

Problem solving by search

Tomáš Svoboda and Matěj Hoffmann

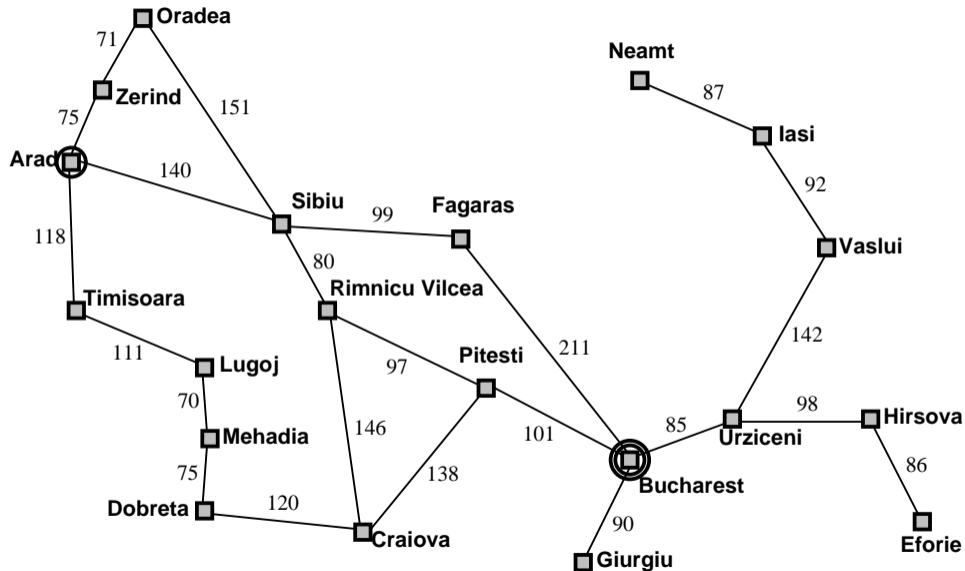
Vision for Robots and Autonomous Systems, Center for Machine Perception
Department of Cybernetics
Faculty of Electrical Engineering, Czech Technical University in Prague

February 17, 2022

Outline

- ▶ Search problem.
- ▶ State space graphs.
- ▶ Search trees.
- ▶ Strategies: which tree branches to choose?
- ▶ Strategy/Algorithm properties.
- ▶ Programming infrastructure.

Example: Traveling in Romania



Example: Map of Romania

Goal:

be in Bucharest

Problem formulation:

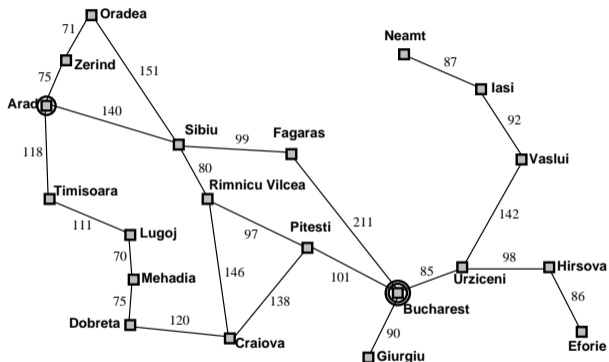
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actions: drive between cities

Solution:

Sequence of cities (path)

(action sequence [2])



