

# Principles of AI Planning

## 6. Planning as search: search algorithms

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# 1 Introduction to search algorithms for planning



- Search nodes & search states
- Search for planning
- Common procedures for search algorithms

## Introduction

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Common procedures

## Uninformed search

Heuristic search

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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

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- 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).

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# Search states vs. search nodes

In search, one distinguishes:

- **search states**  $s \rightsquigarrow$  states (vertices) of the transition system
- **search nodes**  $\sigma \rightsquigarrow$  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  $\sigma$ , but typical information includes:

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

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

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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.

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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).

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

Search space for progression search

states: all states of  $\Pi$  (assignments to  $A$ )

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

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

Search space for regression search

states: all formulae over  $A$  (how many?)

■  $\text{init}() = \gamma$

■  $\text{is-goal}(\varphi) = \begin{cases} \text{true} & \text{if } I \models \varphi \\ \text{false} & \text{otherwise} \end{cases}$

■  $\text{succ}(\varphi) = \{ \langle o, \varphi' \rangle \mid o \in O, \varphi' = \text{regr}_o(\varphi), \varphi' \text{ is satisfiable} \}$

(modified if splitting is used)

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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)

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# 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.

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.

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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.

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

## Procedure make-root-node

**def** make-root-node(s):

$\sigma :=$  **new** node

$state(\sigma) := s$

$parent(\sigma) :=$  undefined

$action(\sigma) :=$  undefined

$g(\sigma) := 0$

**return**  $\sigma$

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

## Procedure make-node

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

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

## Procedure extract-solution

```
def extract-solution( $\sigma$ ):  
    solution := new list  
    while parent( $\sigma$ ) is defined:  
        solution.push-front(action( $\sigma$ ))  
         $\sigma$  := parent( $\sigma$ )  
    return solution
```

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## 2 Uninformed search algorithms



- Breadth-first search without duplicate detection
- Breadth-first search with duplicate detection
- Random walk

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**Uninformed search**

Breadth-first w/o duplicate detection

Breadth-first with duplicate detection

Random walk

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- 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**

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# Breadth-first search without duplicate detection



## Breadth-first search

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

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

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## Breadth-first search with duplicate detection

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

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## Breadth-first search with duplicate detection

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

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## Random walk

$\sigma := \text{make-root-node}(\text{init}())$

**forever:**

**if**  $\text{is-goal}(\text{state}(\sigma))$ :

**return**  $\text{extract-solution}(\sigma)$

    Choose a random element  $\langle o, s \rangle$  from  $\text{succ}(\text{state}(\sigma))$ .

$\sigma := \text{make-node}(\sigma, o, s)$

- 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.

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# 3 Heuristic search algorithms



- Heuristics: definition and properties
- Systematic heuristic search algorithms
- Heuristic local search algorithms

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- 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
- ...

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- 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
- ...

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# Heuristic search: idea



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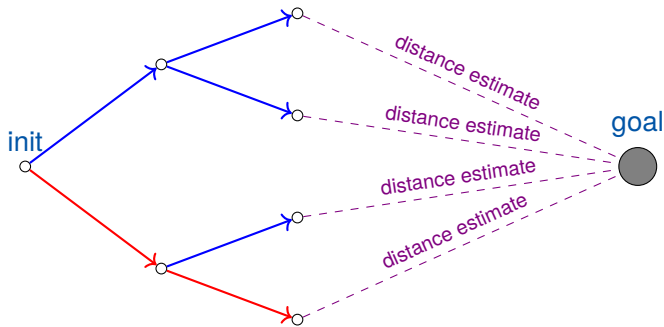
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A **heuristic search algorithm** requires one more operation in addition to the definition of a search space.

## Definition (heuristic function)

Let  $\Sigma$  be the set of nodes of a given search space.

A **heuristic function** or **heuristic** (for that search space) is a function  $h : \Sigma \rightarrow \mathbb{N}_0 \cup \{\infty\}$ .

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

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# 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.

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# 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  $h'(\sigma) := h(\text{state}(\sigma))$ .
  - 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  $\text{state}(\sigma)$  **pseudo-heuristics**.
- In practice there are sometimes good reasons to have the heuristic value depend on the generating path of  $\sigma$  (e. g., **landmark pseudo-heuristic**, Richter et al. 2008).

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Let  $\Sigma$  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  $\sigma$  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  $\sigma$ .

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  $\sigma'$  is a successor of  $\sigma$

Relationships?

