

Problem solving by search II

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Outline

- ▶ Graph search
- ▶ Heuristics (how to search faster)
- ▶ Greedy
- ▶ A*. A-star search.

A Maze, what could possibly go wrong?

	0	1	2	3	4	
0	0.00	0.00	0.00	0.00	0.00	0
1	0.00	0.00	0.00	0.00	0.00	1
2	0.00	0.00	0.00	0.00	0.00	2
3	0.00	0.00	0.00	0.00	0.00	3
4	0.00	0.00	0.00	0.00	0.00	4
	0	1	2	3	4	

<https://youtu.be/WKSoedfRZQ4>

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Notes

Analyze the demo run (BFS). What happened? Why did it take that long?

Because it is TREE_SEARCH...

Many loops are created and all nodes with depth < 7 need to be expanded first. Goal is at depth 8.

Notes for teacher:

Working note for demo:

```
python3 easy_search_agents.py
```

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's' for skip

code settings:

```
MAP = 'maps/easy/easy2.bmp'
```

```
TREE_SEARCH = True
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```
node_type = 'BFS'
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How to decode printout on command line:

- Every iteration ends with: `print('End of while loop: length of the frontier:', len(frontier), 'length of the expanded:', len(expanded.states), frontier, frontier.is_empty())`
- But note that the algo is written in a general way (like UCS), stopping after expanding the goal node – that is why you see also depth 9 in the frontier notes at the end.
- Size of the visualiation can be altered in `./kuimaze/maze.py`, look for `MAX_CELL_SIZE`

Tree search the maze

function TREE_SEARCH(env) **return** a solution or failure

 initialize the **frontier**

while frontier **do**

 node = frontier.pop()

if goal in node **then**

 break

end if

 nodes = env.expand(node.state)

 Add nodes to frontier

end while

end function

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0	0.00	0.00	0.00	0.00	0.00	0
1	0.00	0.00	0.00	0.00	0.00	1
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4	0.00	0.00	0.00	0.00	0.00	4
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Notes

Make a **frontier** and **expand** columns on a paper and follow the algorithm by putting and removing (scratching out) nodes from the list.

Note that there are many more nodes than states (*search tree* vs. *state space*).

Tree search seems hugely ineffective. Note that this is (also) because of the state space. It's a maze with undirected edges. If we had directed edges, there would be much much fewer cycles.

A graph search

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function GRAPH_SEARCH(env) return a solution or failure
  init frontier by the start state
  initialize the explored set to be empty
  while frontier do
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    add node.state to explored
    if goal in node then break
    end if
    nodes = env.expand(node.state)
    for all nodes do
      if node.state not in explored (or in frontier) then
        add nodes to frontier
      end if
    end for
  end while
end function
```



Do not forget: node is not the same as state!

Notes

Think about what is node and what state. What is main difference? How are they connected? Where do they appear? What is node/state in the maze problem?

The main idea: Do not expand a **state** twice.

What would be a good data structure to implement the *explored* set? Yes, it would be a *set* ;) – where every element is present only once. Unlike *list*.

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Do not forget: `node` is not the same as `state`!

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The BFS graph search

function BFS_GRAPH_SEARCH(env) **return** a solution or failure

node ← env.observe()

frontier ← FIFOQueue(node)

explored ← set()

while frontier not empty **do**

node ← frontier.pop()

explored.add(node.state)

▷ adding state not node!

child_nodes ← env.expand(node.state)

for all child_nodes **do**

if child_node.state not in explored or in frontier **then**

if child_node contains Goal **then return** child_node

end if

frontier.insert(child_node)

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end for

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end function

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Notes

Why adding/checking state and not node in explored data structure? Can I do the simple presence check for all kind of graph search algorithms?

Run demo again with BFS graph search.

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Result can be also seen at: https://youtu.be/4yu_nsWZ2ck

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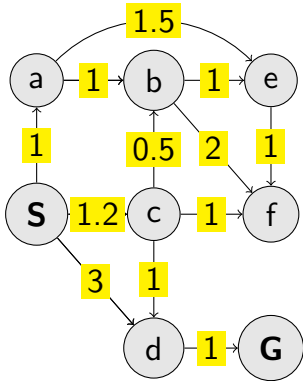
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What about uniform costs graph search?



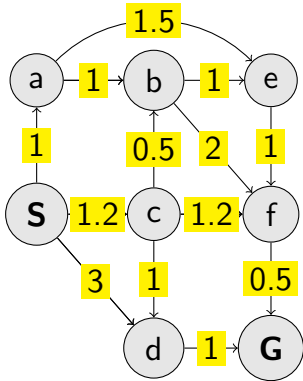
Notes

When following the algorithm (animation) use the paper list of frontier and explored

Note the extra features of UCS vs. BFS in action:

1. Update of cost:
 - "b,2" disappears as "b,1.7" appears – update with lower cost.
 - Similarly, "e,2.7" and "f,3.7" appear to immediately disappear again – their cost is higher than already available for those states.
2. Termination only after expanding node with goal state.