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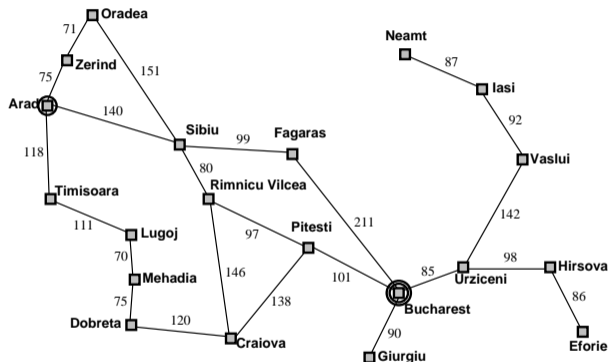
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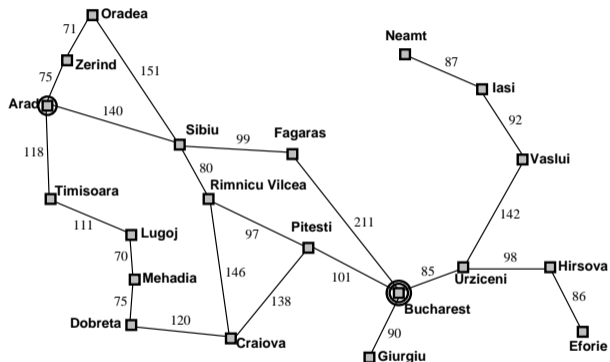
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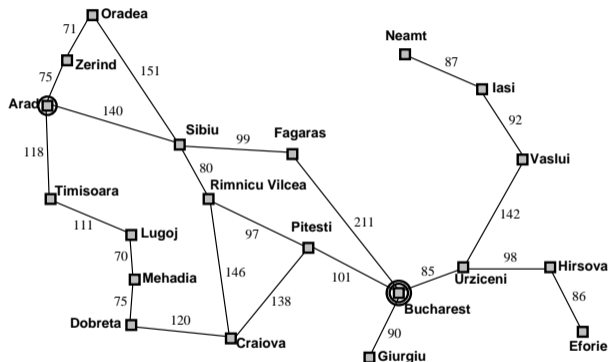
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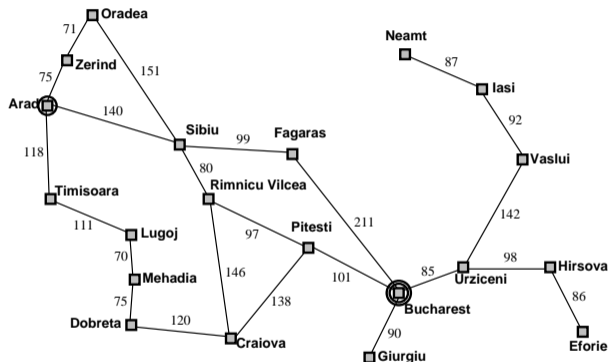
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Example: The 8-puzzle

7	2	4
5		6
8	3	1

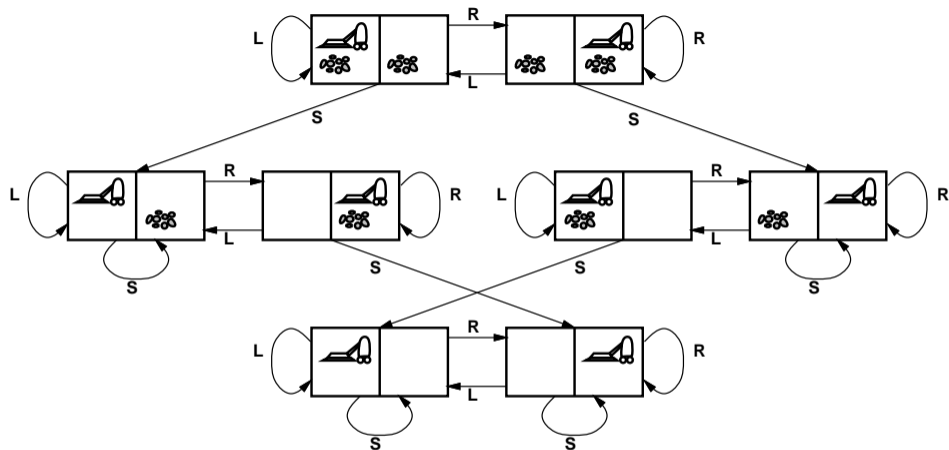
Start State

1	2	3
4	5	6
7	8	

Goal State

states?
actions?
solution?
cost?

Example: Vacuum cleaner



states?
actions?
solution?
cost?

A Search Problem

- ▶ **State space** (including Start/Initial state): position, board configuration,
- ▶ Actions : drive to, Up, Down, Left ...
- ▶ Transition model : Given state and action return state (and cost)
- ▶ Goal test : Are we done?

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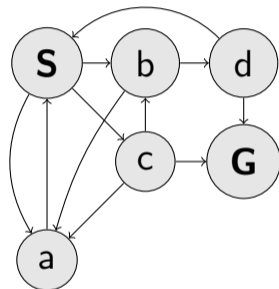
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State Space Graphs

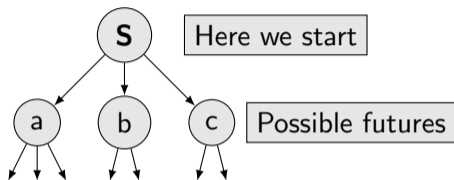
State space graph: a representation of a search problem

- ▶ Graph Nodes – states – are abstracted world configurations
- ▶ Arcs represent action results
- ▶ Goal test – a set of goal nodes

Each state occurs only *once* in a state (search) space.