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## 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*():

$\sigma = \textit{open.pop-min}()$

**if** *state*( $\sigma$ )  $\notin$  *closed*:

*closed* := *closed*  $\cup$  {*state*( $\sigma$ )}

**if** *is-goal*(*state*( $\sigma$ )):

**return** *extract-solution*( $\sigma$ )

**for each**  $\langle o, s \rangle \in \textit{succ}(\textit{state}(\sigma))$ :

$\sigma' := \textit{make-node}(\sigma, o, s)$

**if**  $h(\sigma') < \infty$ :

*open.insert*( $\sigma'$ )

**return** unsolvable

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- 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)

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## 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*():

$\sigma = \textit{open.pop-min}()$

**if** *state*( $\sigma$ )  $\notin$  *closed* **or**  $g(\sigma) < \textit{distance}(\textit{state}(\sigma))$ :

*closed* := *closed*  $\cup$  {*state*( $\sigma$ )}

*distance*(*state*( $\sigma$ )) :=  $g(\sigma)$

**if** *is-goal*(*state*( $\sigma$ )):

**return** *extract-solution*( $\sigma$ )

**for each**  $\langle o, s \rangle \in \textit{succ}(\textit{state}(\sigma))$ :

$\sigma' := \textit{make-node}(\sigma, o, s)$

**if**  $h(\sigma') < \infty$ : *open.insert*( $\sigma'$ )

**return** unsolvable

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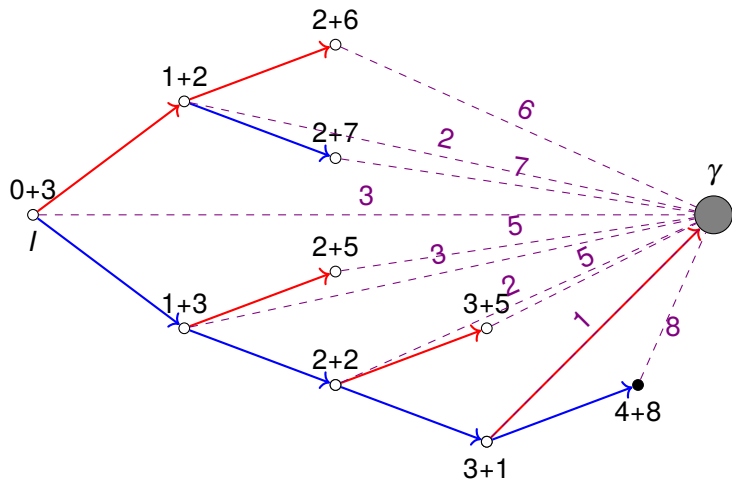
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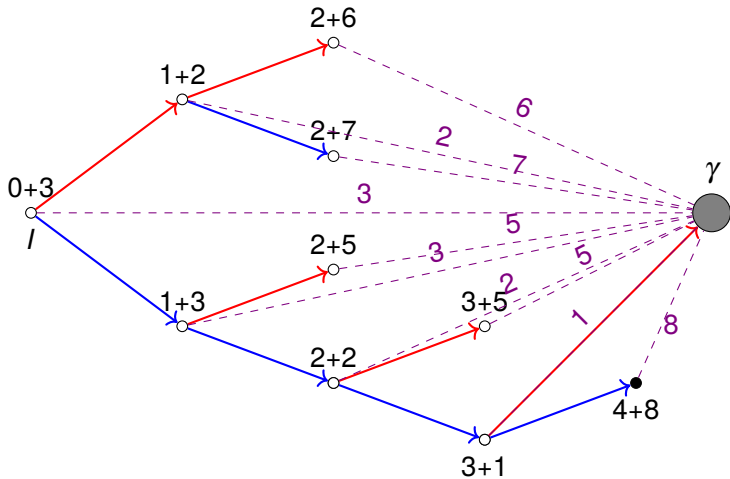
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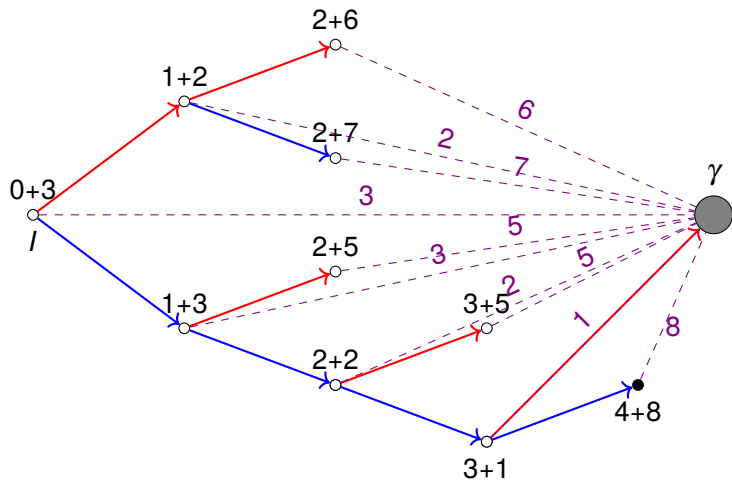
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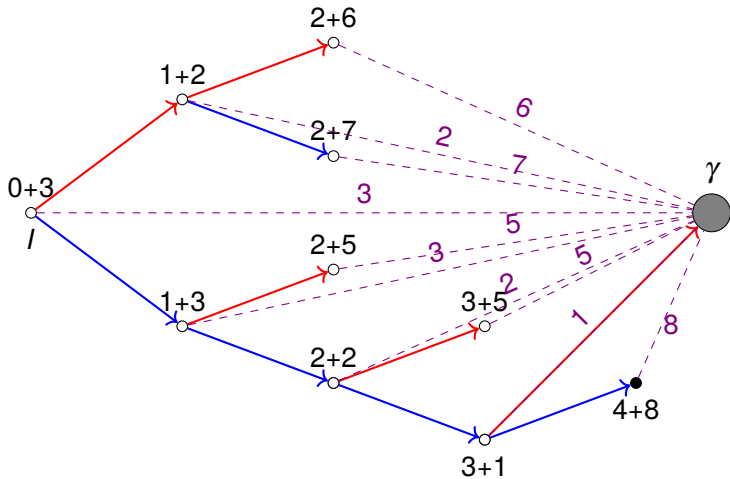
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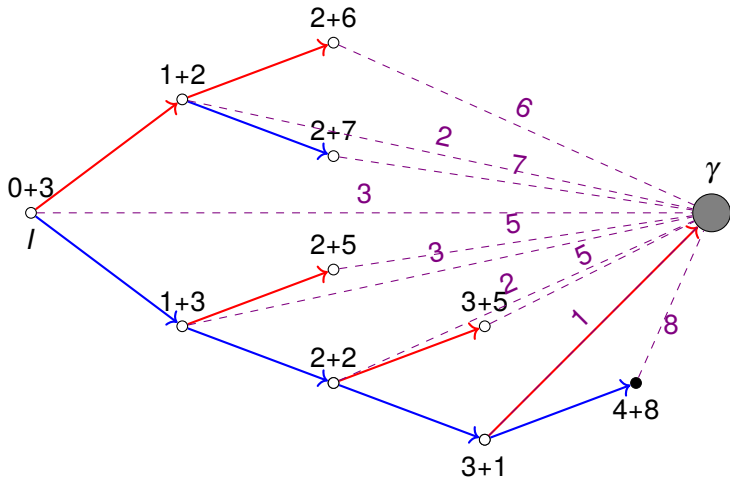
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- **f value** of a node: defined by  $f(\sigma) := g(\sigma) + h(\sigma)$
- **generated nodes**: nodes inserted into *open* at some point
- **expanded nodes**: nodes  $\sigma$  popped from *open* for which the test against *closed* and *distance* succeeds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

