Artificial Intelligence

CSE 4617

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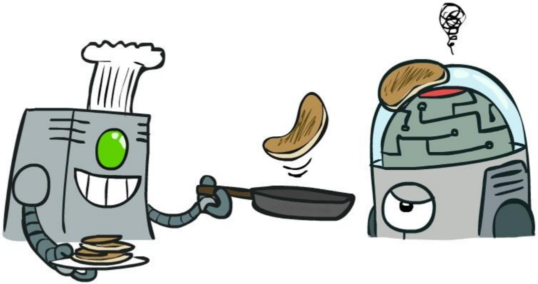
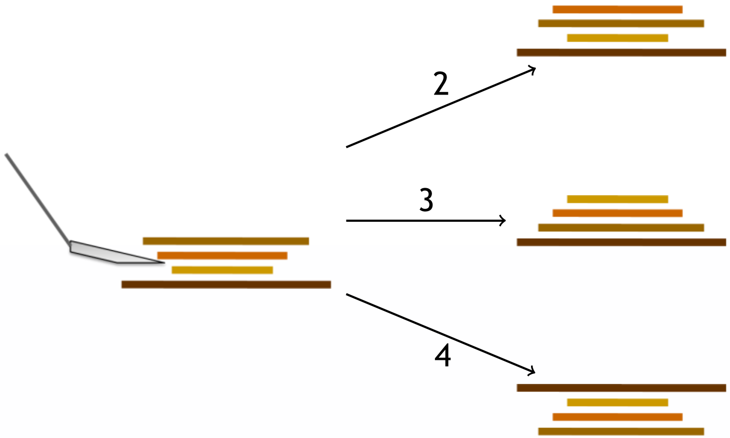
Example: Pancake Problem



Example: Pancake Problem



Cost: Number of pancakes flipped

Example: Pancake Problem

BOUNDS FOR SORTING BY PREFIX REVERSAL

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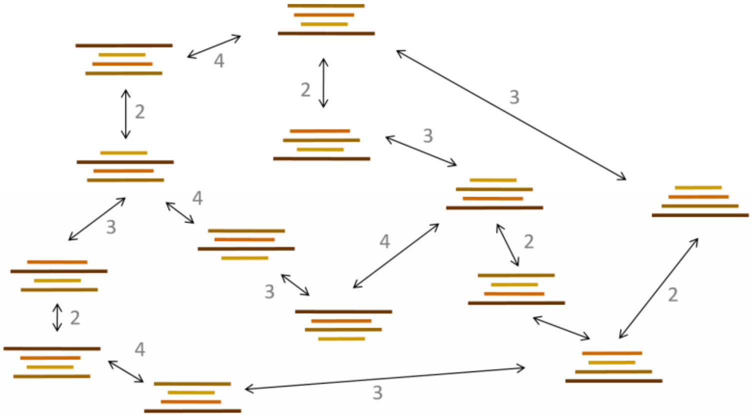
Received 18 January 1978
Revised 28 August 1978

For a permutation σ of the integers from 1 to n, let $f(\sigma)$ be the smallest number of prefix reversals that will transform σ to the identity permutation, and let $f(n)$ be the largest such $f(\sigma)$ for all σ in (the symmetric group) S_n. We show that $f(n) \leq (5n+5)/3$, and that $f(n) \geq 17n/16$ for n a multiple of 16. If, furthermore, each integer is required to participate in an even number of reversed prefixes, the corresponding function $g(n)$ is shown to obey $3n/2 - 1 \leq g(n) \leq 2n+3$.

Example: Pancake Problem

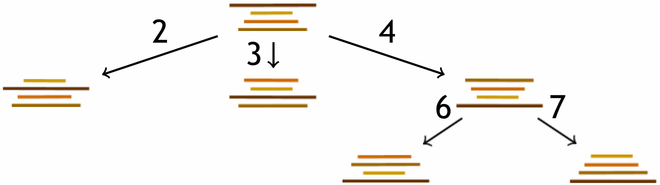
State space graph with costs as weights[1]



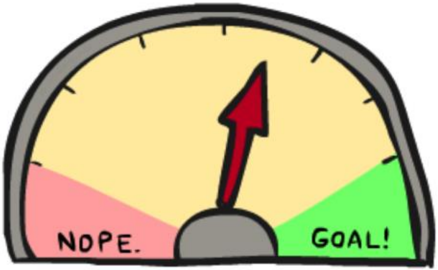
[1] Slide does not contain entire state space graph

