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Automated
(AI) Planning

Planning by
state-space
search

Progression

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Heuristic
search

Automated (AI) Planning

Planning tasks & Search

Carmel Domshlak

State-space search

- **state-space search**: one of the big success stories of AI
- many planning algorithms based on state-space search (we'll see some other algorithms later, though)
- will be the focus of this and the following topics
- we **assume prior knowledge** of basic search algorithms
 - uninformed vs. informed
 - systematic vs. local
- background on search: Russell & Norvig, Artificial Intelligence – A Modern Approach, chapters 3 and 4

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Satisficing or optimal planning?

Must carefully distinguish two different problems:

- **satisficing planning:** any solution is OK (although shorter solutions typically preferred)
- **optimal planning:** plans must have shortest possible length

Both are often solved by search, but:

- details are **very different**
- almost **no overlap** between good techniques for satisficing planning and good techniques for optimal planning
- many problems that are trivial for satisficing planners are impossibly hard for optimal planners

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Planning by state-space search

How to apply search to planning? \rightsquigarrow many choices to make!

Choice 1: Search direction

- **progression**: forward from initial state to goal
- **regression**: backward from goal states to initial state
- **bidirectional search**

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Choice 2: Search space representation

- search nodes are associated with **states**
- search nodes are associated with **sets of states**

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How to apply search to planning? \rightsquigarrow **many choices to make!**

Choice 3: Search algorithm

- **uninformed search:**
depth-first, breadth-first, iterative depth-first, ...
- **heuristic search (systematic):**
greedy best-first, A^* , Weighted A^* , IDA*, ...
- **heuristic search (local):**
hill-climbing, simulated annealing, beam search, ...

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How to apply search to planning? \rightsquigarrow many choices to make!

Choice 4: Search control

- **heuristics** for informed search algorithms
- **pruning techniques**: invariants, symmetry elimination, helpful actions pruning, . . .

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Search-based satisficing planners

FF (Hoffmann & Nebel, 2001)

- search direction: forward search
- search space representation: single states
- search algorithm: enforced hill-climbing (informed local)
- heuristic: FF heuristic (inadmissible)
- pruning technique: helpful actions (incomplete)

↪ one of the best satisficing planners

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Search-based optimal planners

Fast Downward + h^{HHH} (Helmert, Haslum & Hoffmann, 2007)

- search direction: forward search
- search space representation: single states
- search algorithm: A* (informed systematic)
- heuristic: merge-and-shrink abstractions (admissible)
- pruning technique: none

↪ one of the best optimal planners

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Our plan for the next lectures

Choices to make:

- ① search direction: progression/regression/both
~> **this chapter**
- ② search space representation: states/sets of states
~> **this chapter**
- ③ search algorithm: uninformed/heuristic; systematic/local
~> **this chapter**
- ④ search control: heuristics, pruning techniques
~> **following chapters**

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Planning by forward search: progression

Progression: Computing the successor state $app_o(s)$ of a state s with respect to an operator o .

Progression planners find solutions by forward search:

- start from initial state
- iteratively pick a previously generated state and **progress it** through an operator, generating a new state
- solution found when a goal state generated

pro: very easy and efficient to implement

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Search space representation in progression planners

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Two alternative search spaces for progression planners:

① search nodes correspond to states

- when the same state is generated along different paths, it is not considered again (**duplicate detection**)
- **pro**: fast
- **con**: memory intensive (must maintain **closed list**)

② search nodes correspond to operator sequences

- different operator sequences may lead to identical states (**transpositions**)
- **pro**: can be very memory-efficient
- **con**: much wasted work (often exponentially slower)

↪ first alternative usually preferable

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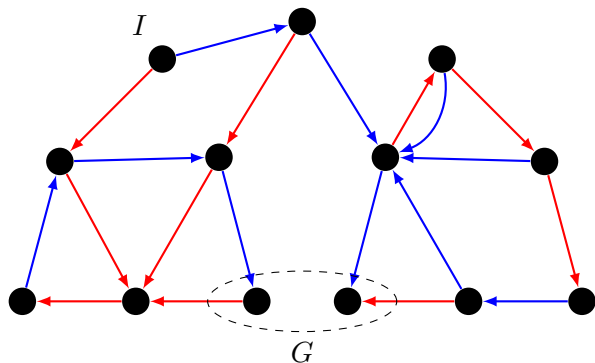
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Progression planning example (depth-first search)