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- 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 (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

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## Weighted A\* (with duplicate detection and reopening)

*open* := **new** min-heap ordered by  $(\sigma \mapsto g(\sigma) + W \cdot h(\sigma))$

*open.insert*(make-root-node(*init*()))

*closed* :=  $\emptyset$

*distance* :=  $\emptyset$

**while not** *open.empty*():

$\sigma = \text{open.pop-min}()$

**if** *state*( $\sigma$ )  $\notin$  *closed* **or**  $g(\sigma) < \text{distance}(\text{state}(\sigma))$ :

*closed* := *closed*  $\cup$  {*state*( $\sigma$ )}

*distance*( $\sigma$ ) :=  $g(\sigma)$

**if** *is-goal*(*state*( $\sigma$ )):

**return** *extract-solution*( $\sigma$ )

**for each**  $\langle o, s \rangle \in \text{succ}(\text{state}(\sigma))$ :

$\sigma' := \text{make-node}(\sigma, o, s)$

**if**  $h(\sigma') < \infty$ : *open.insert*( $\sigma'$ )

**return** unsolvable

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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  $W \rightarrow \infty$ , behaves like greedy best-first search

Properties:

- one of the 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

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## Hill-climbing

$\sigma := \text{make-root-node}(\text{init}())$

**forever:**

**if**  $\text{is-goal}(\text{state}(\sigma))$ :

**return**  $\text{extract-solution}(\sigma)$

$\Sigma' := \{ \text{make-node}(\sigma, o, s) \mid \langle o, s \rangle \in \text{succ}(\text{state}(\sigma)) \}$

$\sigma :=$  an element of  $\Sigma'$  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

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## Enforced hill-climbing: procedure improve

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

$\rightsquigarrow$  breadth-first search for more promising node than  $\sigma_0$

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## Enforced hill-climbing

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

- one of the three most commonly used algorithms for satisficing planning
- can fail if procedure *improve* fails (when the goal is unreachable from  $\sigma_0$ )
- complete for **undirected** search spaces (where the successor relation is symmetric) if  $h(\sigma) = 0$  for all goal nodes and only for goal nodes

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- distinguish: **planning states**, **search states**, **search nodes**
  - **planning state**: situation in the world modelled by the task
  - **search state**: subproblem remaining to be solved
    - In **state-space search** (usually progression search), planning states and search states are identical.
    - In regression search, search states usually describe sets of states (“subgoals”).
  - **search node**: search state + info on “how we got there”
- search algorithms mainly differ in **order of node expansion**
  - **uninformed** vs. **informed** (**heuristic**) search
  - **local** vs. **systematic** search

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- **heuristics**: estimators for “distance to goal node”
  - usually: the more accurate, the better performance
  - desiderata: **safe, goal-aware, admissible, consistent**
  - the ideal: **perfect heuristic  $h^*$**
- most common algorithms for **satisficing planning**:
  - **greedy best-first search**
  - **weighted A\***
  - **enforced hill-climbing**
- most common algorithm for **optimal planning**:
  - **A\***

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search

Heuristic  
search

Summary