General Search Tree

function TREE-SEARCH(*problem*, *strategy*) **returns** a solution, or failure
    initialize the search tree using the initial state of *problem*
    loop do
        if there are no candidates for expansion **then return** failure
        choose a leaf node according to *strategy*
        if the node contains a goal state **then return** the corresponding solution
        else expand the node and add the resulting node to the search tree
    end



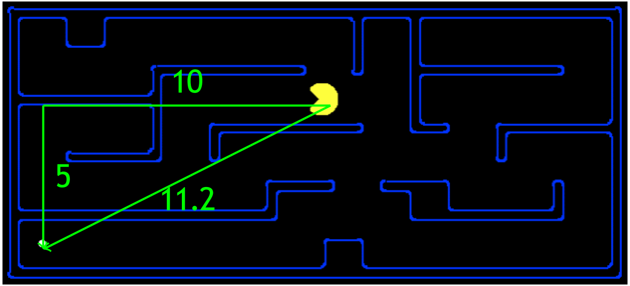
Informed Search



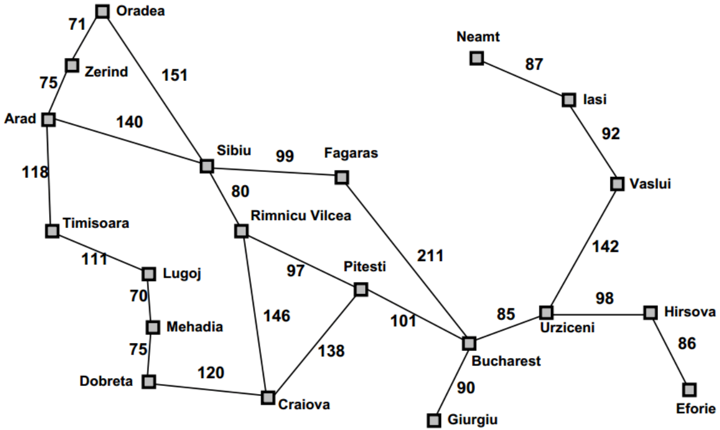
Video: ContoursPacmanSmallMaze-UCS

Search Heuristics

- A function that *estimates* how close a state is to a goal
- Designed for a particular search problem
- Example: Manhatten distance, Euclidean distance for pathing

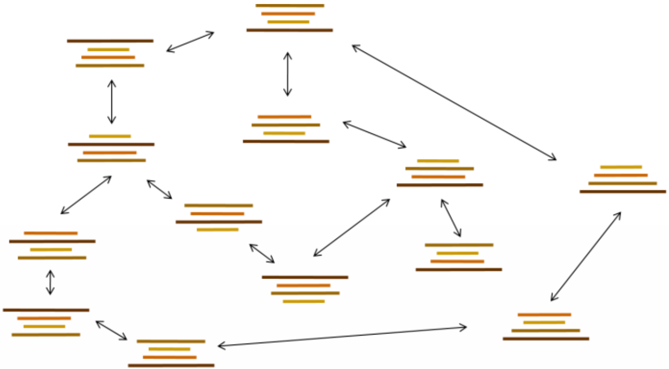


Example: Heuristic Function

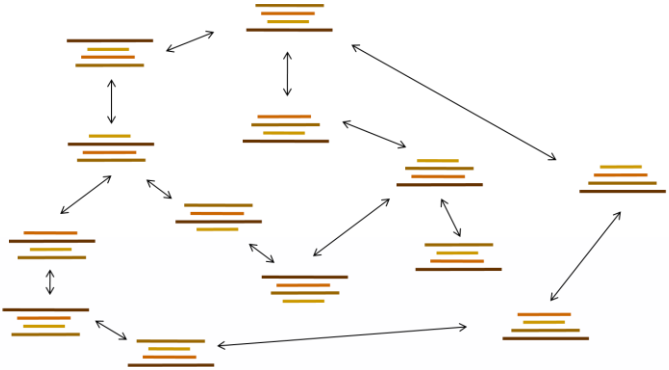


Straight-line distance to Bucharest	
Arad	366
Bucharest	0
Craiova	160
Dobreta	242
Eforie	161
Fagaras	178
Giurgiu	77
Hirsova	151
Iasi	226
Lugoj	244
Mehadia	241
Neamt	234
Oradea	380
Pitesti	98
Rimnieu Vileea	193
Sibiu	253
Timisoara	329
Urziceni	80
Vaslui	199
Zerind	374