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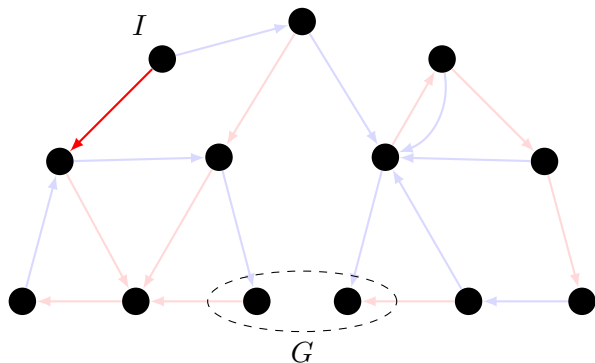
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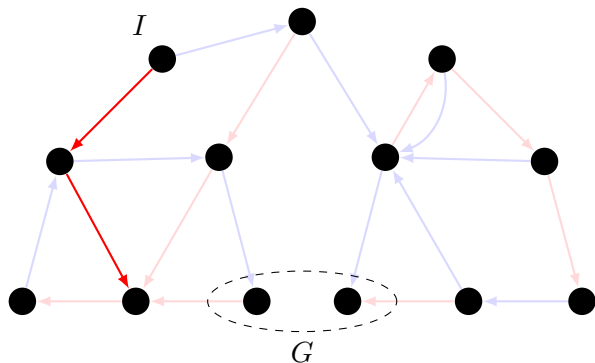
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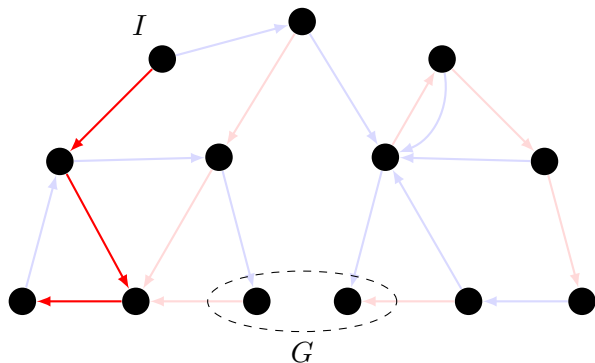
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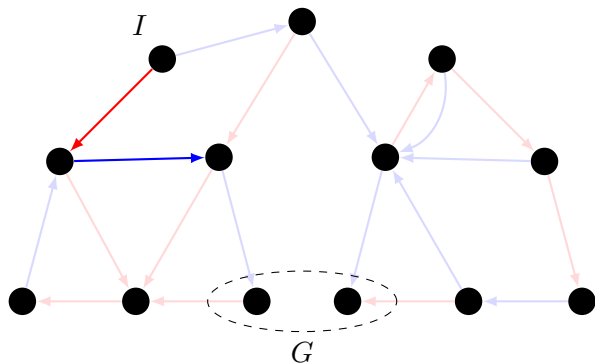
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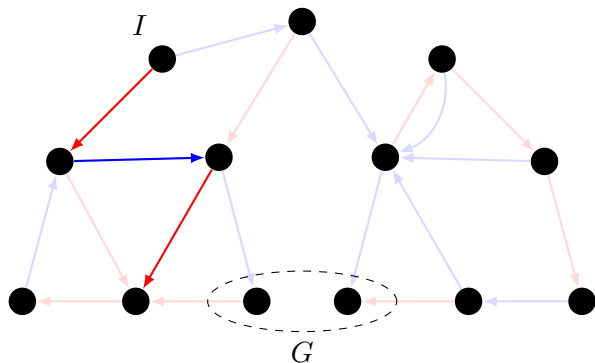
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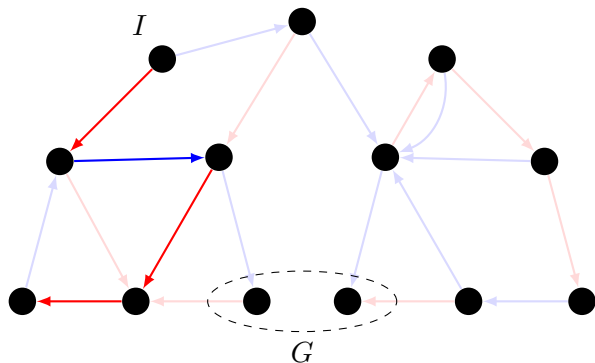
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Forward search vs. backward search

