing a goal state.

Procedure extract-solution

def extract-solution(σ):
  solution := **new** list
  while *parent*(σ) is defined:
    solution.push-front(*action*(σ))
    σ := *parent*(σ)
  return *solution*

Uninformed search algorithms

- Uninformed algorithms are less relevant for planning than heuristic ones, so we keep their discussion brief.
- Uninformed algorithms are mostly interesting to us because we can compare and contrast them to related heuristic search algorithms.

Popular uninformed systematic search algorithms:

- breadth-first search
- depth-first search
- iterated depth-first search

Popular uninformed local search algorithms:

- random walk

Breadth-first search without duplicate detection

Breadth-first search

queue := **new** fifo-queue
queue.push-back(make-root-node(init()))
while not *queue*.empty():
    σ = *queue*.pop-front()
    if is-goal(state(σ)):
        return extract-solution(σ)
    for each $\langle o, s\rangle \in$ succ(*state*(σ)):
        σ' := make-node(σ, o, s)
        queue.push-back(σ')
return unsolvable

- Possible improvement: duplicate detection (see next slide).
- Another possible improvement: test if σ' is a goal node; if so, terminate immediately. (We don't do this because it obscures the similarity to some of the later algorithms.)

Breadth-first search with duplicate detection

Breadth-first search with duplicate detection

queue := **new** fifo-queue
queue.push-back(make-root-node(init()))
closed := $\emptyset$
while not *queue*.empty():
    σ = *queue*.pop-front()
    if *state*(σ) $\notin$ *closed*:
        closed := *closed* $\cup$ {*state*(σ)}
        if is-goal(state(σ)):
            return extract-solution(σ)
        for each $\langle o, s\rangle \in$ succ(*state*(σ)):
            σ' := make-node(σ, o, s)
            queue.push-back(σ')
return unsolvable

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        if is-goal(state(σ)):
            return extract-solution(σ)
        for each $\langle o, s\rangle \in$ succ(*state*(σ)):
            σ' := make-node(σ, o, s)
            queue.push-back(σ')
return unsolvable

Random walk

Random walk

σ := make-root-node(init())
forever:
    if is-goal(state(σ)):
        return extract-solution(σ)
    Choose a random element $\langle o, s\rangle$ from succ(state(σ)).
    σ := make-node(σ, o, s)

- The algorithm usually does not find any solutions, unless almost every sequence of actions is a plan.
- Often, it runs indefinitely without making progress.
- It can also fail by reaching a dead end, a state with no successors. This is a weakness of many local search approaches.

Heuristic search algorithms: systematic

- Heuristic search algorithms are the most common and overall most successful algorithms for classical planning.

Popular systematic heuristic search algorithms:

- greedy best-first search
- A*
- weighted A*
- IDA*
- depth-first branch-and-bound search
- breadth-first heuristic search
- ...

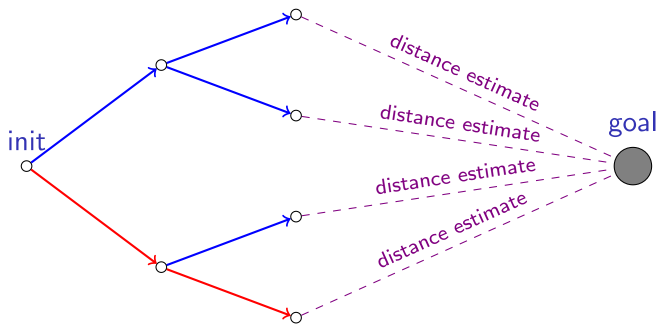
Heuristic search algorithms: local

- Heuristic search algorithms are the most common and overall most successful algorithms for classical planning.

Popular heuristic local search algorithms:

- hill-climbing
- enforced hill-climbing
- beam search
- tabu search
- genetic algorithms
- simulated annealing
- ...

Heuristic search: idea



Required ingredients for heuristic search

A heuristic search algorithm requires one more operation in addition to the definition of a search space.

Definition (heuristic function)

Let Σ be the set of nodes of a given search space.
A heuristic function or heuristic (for that search space) is a function $h : \Sigma \to \mathbb{N}_0 \cup \{\infty\}$.

The value $h(\sigma)$ is called the heuristic estimate or heuristic value of heuristic h for node σ. It is supposed to estimate the distance from σ to the nearest goal node.

What exactly is a heuristic estimate?

What does it mean that h "estimates the goal distance"?