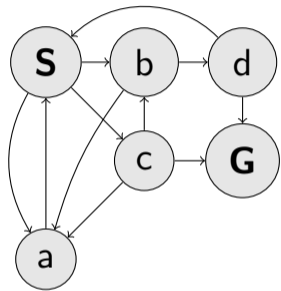


Search Trees



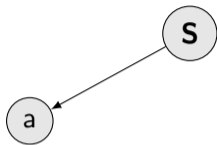
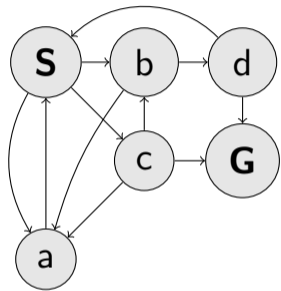
- ▶ A “what if” tree of plans and their outcomes
- ▶ Start node is the root
- ▶ Children are successors
- ▶ Nodes show/contains states, but correspond to *plans* that achieve those states

State Space Graphs vs. Search Trees



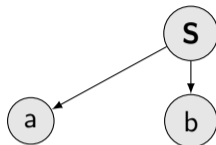
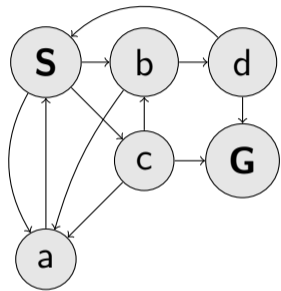
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State Space Graphs vs. Search Trees