Going through a transition graph in forward and backward directions is **not symmetric**:

- forward search starts from a **single** initial state; backward search starts from a **set** of goal states
- when applying an operator o in a state s in forward direction, there is a **unique successor state** s' ; if we applied operator o to end up in state s' , there can be **several possible predecessor states** s

↪ most natural representation for backward search in planning associates **sets of states** with search nodes

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Planning by backward search: regression

Regression: Computing the possible predecessor states $regr_o(S)$ of a set of states S with respect to the last operator o that was applied.

Regression planners find solutions by backward search:

- start from set of goal states
- iteratively pick a previously generated state set and **regress it** through an operator, generating a new state set
- solution found when a generated state set includes the initial state

Pro: can handle many states simultaneously

Con: basic operations complicated and expensive

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Search space representation in regression planners

identify state sets with **logical formulae**:

- **search nodes correspond to state sets**
- each state set is represented by a **logical formula**:
 ϕ represents $\{s \in S \mid s \models \phi\}$
- many basic search operations like detecting duplicates are NP-hard or coNP-hard

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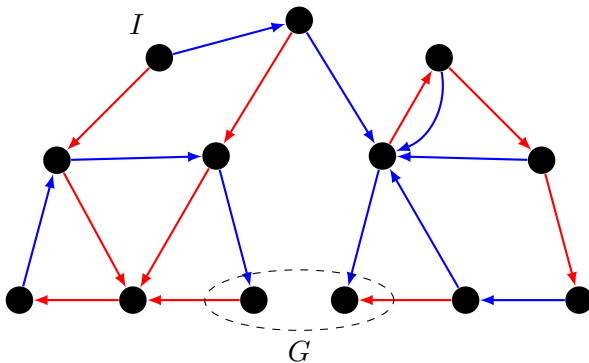
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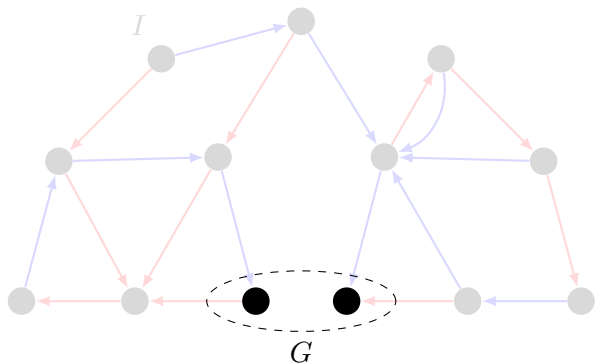
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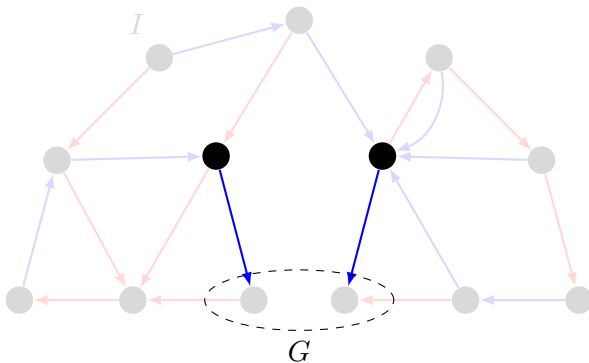
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Regression planning example (depth-first search)

$$\phi_1 = \text{regr} \rightarrow (G)$$

$$\phi_1 \rightarrow G$$



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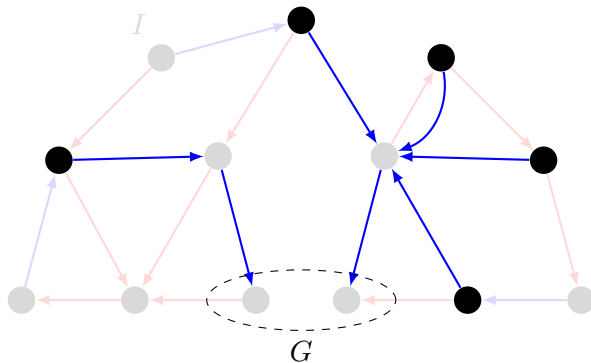
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Regression planning example (depth-first search)

$$\phi_1 = \text{regr} \rightarrow (G)$$

$$\phi_2 = \text{regr} \rightarrow (\phi_1)$$

$$\phi_2 \rightarrow \phi_1 \rightarrow G$$



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Regression for STRIPS planning tasks

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Definition (STRIPS planning task)

A planning task is a **STRIPS planning task** if all operators are STRIPS operators and the goal is a conjunction of literals.