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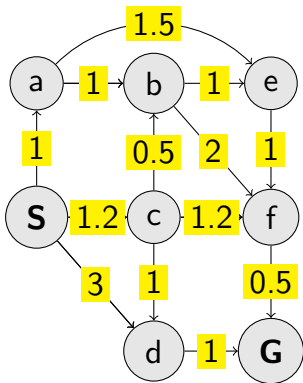
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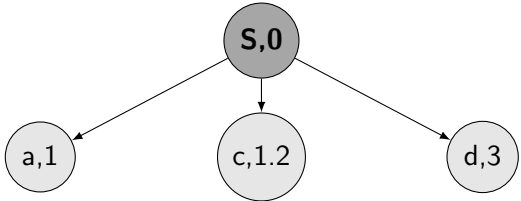
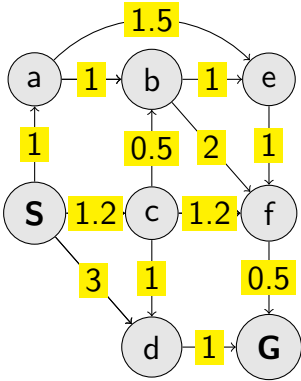
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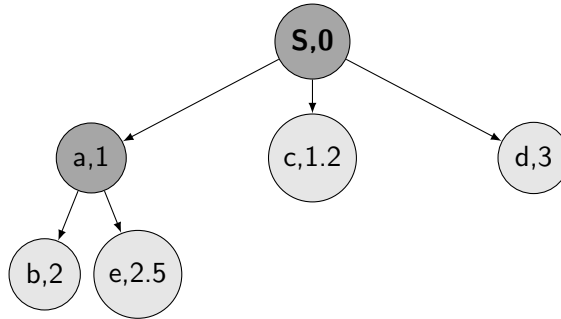
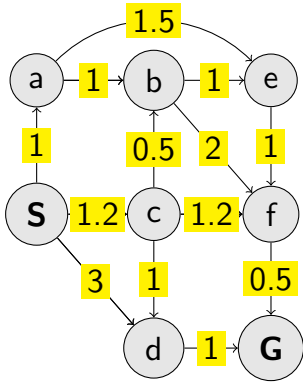


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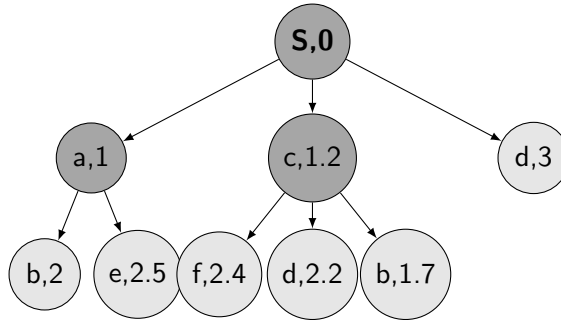
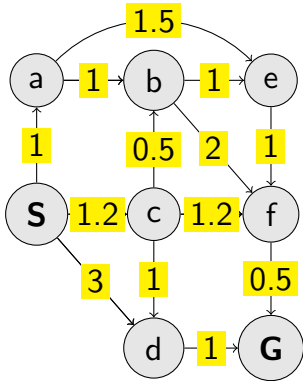
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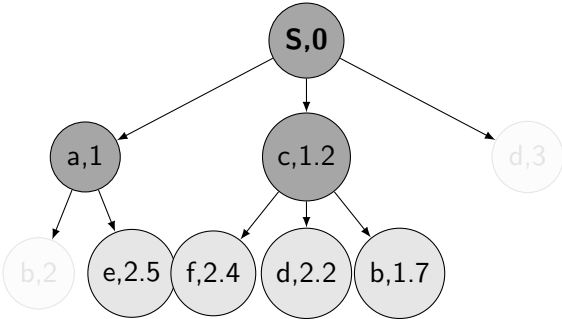
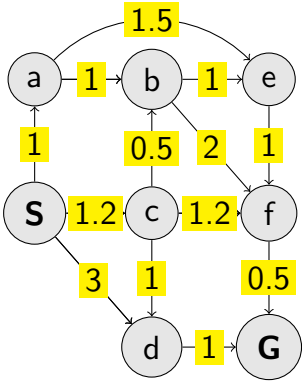
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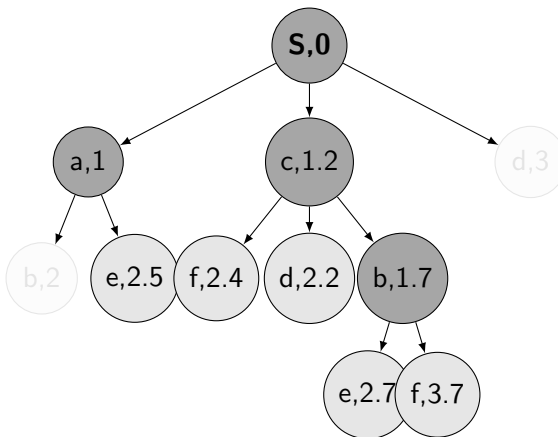
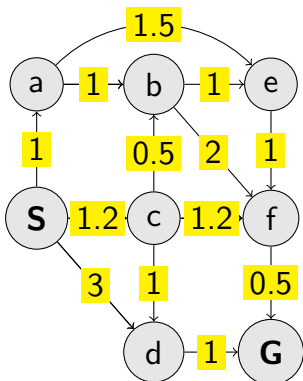