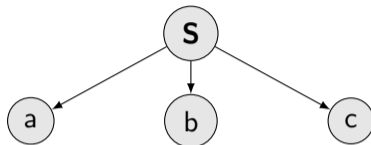
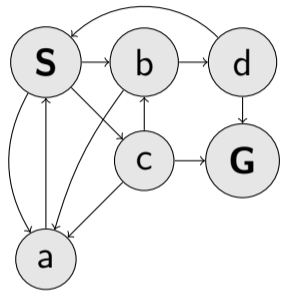
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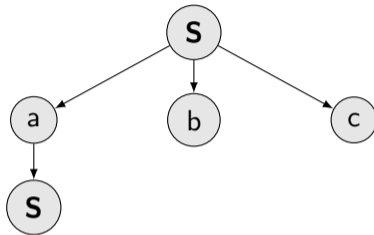
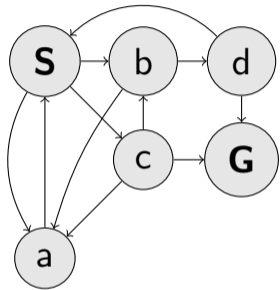
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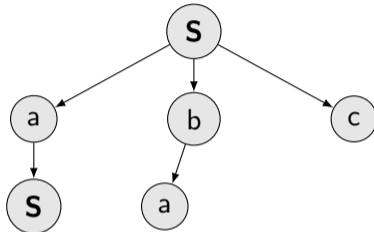
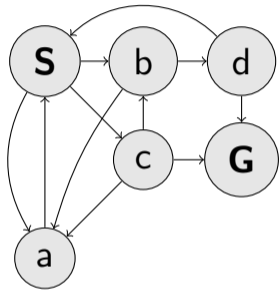
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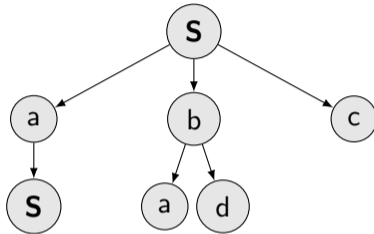
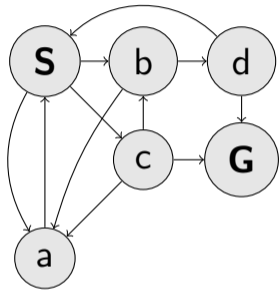
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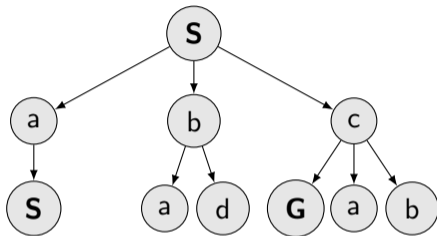
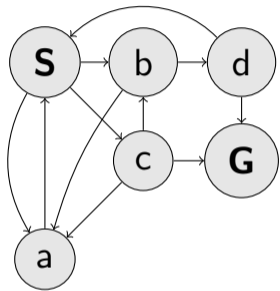
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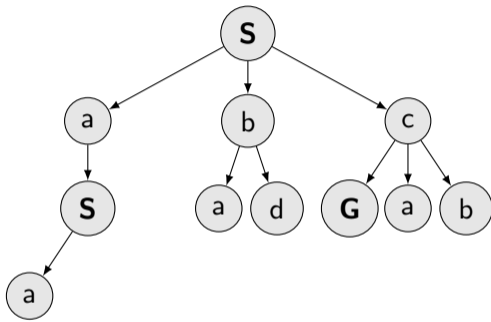
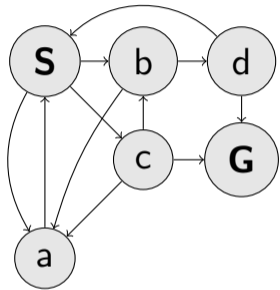
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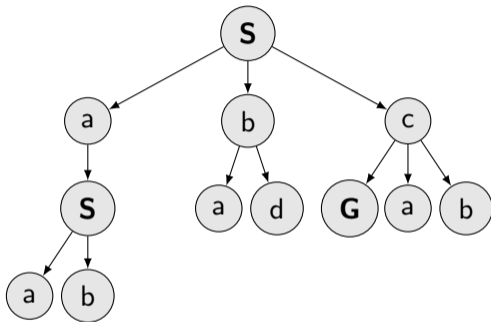
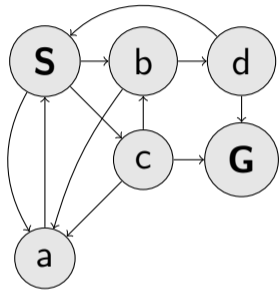
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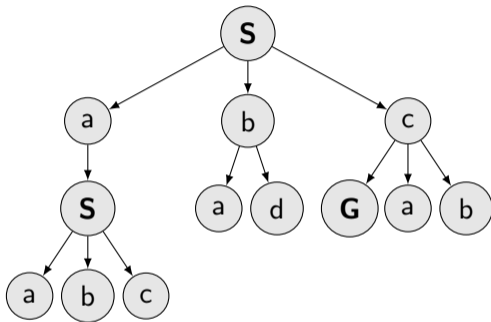
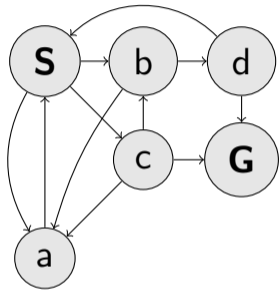
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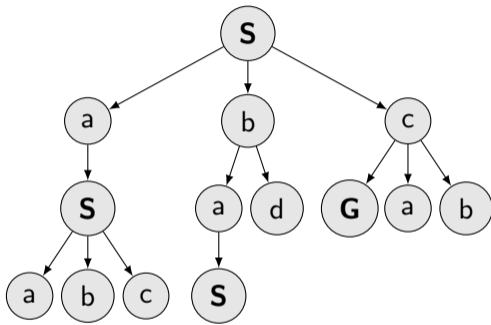
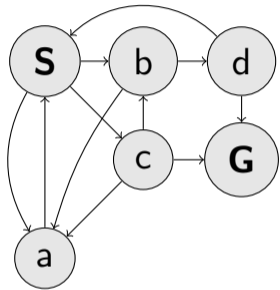
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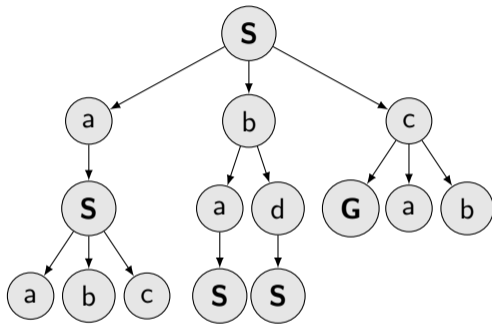
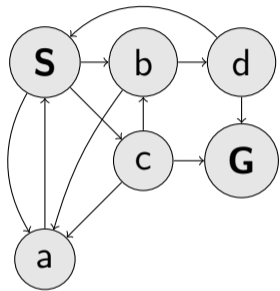
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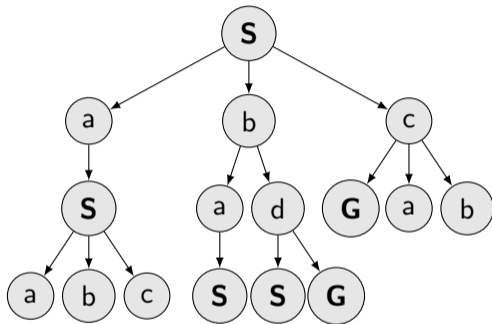
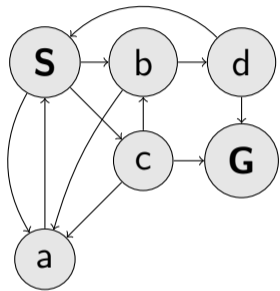
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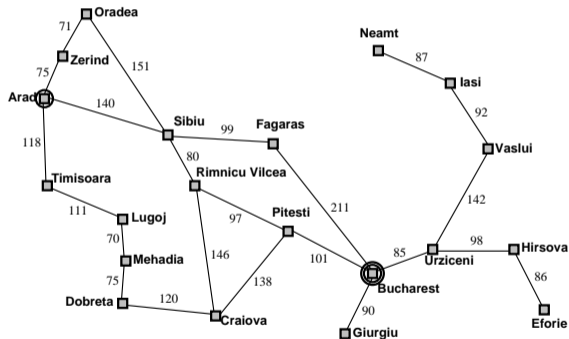
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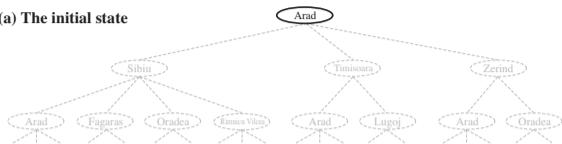