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Regression for **STRIPS planning tasks** is very simple:

- Goals are conjunctions of literals $l_1 \wedge \dots \wedge l_n$.
- **First step**: Choose an operator that makes some of l_1, \dots, l_n true and makes none of them false.
- **Second step**: Remove goal literals achieved by the operator and add its preconditions.
- \rightsquigarrow Outcome of regression is again conjunction of literals.

Choices to make:

- 1 search direction: progression/regression/both
~> above
- 2 search space representation: states/sets of states
~> above
- 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.

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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).

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Search for planning: progression

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

Search space for progression search

states: all states of Π (assignments to V)

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

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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)

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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. An efficiently implemented uninformed algorithm is not easy to beat in most domains. (But doable! We'll see that later.)

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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Uninformed search algorithms

Less relevant for planning, yet not irrelevant

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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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
- ...

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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
- ...

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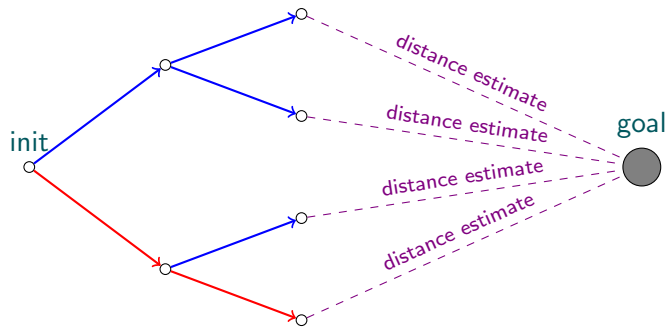
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Heuristic search: idea



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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 $h : \Sigma \rightarrow \mathbb{N}_0 \cup \{\infty\}$.

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.

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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 σ

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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 .

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Properties of heuristics

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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():
     $\sigma$  = open.pop-min()
    if state( $\sigma$ )  $\notin$  closed:
        closed := closed  $\cup$  {state( $\sigma$ )}
        if is-goal(state( $\sigma$ )):
            return extract-solution( $\sigma$ )
        for each  $\langle o, s \rangle \in$  succ(state( $\sigma$ )):
             $\sigma'$  := make-node( $\sigma, o, s$ )
            if  $h(\sigma') < \infty$ :
                open.insert( $\sigma'$ )
return unsolvable
```

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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)

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Local search

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():
     $\sigma = open.pop\text{-min}()$ 
    if  $state(\sigma) \notin closed$  or  $g(\sigma) < distance(state(\sigma))$ :
         $closed := closed \cup \{state(\sigma)\}$ 
         $distance(\sigma) := g(\sigma)$ 
        if is-goal(state( $\sigma$ )):
            return extract-solution( $\sigma$ )
        for each  $\langle o, s \rangle \in succ(state(\sigma))$ :
             $\sigma' := make\text{-node}(\sigma, o, s)$ 
            if  $h(\sigma') < \infty$ :
                open.insert( $\sigma'$ )
return unsolvable

```

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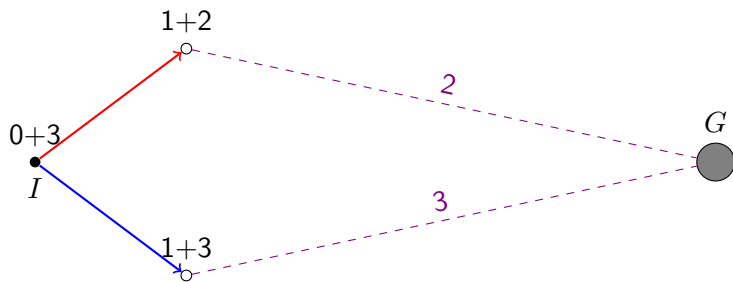
Heuristics