- For most heuristic search algorithms, h does not need to have any strong properties for the algorithm to work (= be correct and complete).
- However, the efficiency of the algorithm closely relates to how accurately h reflects the actual goal distance.
- For some algorithms, like A*, we can prove strong formal relationships between properties of h and properties of the algorithm (optimality, dominance, run-time for bounded error, ...)
- For other search algorithms, "it works well in practice" is often as good an analysis as one gets.

Heuristics applied to nodes or states?

- Most texts apply heuristic functions to states, not nodes.
- This is slightly less general than our definition:
  - Given a state heuristic h, we can define an equivalent node heuristic as $h'(\sigma) := h(state(\sigma))$.
  - The opposite is not possible. (Why not?)
- There is good justification for only allowing state-defined heuristics: why should the estimated distance to the goal depend on how we ended up in a given state s?
- We call heuristics which don't just depend on $state(\sigma)$ pseudo-heuristics.
- In practice there are sometimes good reasons to have the heuristic value depend on the generating path of σ (e. g., the landmark pseudo-heuristic, Richter et al. 2008).

Perfect heuristic

Let Σ be the set of nodes of a given search space.

Definition (optimal/perfect heuristic)

The optimal or perfect heuristic of a search space is the heuristic h^* which maps each search node σ to the length of a shortest path from $state(\sigma)$ to any goal state.

Note: $h^*(\sigma) = \infty$ iff no goal state is reachable from σ.

Properties of heuristics

A heuristic h is called

- safe if $h^*(\sigma) = \infty$ for all $\sigma \in \Sigma$ with $h(\sigma) = \infty$
- goal-aware if $h(\sigma) = 0$ for all goal nodes $\sigma \in \Sigma$
- admissible if $h(\sigma) \leq h^*(\sigma)$ for all nodes $\sigma \in \Sigma$
- consistent if $h(\sigma) \leq h(\sigma') + 1$ for all nodes $\sigma, \sigma' \in \Sigma$ such that σ' is a successor of σ

Relationships?

Greedy best-first search

Greedy best-first search (with duplicate detection)

open := **new** min-heap ordered by $(\sigma \mapsto h(\sigma))$
open.insert(make-root-node(init()))
closed := $\emptyset$
while not *open*.empty():
    σ = *open*.pop-min()
    if *state*(σ) $\notin$ *closed*:
        closed := *closed* $\cup$ {*state*(σ)}
        if is-goal(state(σ)):
            return extract-solution(σ)
        for each $\langle o, s\rangle \in$ succ(*state*(σ)):
            σ' := make-node(σ, o, s)
            if $h(\sigma') < \infty$:
                open.insert(σ')
return unsolvable

Properties of greedy best-first search

- one of the three most commonly used algorithms for satisficing planning
- complete for safe heuristics (due to duplicate detection)
- suboptimal unless h satisfies some very strong assumptions (similar to being perfect)
- invariant under all strictly monotonic transformations of h (e. g., scaling with a positive constant or adding a constant)

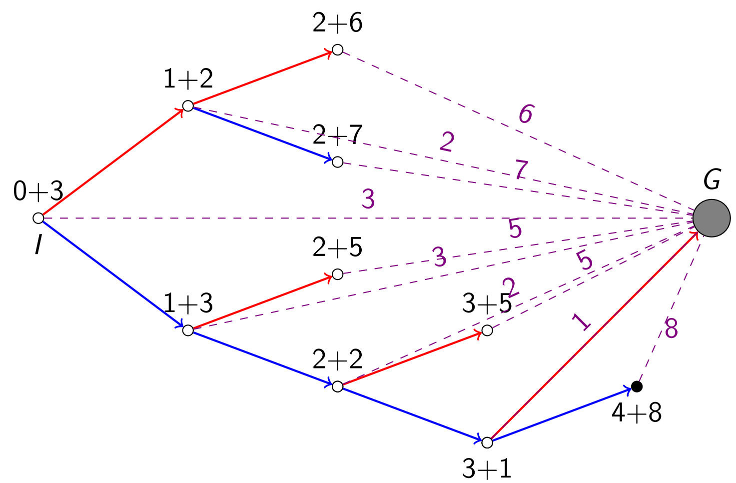
A*

A* (with duplicate detection and reopening)

open := **new** min-heap ordered by $(\sigma \mapsto g(\sigma) + h(\sigma))$
open.insert(make-root-node(init()))
closed := $\emptyset$
distance := $\emptyset$
while not *open*.empty():
    σ = *open*.pop-min()
    if *state*(σ) $\notin$ *closed* **or** $g(\sigma) <$ *distance*(*state*(σ)):
        closed := *closed* $\cup$ {*state*(σ)}
        distance(σ) := $g(\sigma)$
        if is-goal(state(σ)):
            return extract-solution(σ)
        for each $\langle o, s\rangle \in$ succ(*state*(σ)):
            σ' := make-node(σ, o, s)
            if $h(\sigma') < \infty$:
                open.insert(σ')
return unsolvable