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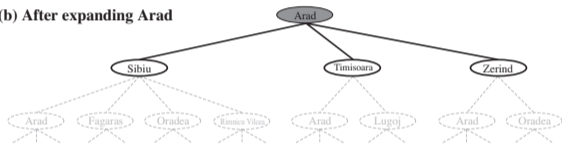
From problem/transition graph to search tree (Romania)



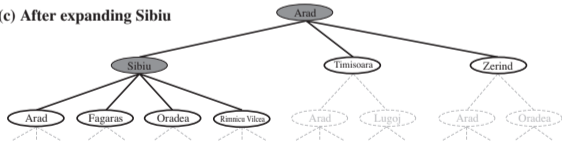
(a) The initial state



(b) After expanding Arad



(c) After expanding Sibiu

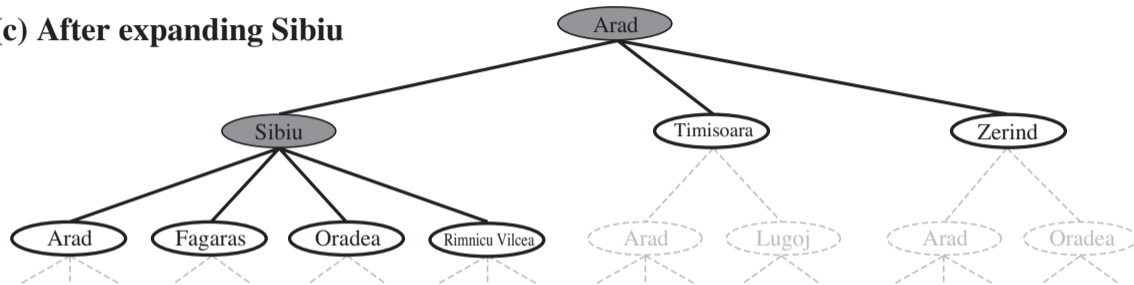


Problem/transition graph is revealed incrementally.

The revealing strategy can be visualized as a search tree.

Search elements - unvisited, dead, alive states

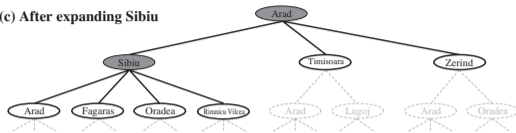
(c) After expanding Sibiu



- ▶ Expand **plans** - possible ways (**tree nodes**).
- ▶ Manage/Maintain **fringe** (or **frontier**) of plans under consideration.
- ▶ Expand new nodes *wisely(?)*.

Tree search algorithm

(c) After expanding Sibiu



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

initialize by using the initial state of the problem

loop

if no candidates for expansion **then return** failure

else choose a leaf node for expansion

end if

if the node contains a goal state **then return** the solution

end if

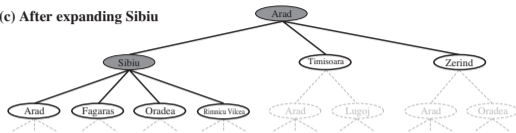
Expand the node and add the resulting nodes to the tree

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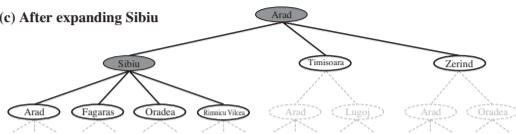
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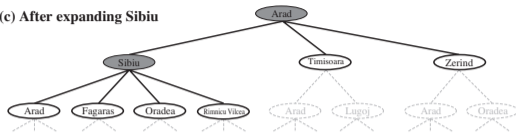
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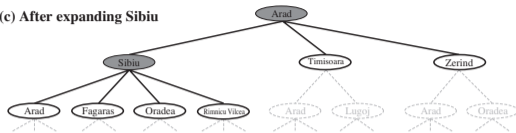
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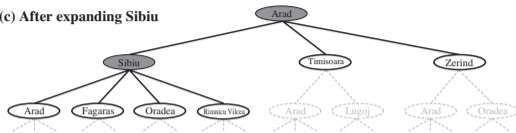
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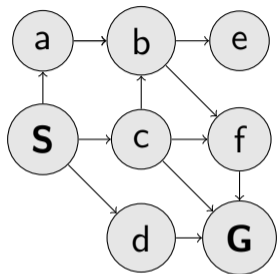
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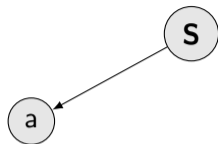
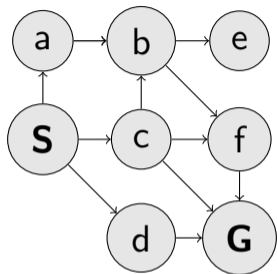
Example of a tree search



Which nodes to *explore*?