Example: Heuristic Function

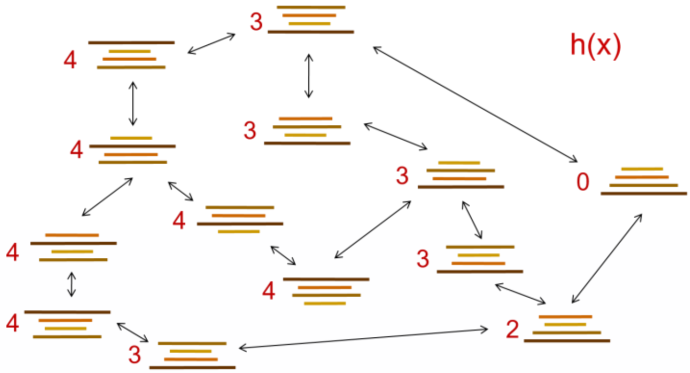


Example: Heuristic Function



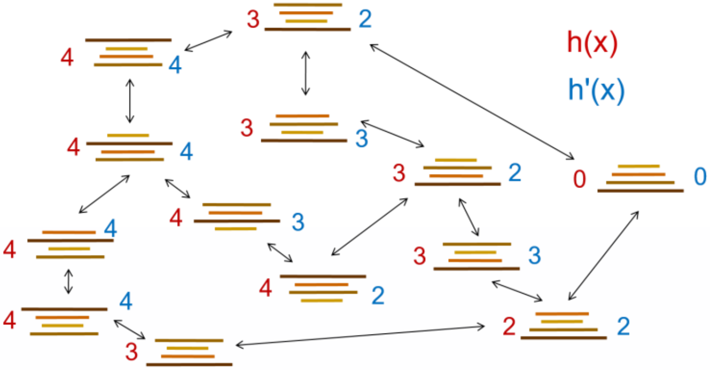
Bad heuristic: The number of correctly positioned pancakes

Example: Heuristic Function



$h(x)$ = The ID of the largest pancake that is still out of place

Example: Heuristic Function



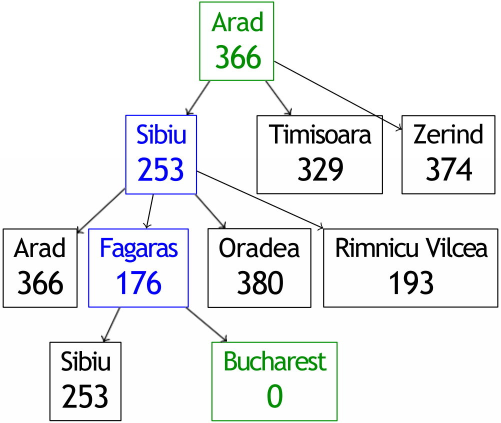
$h(x)$ = The ID of the largest pancake that is still out of place

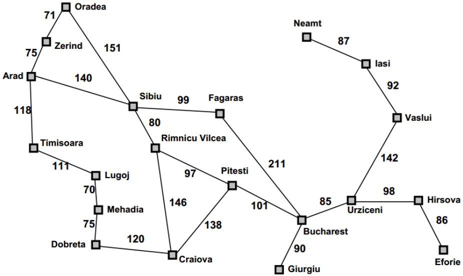
$h^j(x)$ = The number of the incorrectly placed pancakes

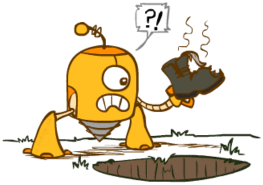
Greedy Search

Greedy Search

- Expand the node that seems closest

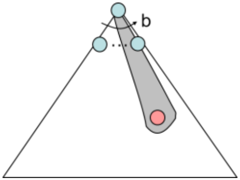


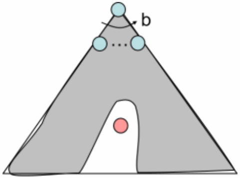




Greedy Search

- Strategy: expand a node that you think is closest to a goal state
  - Heuristic: estimate of distance to nearest goal for each state
- A common case:
  - Best-first takes you straight to the (wrong) goal
- Worst-case: like a badly-guided DFS