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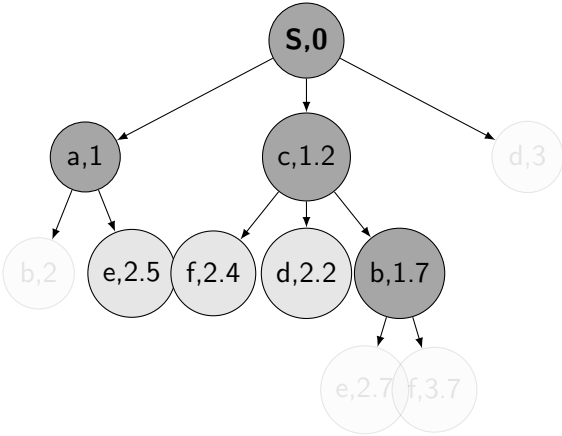
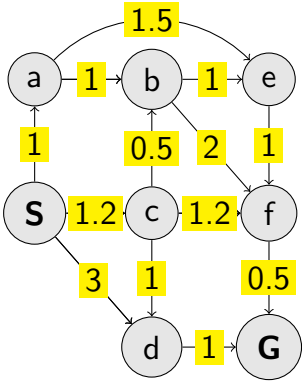
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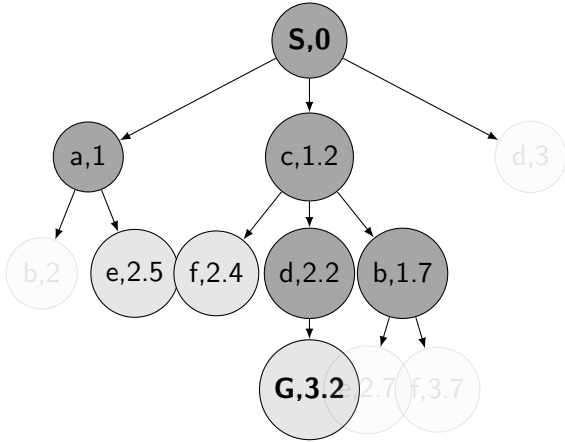
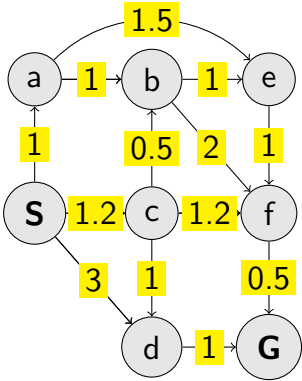


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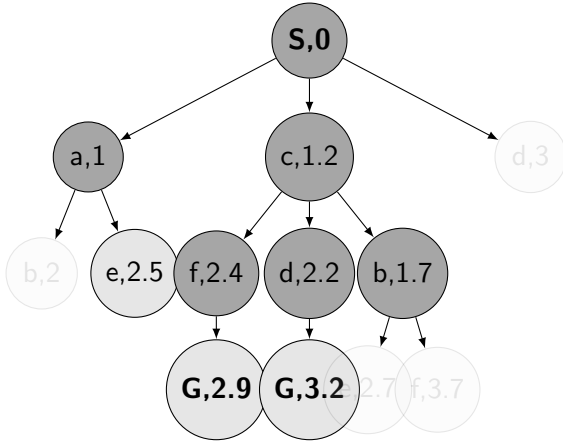
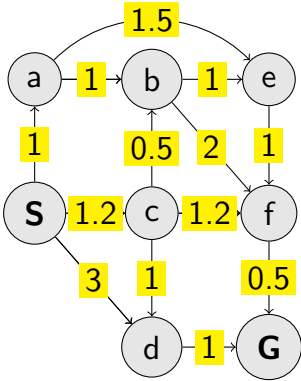


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2. Termination only after expanding node with goal state.

What about uniform costs graph search?

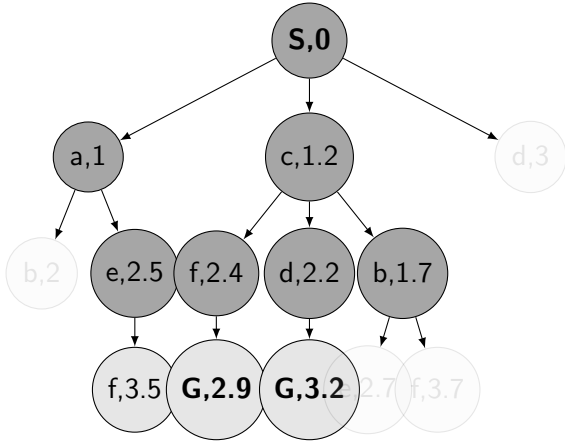
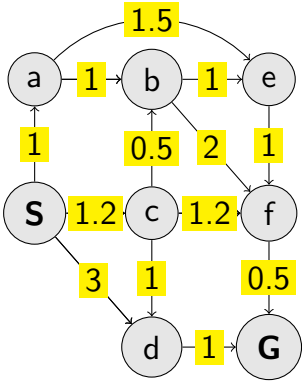