What are the properties of a strategy/algorithm?

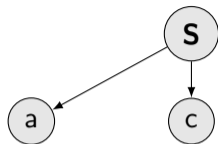
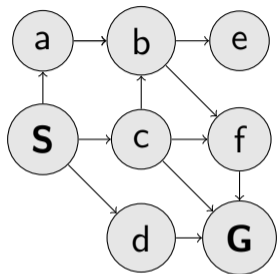
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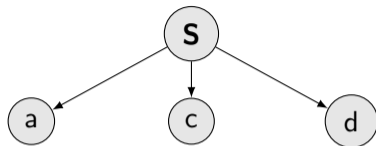
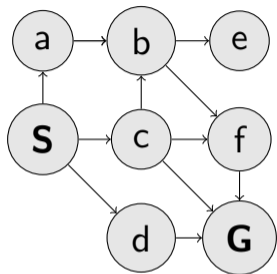
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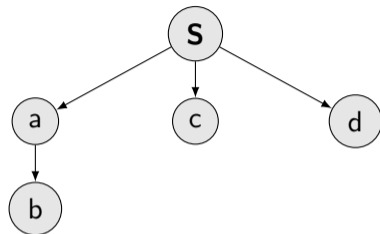
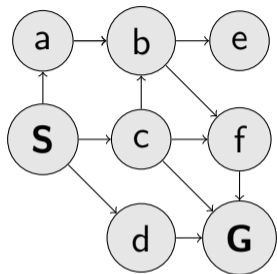
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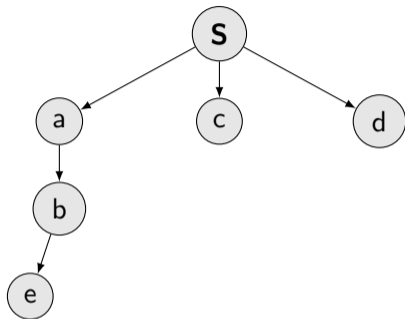
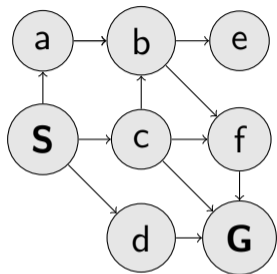
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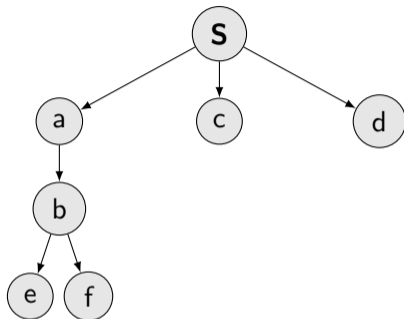
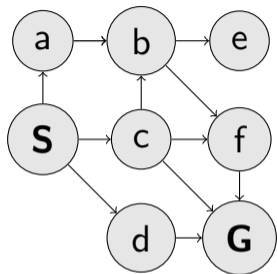
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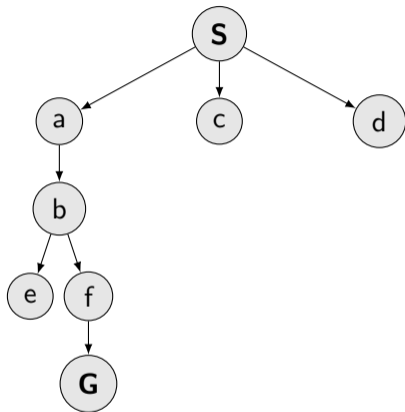
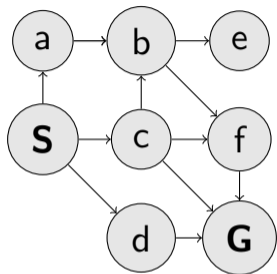
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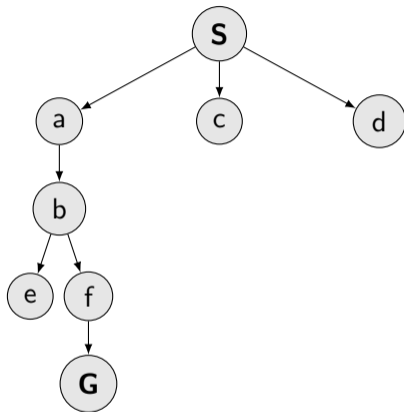
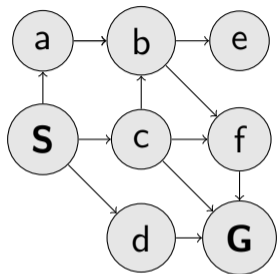
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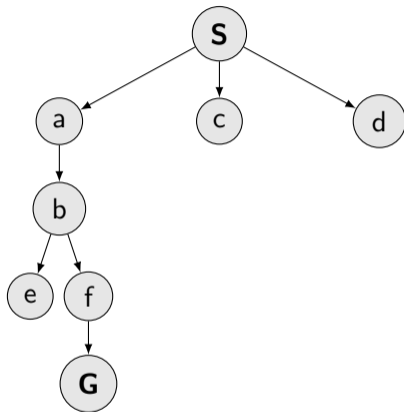
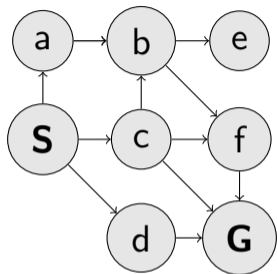
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Which nodes to *explore*?