Video: Empty-greedy, ContoursPacmanSmallMaze-greedy

A* Search

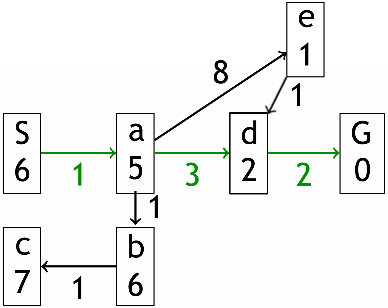
UCS

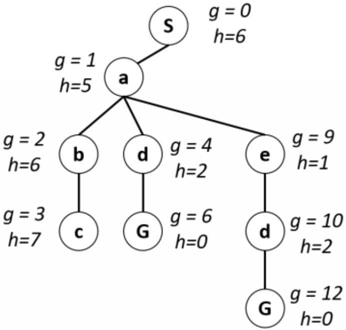
Greedy

A*

Combining UCS and Greedy

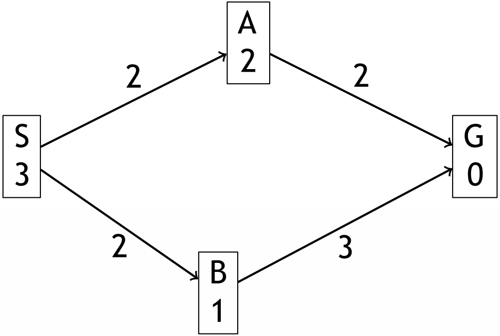
- Uniform-cost orders by path cost, or *backward cost* $g(n)$
- Greedy orders by goal proximity, or *forward cost* $h(n)$
- A* Search orders by the sum: $f(n) = g(n) + h(n)$





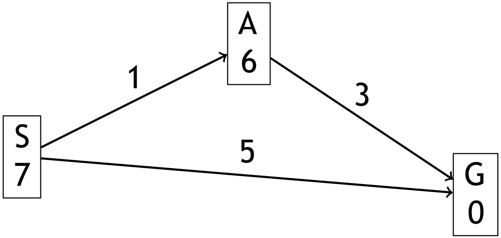
When should A* terminate?

- Should we stop when we enqueue a goal?



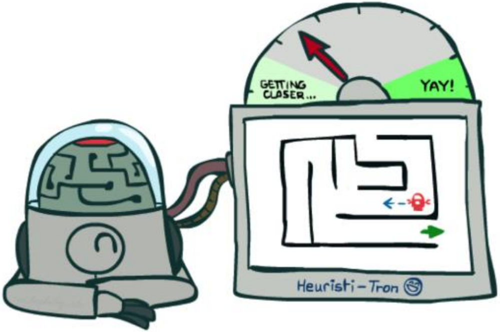
- No: only stop when you dequeue the goal

Is A* optimal?

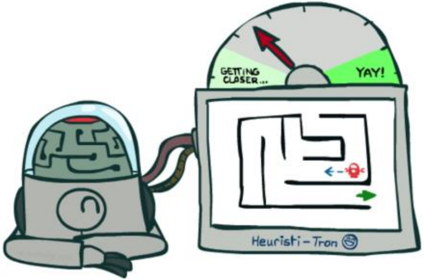


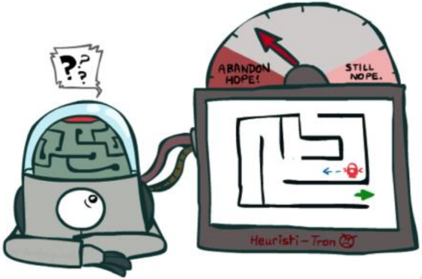
- What went wrong?
  - Actual bad goal cost < estimated good goal cost
- We need estimates to be less than the actual cost

Admissible Heuristics



Admissible Heuristics





Admissible (optimistic) heuristics slow down bad plans but never outweigh true costs

Inadmissible (pessimistic) heuristics breaks optimality by trapping good plans on the fringe

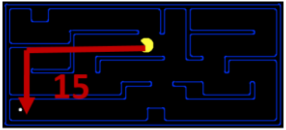
Admissible Heuristics

- A heuristic h is admissible (optimistic) if:

$$0 \leq h(n) \leq h^*(n)$$

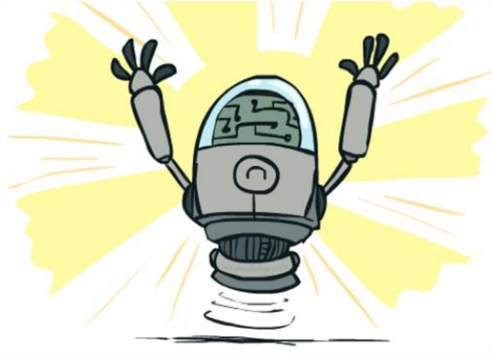
where $h^*(n)$ is the true cost to a nearest goal

- Example:



- Coming up with admissible heuristics is most of what's involved in using A* in practice

Optimality of A* Tree Search



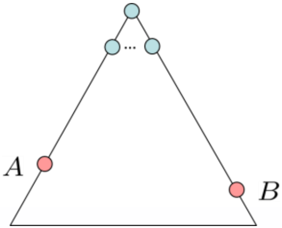
Optimality of A* Tree Search

Assume:

- A is an optimal goal node
- B is a suboptimal goal node
- h is admissible

Claim:

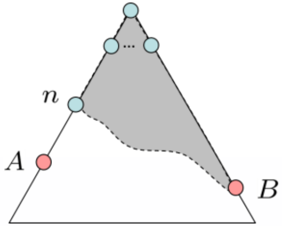
- A will exit the fringe before B



Optimality of A* Tree Search

Proof:

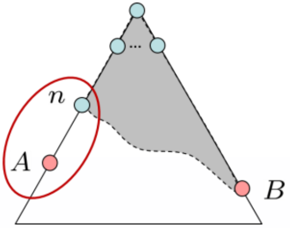
- Imagine B is on the fringe
- Some ancestor *n* of A is also on the fringe, too (maybe A)
- Claim: *n* will be expanded before B



Optimality of A* Tree Search

Proof:

- Imagine B is on the fringe
- Some ancestor n of A is also on the fringe, too (maybe A)
- Claim: n will be expanded before B
  1. $f(n) \leq f(A)$
     - $f(n) = g(n) + h(n)$ [Definition of f-cost]
     - $f(n) \leq g(A)$ [Admissiblity of heuristics]
     - $g(A) = f(A)$ [h(A)=0 at goal]



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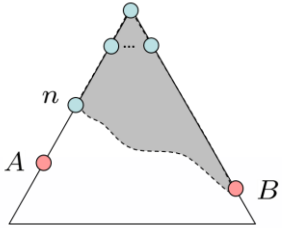
  2. $f(A) < f(B)$



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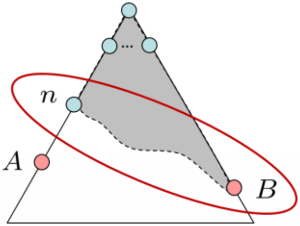
  2. $f(A) < f(B)$
     - $g(A) < g(B)$ [B is suboptimal]
     - $f(A) < f(B)$ [h=0 at goal]
  3. $f(n) \leq f(A) < f(B) \rightarrow n$ expands before B



Optimality of A* Tree Search

Proof:

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- Claim: n will be expanded before B
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     - $g(A) = f(A)$ [h(A)=0 at goal]
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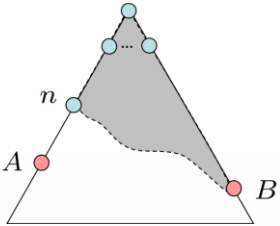
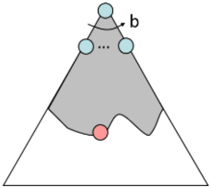
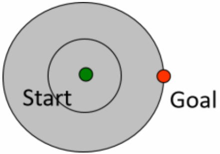
     - $g(A) < g(B)$ [B is suboptimal]
     - $f(A) < f(B)$ [h=0 at goal]
  3. $f(n) \leq f(A) < f(B) \rightarrow n$ expands before B
- All ancestor of A expand before B
- A expands before B $\rightarrow$ A* search is optimal

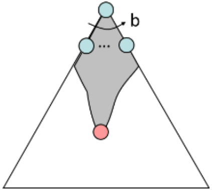


UCS vs A*

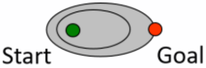


UCS





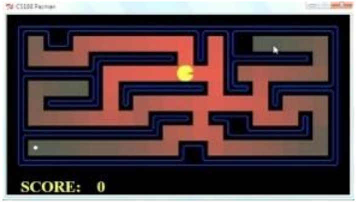
A*



Video: Empty-UCS, Empty-astar, ContoursPacmanSmallMaze-astar.mp4

UCS vs A*

Greedy



UCS

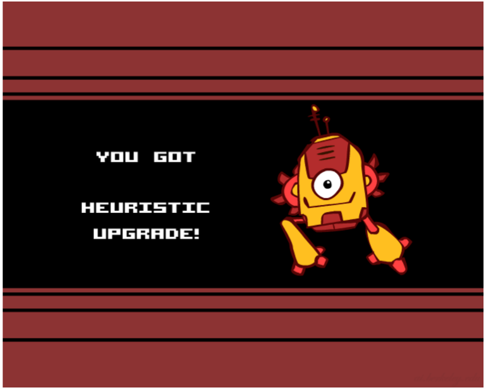
A*

A* Applications

- Video games
- Pathing/routing problems
- Resource planning problems
- Robot motion planning
- Language analysis
- Machine translation
- Speech recognition
- . . .