Notes

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Note the extra features of UCS vs. BFS in action:

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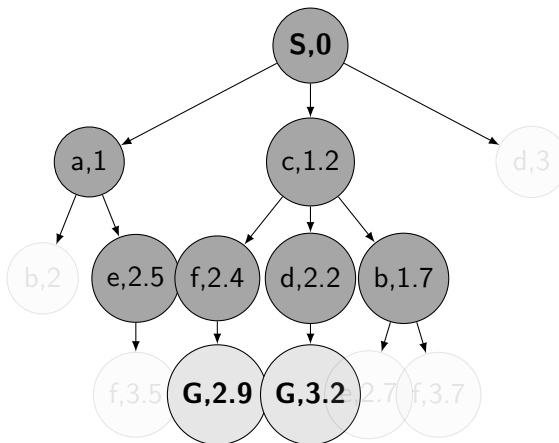
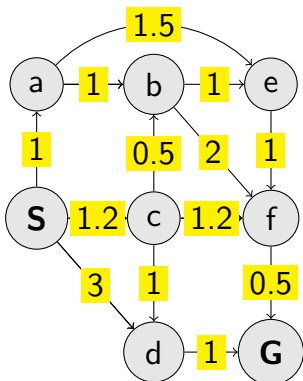


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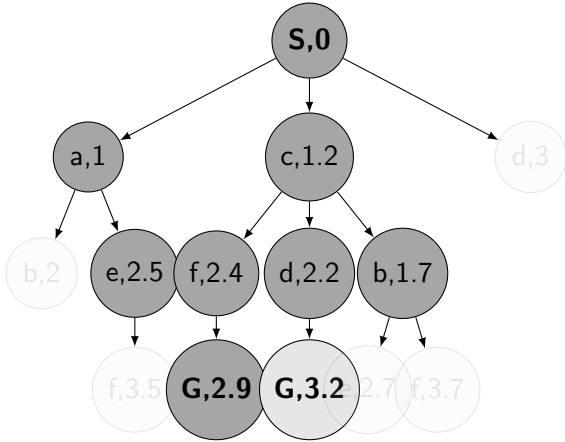
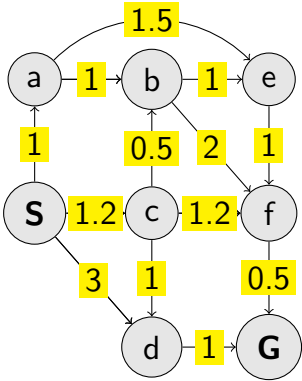
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The UCS graph search

function UCS_GRAPH_SEARCH(env) **return** a solution or failure

node ← env.observe()

frontier ← priority_queue(node)

explored ← set()

▷ path_cost for ordering

while frontier not empty **do**

node ← frontier.pop()

if node contains Goal **then return** node

▷ check here!

end if

explored.add(node.state)

child_nodes ← env.expand(node.state)

for all child_nodes **do**

if child_node.state not in explored or in frontier **then**

frontier.insert(child_node)

else if child_node.state in frontier with higher cost **then**

replace that node with the child_node

end if

end for

end while

end function

8 / 25

Notes

Does the algorithm always find the best (cheapest) path? Are there any requirements for the path optimality function?

The UCS graph search

function UCS_GRAPH_SEARCH(env) **return** a solution or failure

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frontier ← priority_queue(node)

▷ path_cost for ordering

explored ← set()

while frontier not empty **do**

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if node contains Goal **then return** node

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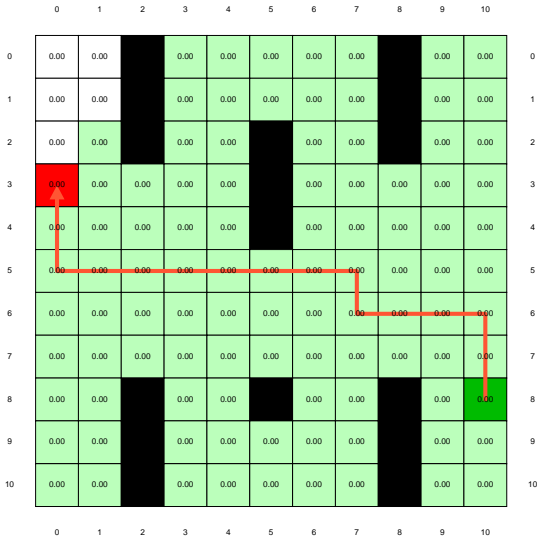
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8 / 25

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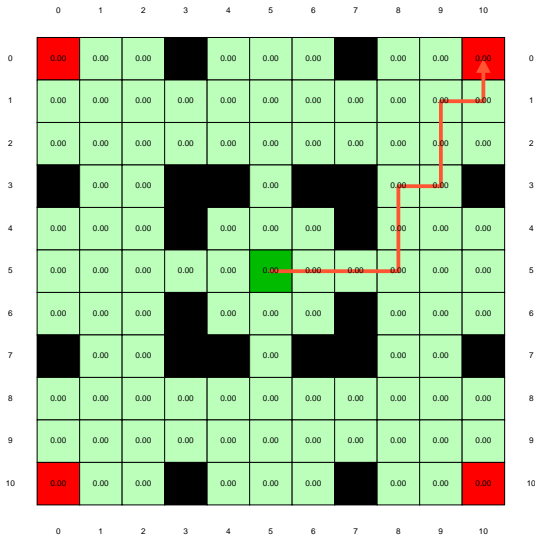
Few examples of search strategies so far



Run the demos.