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Search (algorithm) properties

- ▶ Guaranteed to find a solution (if exists)? Complete?
- ▶ Guaranteed to find the least cost path? Optimal?
- ▶ How many steps - an operation with a node? Time complexity?
- ▶ How many nodes to remember? Space/Memory complexity?

How many nodes in a (search) tree? What are tree parameters?

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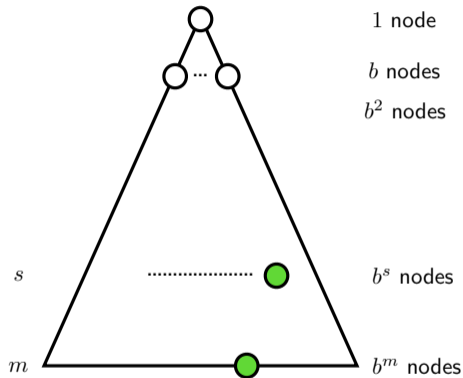
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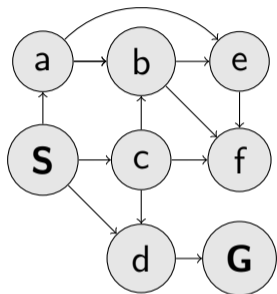
Strategies

How to traverse/build a search tree?

- ▶ **Depth** of the tree d .
- ▶ **Max-Depth** of the tree m . Can be ∞ .
- ▶ **Branching** factor b .
- ▶ s denotes the **shallowest Goal**.
- ▶ How many nodes in the whole tree?

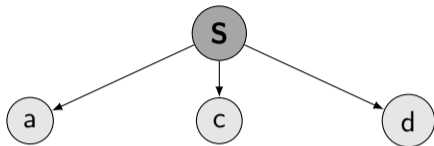
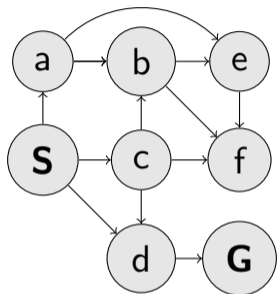


Depth-First Search (DFS)



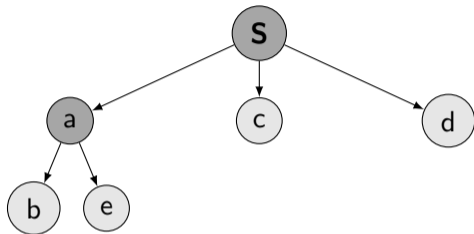
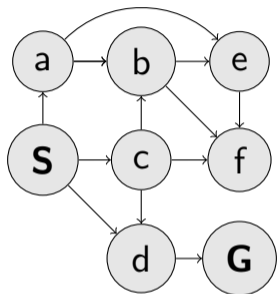
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Depth-First Search (DFS)