Video: tinyMaze, guessAlgorithm

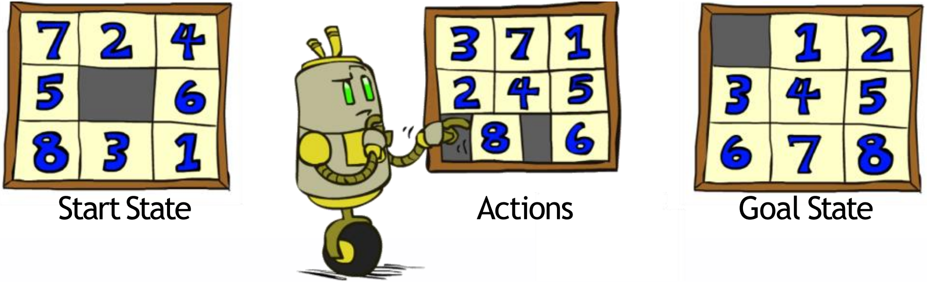
Creating Admissible Heuristics



Creating Admissible Heuristics

- Most of the work in solving hard search problems optimally is in coming up with admissible heuristics

Example: 8 Puzzle

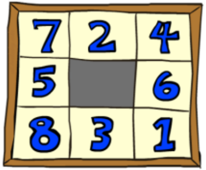


- What are the states? → Puzzle configurations
- How many states? → $9!$
- What are the actions? → Move the empty piece in four directions
- How many successors are there from the start state? → 4
- What should the cost be? → Number of moves

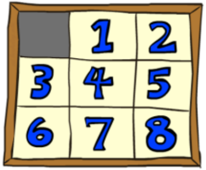
Example: 8 Puzzle

Attempt 1:

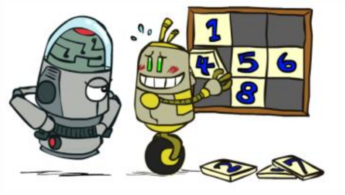
- Number of misplaced tiles
- Why is it admissible?
- $h(start) = 8$
- *Relaxed-problem* heuristic



Start State



Goal State

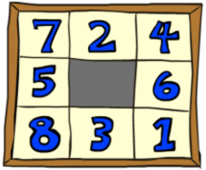


	Average nodes expanded when the optimal path has...		
	...4 steps	...8 steps	...12 steps
UCS	112	6,300	3.6×10^6
TILES	13	39	227

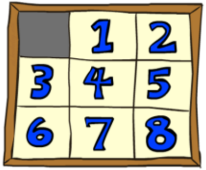
Example: 8 Puzzle

Attempt 2:

- What if we had an easier 8-puzzle where any tile could slide any direction at any time, ignoring other tiles?
- Total *Manhatten* distance
- Why is it admissible?
- $h(start) = 3 + 1 + 2 + \cdots = 18$



Start State



Goal State

	Average nodes expanded when the optimal path has…		
	…4 steps	…8 steps	…12 steps
TILES	13	39	227
MANHATTAN	12	25	73

Example: 8 Puzzle

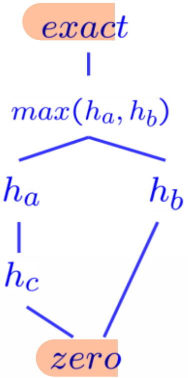
Attempt 3?

- What if we use the actual costs as heuristics?
  - Would it be admissible?
  - Would we save on nodes expanded?
  - What's wrong with it?

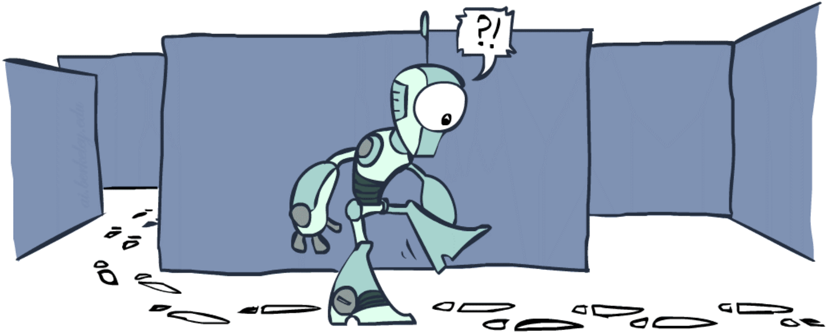
- With A*: a trade-off between quality of estimate and work per node
  - As heuristics get closer to the true cost, you will expand fewer nodes but usually do more work per node to compute the heuristic itself