Notes

What is wrong with UCS and other strategies?



Run the demo, or see <https://youtu.be/TT5MY8xCgAg>

Notes

Node selection, take argmin $f(n)$

Selecting next node to expand/visit:

$$\text{node} \leftarrow \underset{n \in \text{frontier}}{\text{argmin}} f(n)$$

What is $f(n)$ for DFS, BFS, and UCS?

- ▶ DFS: $f(n) = -n.\text{depth}$
- ▶ BFS: $f(n) = n.\text{depth}$
- ▶ UCS: $f(n) = n.\text{path_cost}$

The good: (one) frontier as a priority queue

(I.e., priority queue will work universally. Still, stack (LIFO) and queue (FIFO) are (conceptually) the perfect data structures for DFS and BFS, respectively.)

The bad: All the $f(n)$ correspond to the cost from n to the start - only backward cost; cost-to-come (to n).

Notes

Do humans look back when planing path? Is looking back important at all? If yes, when?

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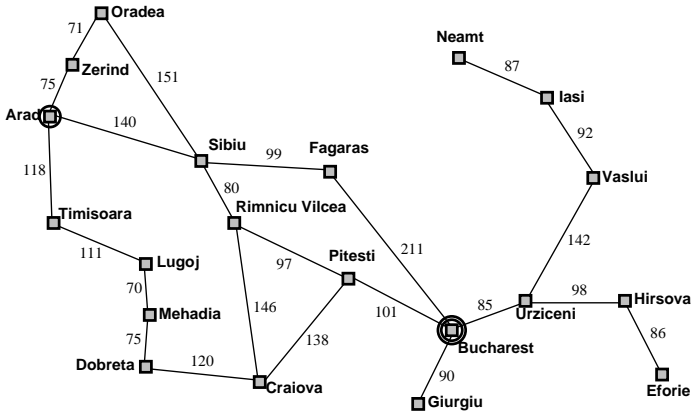
How far are we from the goal cost-to-go ? – Heuristics

- ▶ A function that estimates how close a state is to the goal.
- ▶ Designed for a particular problem.
- ▶ We will use $h(n)$ – heuristic value of node n .

Notes

What happens if $h(n) = \text{true cost}$?

Example of heuristics



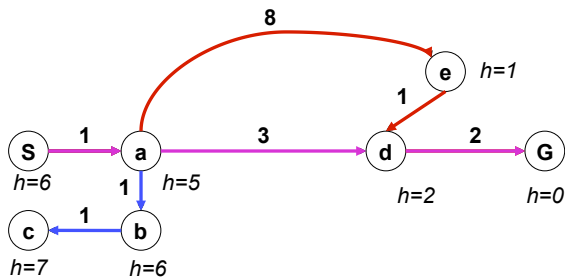
Arad	366	Mehadia	241
Bucharest	0	Neamt	234
Craiova	160	Oradea	380
Drobeta	242	Pitesti	100
Eforie	161	Rimnicu Vilcea	193
Fagaras	176	Sibiu	253
Giurgiu	77	Timisoara	329
Hirsova	151	Urziceni	80
Iasi	226	Vaslui	199
Lugoj	244	Zerind	374

Notes

Straight-line distance to Bucharest.

Illustration of *greedy* failing: Imagine going from Iasi to Fagaras. Neamt will be chosen for expansion. This will add Iasi back. Iasi is closer to Fagaras than Vaslui is and will be expanded again. Infinite loop... (3.5.1. in [2])

Greedy, take the node argmin $h(n)$



1

What is wrong (and nice) with the Greedy?

¹Graph example: Ted Grenager

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Notes

Also called "Greedy best-first search" [2].

What will happen in this example:

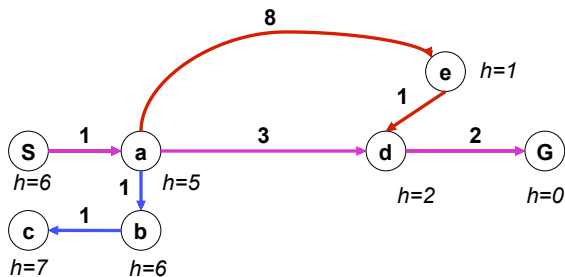
1. Expand "S". Add "a" to frontier.
2. Expand "a". Add "b", "d", "e".
3. Expand "e" ($h = 1$). We already have "d".
4. Expand "d". Get "G".