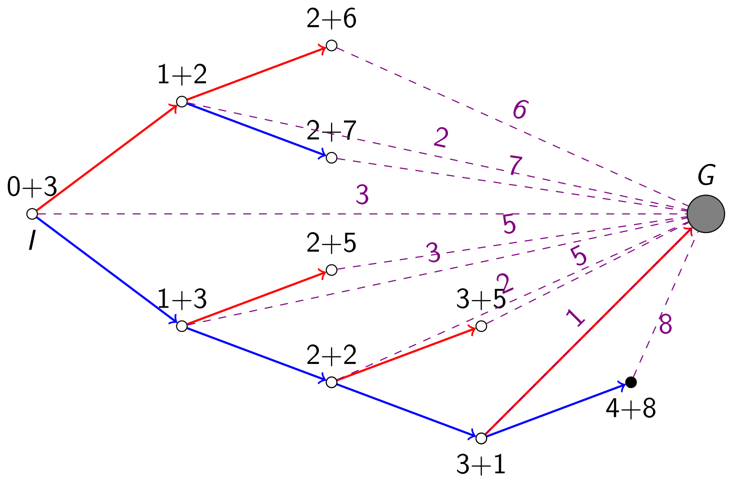
A* example

Example



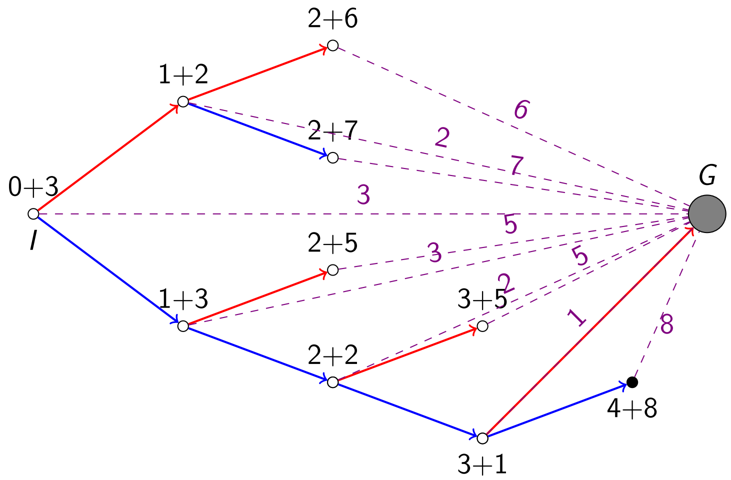
A* example

Example



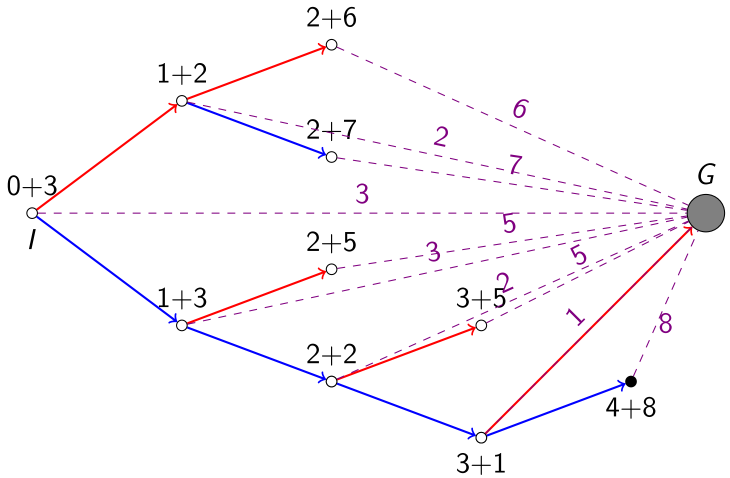
A* example

Example



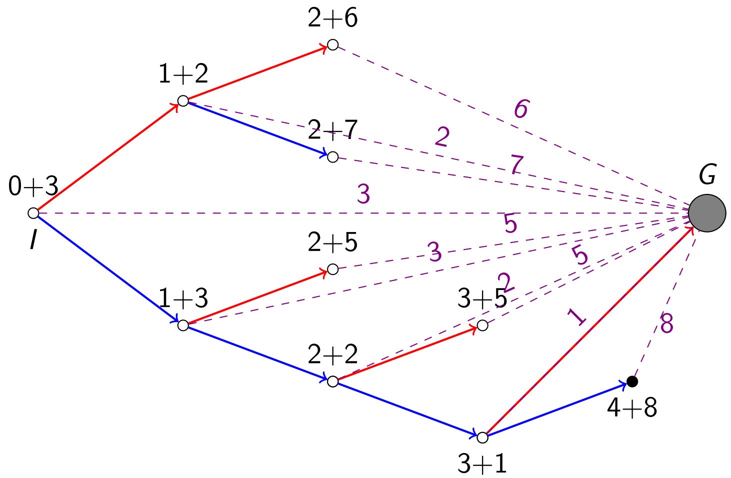
A* example

Example



A* example

Example



Terminology for A*

- *f* value of a node: defined by $f(\sigma) := g(\sigma) + h(\sigma)$
- generated nodes: nodes inserted into *open* at some point
- expanded nodes: nodes σ popped from *open* for which the test against *closed* and *distance* succeeds
- reexpanded nodes: expanded nodes for which $state(\sigma) \in closed$ upon expansion (also called reopened nodes)

Properties of A*

- the most commonly used algorithm for optimal planning
- rarely used for satisficing planning
- complete for safe heuristics (even without duplicate detection)
- optimal if *h* is admissible and/or consistent (even without duplicate detection)
- never reopens nodes if *h* is consistent

Implementation notes:

- in the heap-ordering procedure, it is considered a good idea to break ties in favour of lower *h* values
- can simplify algorithm if we know that we only have to deal with consistent heuristics
- common, hard to spot bug: test membership in *closed* at the wrong time

Weighted A*

Weighted A* (with duplicate detection and reopening)

```
open := new min-heap ordered by (σ ↦ g(σ) + W · h(σ))
open.insert(make-root-node(init()))
closed := ∅
distance := ∅
while not open.empty():
    σ = open.pop-min()
    if state(σ) ∉ closed or g(σ) < distance(state(σ)):
        closed := closed ∪ {state(σ)}
        distance(σ) := g(σ)
        if is-goal(state(σ)):
            return extract-solution(σ)
        for each ⟨o, s⟩ ∈ succ(state(σ)):
            σ' := make-node(σ, o, s)
            if h(σ') < ∞:
                open.insert(σ')
return unsolvable
```


Properties of weighted A*

The weight $W \in \mathbb{R}_0^+$ is a parameter of the algorithm.