Semi-Lattice of Heuristics

- Trivial heuristics
  - Bottom of lattice is the zero heuristic
  - Top of lattice is the exact heuristic
- Dominance: $h_a \geq h_c$ if
  $\forall n : h_a(n) \geq h_c(n)$
- Heuristics can form a semi-lattice:
  - Max of admissible heuristics is admissible
    $h(n) = \max(h_a(n), h_b(n))$



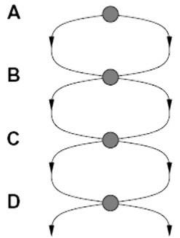
Graph Search



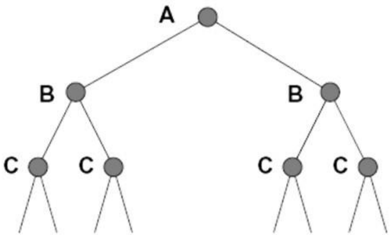
Graph Search

- Tree search requires extra work: Failure to detect repeated states can cause exponentially more work

State Space Graph



Search Tree



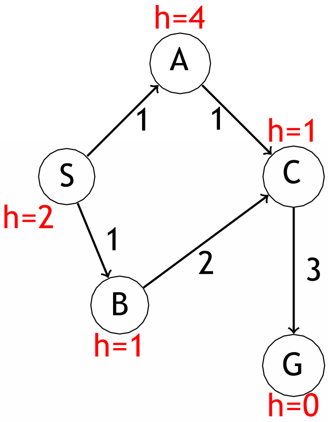
- Idea: never expand a state twice

Graph Search

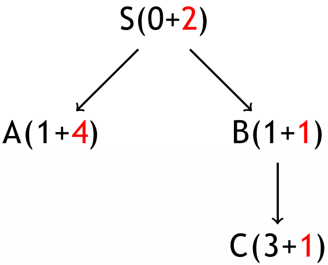
- Idea: never expand a state twice
- How to implement?
  - Tree search + set of expanded states ("closed set")
  - Expand the search tree node-by-node, but…
  - Before expanding a node, check to make sure its state has never been expanded before
  - If not new, skip it, if new add to closed set
- Important: store the closed set as a set, not a list
- Can graph search wreck completeness? Why/why not?
- How about optimality?

A* Graph Search Gone W rong?

- State space graph

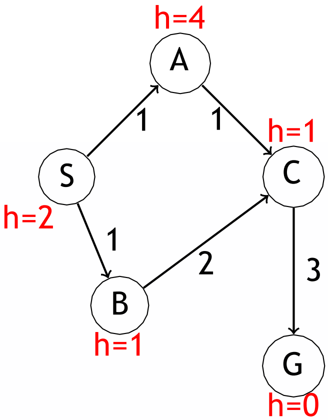


- Search tree

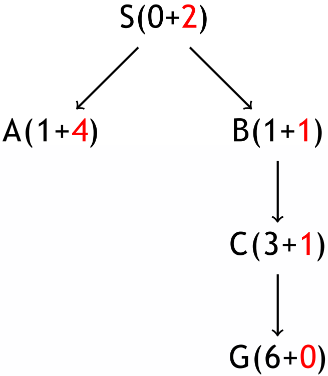


A* Graph Search Gone W rong?

- State space graph

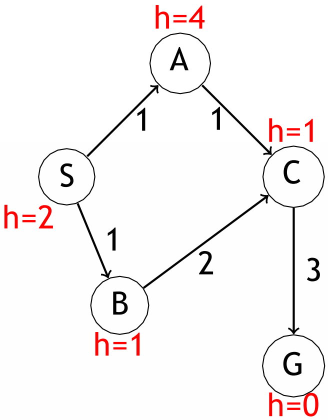


- Search tree

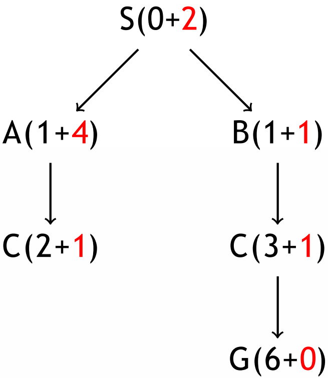


A* Graph Search Gone Wrong?

- State space graph

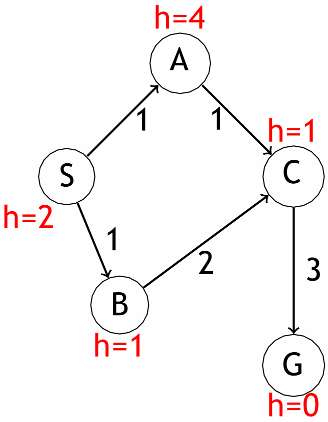


- Search tree

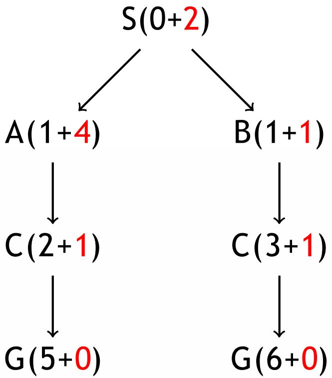


A* Graph Search Gone W rong?