Wrong:

- not optimal
- not complete (tree search version) (Can be shown on the Romania example – go back.)
- (graph search version is complete only in finite state spaces)

Nice: it is simple.

Greedy, take the node argmin $h(n)$



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14 / 25

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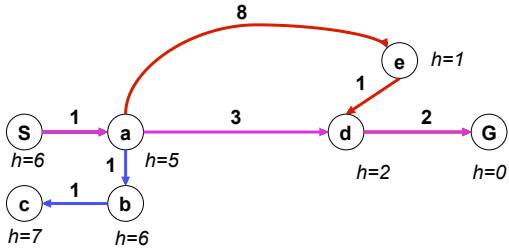
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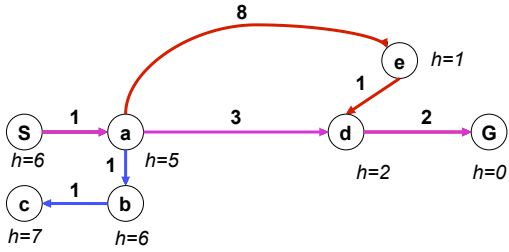


UCS orders by backward (path) cost $g(n)$

Greedy uses heuristics (goal proximity) $h(n)$

A* orders nodes by: $f(n) = g(n) + h(n)$

A* combines UCS and Greedy

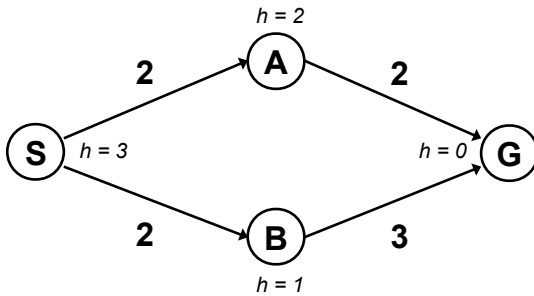


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When to stop A*?



2

²Graph example: Dan Klein and Pieter Abbeel

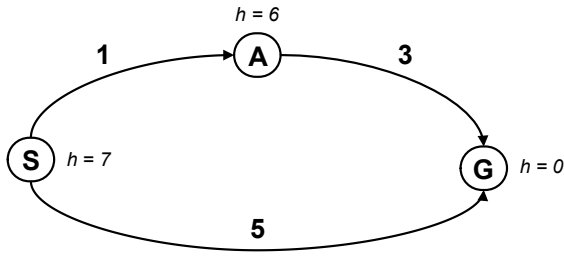
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Notes

1. S
 - $f(S) = g(S) + h(S) = 0 + 3 = 3$
 - expanding/popping this one and crossing out (removing from frontier)
2. $S \rightarrow A$
 - $f(A) = g(A) + h(A) = 2 + 2 = 4$
3. $S \rightarrow B$
 - $f(B) = g(B) + h(B) = 2 + 1 = 3$
 - expanding this one and crossing out
4. $S \rightarrow B \rightarrow G$
 - $f(G) = g(G) + h(G) = 5 + 0 = 5$
 - Should I stop now? No. Pop $S \rightarrow A$ with $f = 4$.
5. $S \rightarrow A \rightarrow G$
 - $f(G) = g(G) + h(G) = 4 + 0 = 4$
 - This is now cheapest on the frontier. I pop/expand and I'm done.

Note: h is a function of the state. g is a function of a node (the path matters).

Is A* optimal?



What is the problem?

³Graph example: Dan Klein and Pieter Abbeel

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Notes

Try to answer the question before going to the next slide.

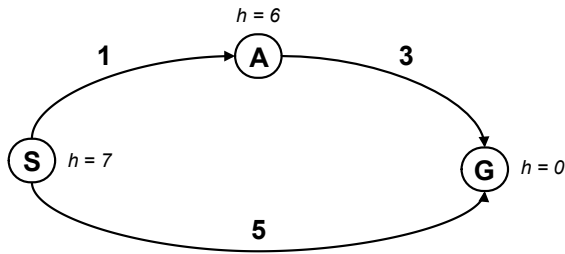
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 - $f(S) = g(S) + h(S) = 0 + 7 = 7$
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2. $S \rightarrow A$
 - $f(A) = g(A) + h(A) = 1 + 6 = 7$
3. $S \rightarrow G$
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Oops! That's not cheapest! What went wrong?

What follows – keep for next slide. Problem with $h(A) = 6$. Overestimating the expense. (Same problem for $h(S)$.)

Estimates need to be \leq actual costs.

Is A* optimal?



3

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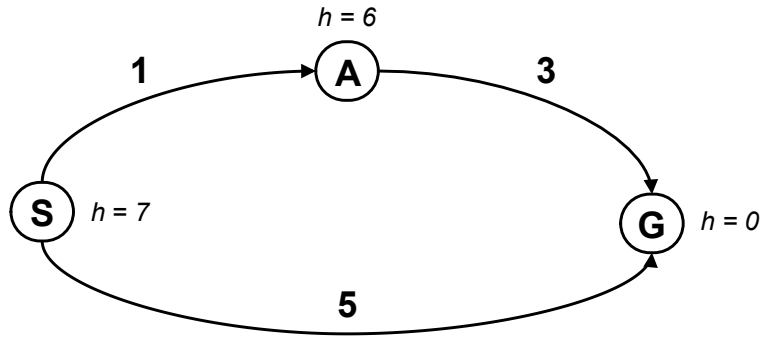
What is the right $h(A)$?