Systematic
search

Local search

A* example

Example



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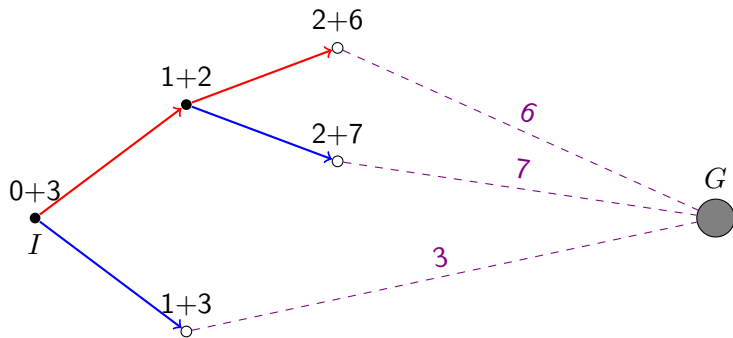
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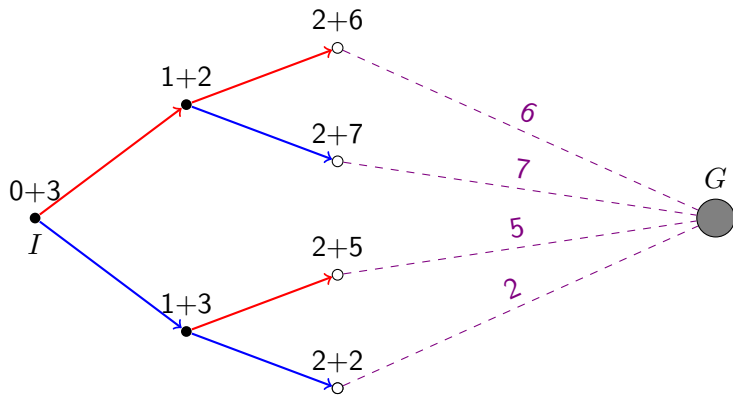
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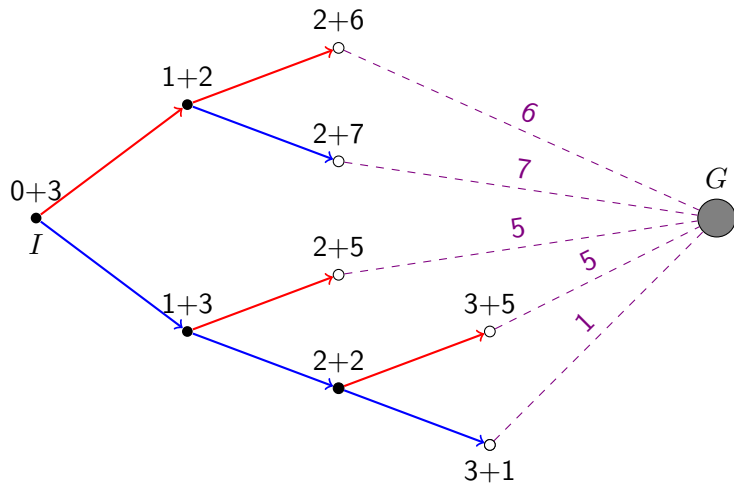
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Terminology for A*

- **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**)

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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

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Weighted A*

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():  
     $\sigma = \textit{open.pop-min}()$   
    if  $\textit{state}(\sigma) \notin \textit{closed}$  or  $g(\sigma) < \textit{distance}(\textit{state}(\sigma))$ :  
         $\textit{closed} := \textit{closed} \cup \{\textit{state}(\sigma)\}$   
         $\textit{distance}(\sigma) := g(\sigma)$   
        if  $\textit{is-goal}(\textit{state}(\sigma))$ :  
            return  $\textit{extract-solution}(\sigma)$   
        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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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 $W \rightarrow \infty$, 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

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Hill-climbing

Hill-climbing

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

forever:

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

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

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

$\sigma := \text{an element of } \Sigma' \text{ minimizing } h \text{ (random tie breaking)}$

- 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

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  $\langle o, s \rangle \in \text{succ}(\text{state}(\sigma))$ :  
                 $\sigma'$  := make-node( $\sigma, o, s$ )  
                queue.push-back( $\sigma'$ )  
  
    fail
```

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

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Enforced hill-climbing (ctd.)

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 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

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