- State space graph



- Search tree



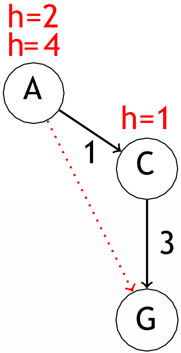
Consistency of Heuristics

- Main idea: estimated heuristics cost ≤ actual costs
  - Admissibility: heuristic cost ≤ actual cost to goal

    $h(A) \leq$ Actual cost from A to G
  - Consistency: heuristic "arc" cost ≤ actual cost for each arc

    h(A) - h(C) ≤ cost(A to C)

    h(A) ≤ h(C) + cost(A to C)



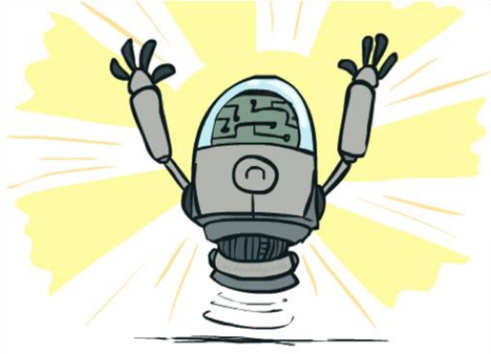
- Consequences of consistency:
  - The f value along a path never decreases

$$h(A) \leq \quad cost(A \ to \ C) + h(C)$$

$$f(A) = g(A) + h(A) \leq g(A) + cost(A \ to \ C) + h(C) = f(C)$$

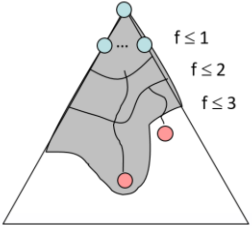
  - A* graph search is optimal

Optimality of A* Graph Search



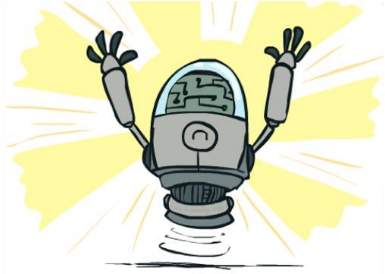
Optimality of A* Graph Search

- Sketch: consider what A* does with a consistent heuristic:
  - Fact 1: In tree search, A* expands nodes in increasing total f value (f-contours)
  - Fact 2: For every state s, nodes that reach s optimally are expanded before nodes that reach s suboptimally
  - Result: A* graph search is optimal



Optimality

- Tree search:
  - A* is optimal if heuristic is admissible
  - UCS is a special case (h = 0)
- Graph search:
  - A* optimal if heuristic is consistent
  - UCS optimal (h = 0 is consistent)
- Consistency implies admissiblity
- In general, most natural admissible heuristics tend to be consistent, especially if from relaxed problems



A* Search: Summary

- A* uses both backward costs and (estimates of) forward costs
- A* is optimal with admissible / consistent heuristics
- Heuristic design is key: often use relaxed problems

Tree Search Pseudo-Code

```
function TREE-SEARCH(problem, fringe) returns a solution, or failure
    fringe ← INSERT(MAKE-NODE(INITIAL-STATE[problem]), fringe)
    loop do
        if fringe is empty then return failure
        node ← REMOVE-FRONT(fringe)
        if GOAL-TEST(problem, STATE[node]) then return node
        for child-node in EXPAND(STATE[node], problem) do
            fringe ← INSERT(child-node, fringe)
        end
    end
```

Graph Search Pseudo-Code

```
function GRAPH-SEARCH(problem, fringe) return a solution, or failure
  closed ← an empty set
  fringe ← INSERT(MAKE-NODE(INITIAL-STATE[problem]), fringe)
  loop do
    if fringe is empty then return failure
    node ← REMOVE-FRONT(fringe)
    if GOAL-TEST(problem, STATE[node]) then return node
    if STATE[node] is not in closed then
      add STATE[node] to closed
      for child-node in EXPAND(STATE[node], problem) do
        fringe ← INSERT(child-node, fringe)
      end
  end
```

Suggested Reading

- Russell & Norvig: Chapter 3.5-3.6
- Poole & Mackworth: Chapter: 3.6-3.7