A: $0 \leq h(A) \leq 4$

B: $h(A) \leq 3$

C: $0 \leq h(A) \leq 3$

D: $0 \leq h(A)$



Notes

$h(A) \leq 3$ it means less than the actual cost of going from A to goal. Heuristic must not be overly pessimistic. B is correct.

Negative $h(n)$ does not break the admissibility property but $h(\text{Goal}) = 0$ must be always kept.

For a discussion, see, e.g.

<https://stackoverflow.com/questions/30067813/are-heuristic-functions-that-produce-negative-values-inadmissible>

Admissible heuristics

A heuristic function h is admissible if:

$$\begin{aligned}h(n) &\leq h^*(n) \\ h(\text{Goal}) &= 0\end{aligned}$$

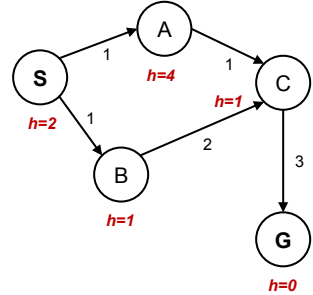
where $h^*(n)$ is the true cost of going from n to the nearest goal.

Optimality of A* tree search

A* is optimal if $h(n)$ is admissible.

A* graph search

```
function GRAPH_SEARCH(env)
  frontier.insert(startnode)
  explored = set()
  while frontier do
    node = frontier.pop()
    if goal in node then break
    end if
    nodes = env.expand(node.state)
    explored.add(node.state)
    for all nodes do
      if node.state not in explored then
        frontier.insert(node)
      end if
    end for
  end while
end function
```



What went wrong?

Graph example: Dan Klein and Peter Abbeel

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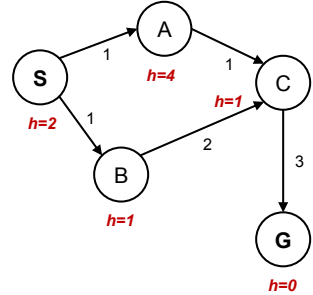
Notes

1. $f(S) = g(S) + h(S) = 0 + 2 = 2$
– expanding/popping this one and crossing out (removing from frontier); *explored set*: S
2. $S \rightarrow A$; $f(A) = g(A) + h(A) = 1 + 4 = 5$
3. $S \rightarrow B$; $f(B) = g(B) + h(B) = 1 + 1 = 2$
4. B is cheapest on the frontier. Expanding and removing from frontier; *explored set*: S, B
5. $B \rightarrow C$; $f(C) = g(C) + h(C) = 3 + 1 = 4$
6. C is cheapest on the frontier. Expanding and removing from frontier; *explored set*: S, B, C
7. $C \rightarrow G$; $f(G) = g(G) + h(G) = 6 + 0 = 6$
8. A is cheapest on the frontier. Expanding and removing from frontier; *explored set*: S, A, B, C
9. $A \rightarrow C$; $f(C) = g(C) + h(C) = 2 + 1 = 3$
10. C is cheapest on the frontier. But, it's on *explored set*! Can't be expanded.
11. Moving on to G , expanding and finishing.

Oops! That's not cheapest! $cost(S \rightarrow B \rightarrow C \rightarrow G) = 6$; $cost(S \rightarrow A \rightarrow C \rightarrow G) = 5$ What went wrong?