- for $W = 0$, behaves like breadth-first search
- for $W = 1$, behaves like A*
- for $W \to \infty$, behaves like greedy best-first search

Properties:

- one of the three most commonly used algorithms for satisficing planning
- for $W > 1$, can prove similar properties to A*, replacing optimal with bounded suboptimal: generated solutions are at most a factor *W* as long as optimal ones

Hill-climbing

Hill-climbing

$\sigma :=$ make-root-node(init())
forever:
  if is-goal(state(σ)):
    return extract-solution(σ)
  $\Sigma' := \{$ make-node$(\sigma, o, s) \mid \langle o, s\rangle \in$ succ(state(σ)) $\}$
  $\sigma :=$ an element of Σ' minimizing h (random tie breaking)

- can easily get stuck in local minima where immediate improvements of $h(\sigma)$ are not possible
- many variations: tie-breaking strategies, restarts

Enforced hill-climbing

Enforced hill-climbing: procedure improve

def *improve*(σ_0):
  queue := **new** fifo-queue
  queue.push-back(σ_0)
  closed := $\emptyset$
  while not *queue*.empty():
    $\sigma =$ *queue*.pop-front()
    if *state*(σ) $\notin$ *closed*:
      closed := *closed* $\cup \{$*state*(σ)$\}$
      if $h(\sigma) < h(\sigma_0)$:
        return σ
      for each $\langle o, s\rangle \in$ succ(*state*(σ)):
        $\sigma' :=$ make-node(σ, o, s)
        queue.push-back(σ')
  fail

$\rightsquigarrow$ breadth-first search for more promising node than σ_0

Enforced hill-climbing (ctd.)

Enforced hill-climbing

$\sigma :=$ make-root-node(init())
while not is-goal(state(σ)):
  $\sigma :=$ improve(σ)
return extract-solution(σ)

- one of the three most commonly used algorithms for satisficing planning
- can fail if procedure improve fails (when the goal is unreachable from σ_0)
- complete for undirected search spaces (where the successor relation is symmetric) if $h(\sigma) = 0$ for all goal nodes and only for goal nodes