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end function
```



What went wrong?

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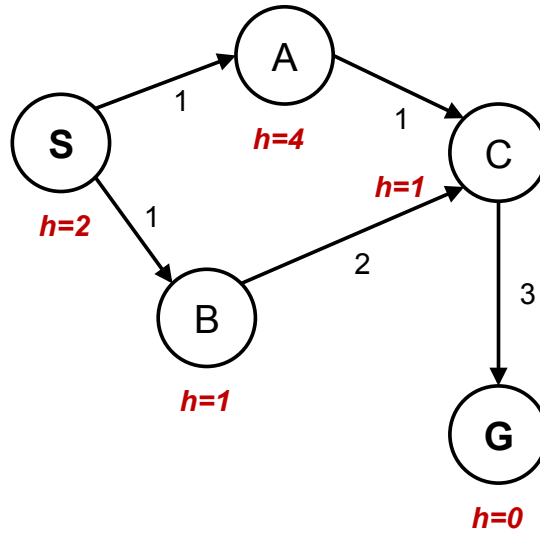
What is the proper $h(A)$?

A: $h(A) = 1$

B: $h(A) = 2$

C: $1 \leq h(A) \leq 2$

D: $0 \leq h(A) \leq 1$

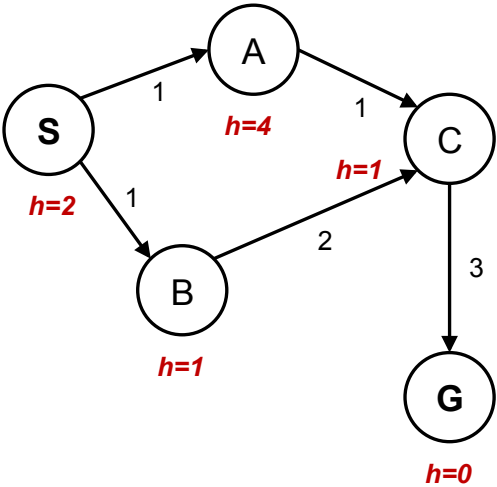


Notes

As it will be explained in the next slides: $h(A) \leq c(A, C) + h(C) = 2$

$h(S) \leq c(S, A) + h(A)$ it means $h(A) \geq h(S) - c(A, S) = 1$

Consistent heuristics



Admissible h :
 $h(A) \leq \text{true cost } A \rightarrow G$

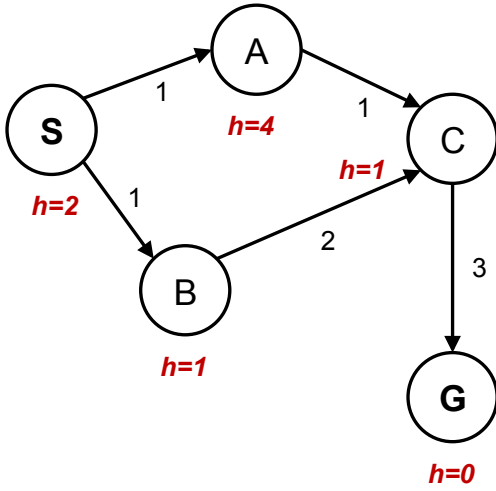
Consistent h :
 $h(A) - h(C) \leq \text{true cost } A \rightarrow C$
 in general:
 $h(n) - h(s) \leq \text{true cost } n \rightarrow s$ for any pair: node n and its successor s

$f(n) = g(n) + h(n)$ along a path never decreases!

Notes

Our heuristic was admissible.
 With *tree search* it would have worked. It would have expanded C and found the alternative, cheaper path.
 For graph search, the problem is the $A \rightarrow C \rightarrow G$ subgraph where the *consistent* heuristic condition is violated.
 The general condition means we have two constraints for (A) for this particular graph:
 $h(S) - h(A) \leq c(S, A)$
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Consistent heuristics



Admissible h :
 $h(A) \leq \text{true cost } A \rightarrow G$

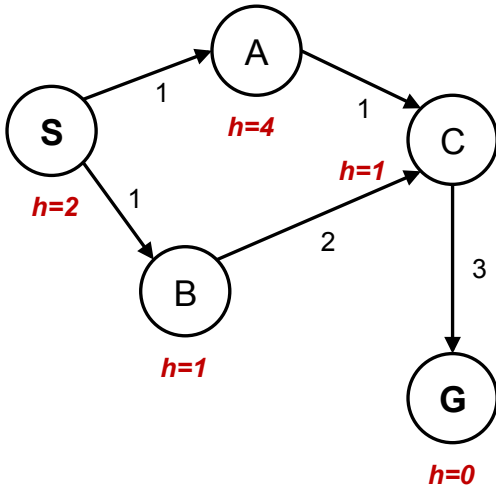
Consistent h :
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in general:
 $h(n) - h(s) \leq \text{true cost } n \rightarrow s$ for any pair: node n and its successor s
 $f(n) = g(n) + h(n)$ along a path never decreases!

Notes

Our heuristic was admissible.
With *tree search* it would have worked. It would have expanded C and found the alternative, cheaper path.
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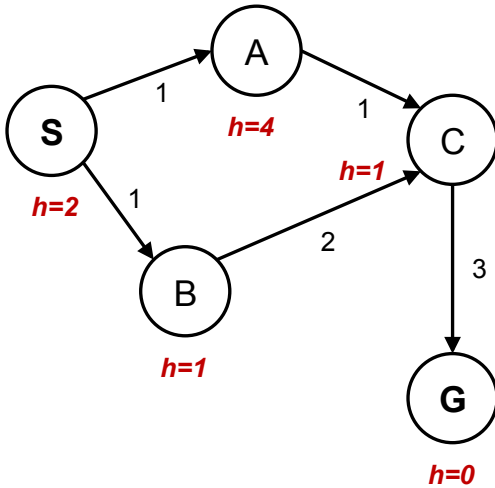
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References, further reading

Some figures from [2]. Chapter 2 in [1] provides a compact/dense intro into search algorithms. (State space) Search algorithms are ubiquitous, explanations in many (text)books about Algorithms.

Nice online course from UC Berkeley (CS 188 Intro to AI):

http://ai.berkeley.edu/lecture_videos.html Lecture: Informed Search.

[1] Steven M. LaValle.

Planning Algorithms.

Cambridge, 1st edition, 2006.

Online version available at: <http://planning.cs.uiuc.edu>.

[2] Stuart Russell and Peter Norvig.

Artificial Intelligence: A Modern Approach.

Prentice Hall, 3rd edition, 2010.

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