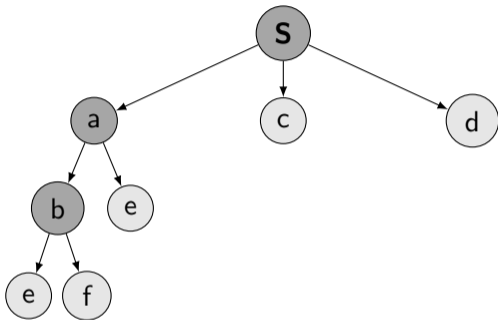
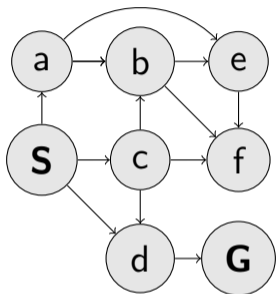
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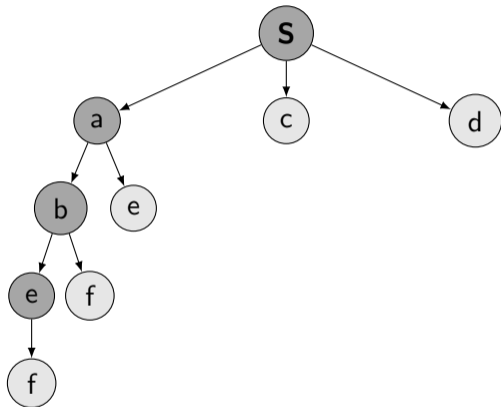
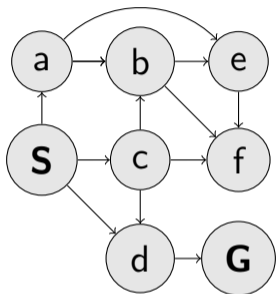
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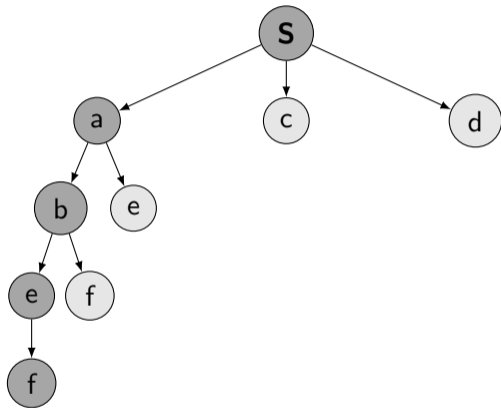
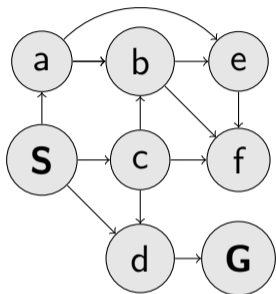
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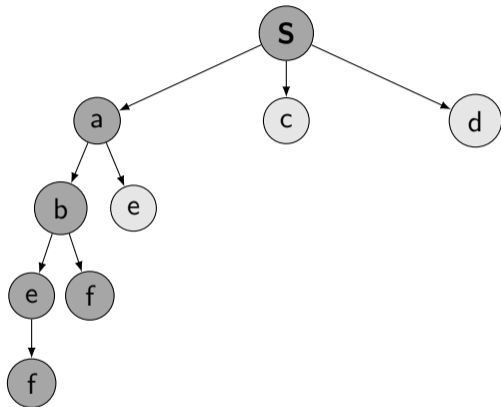
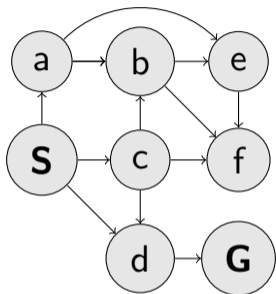
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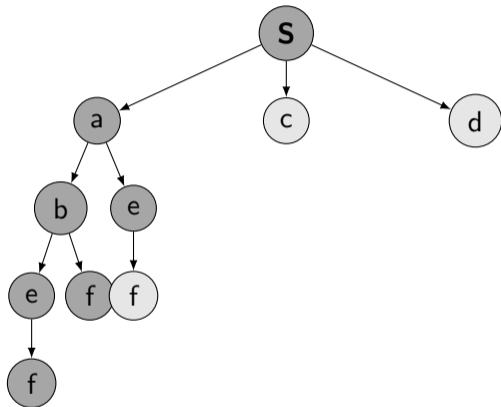
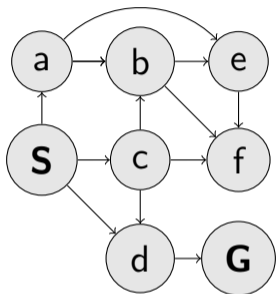
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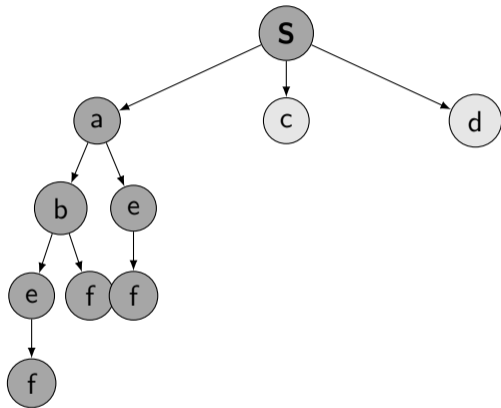
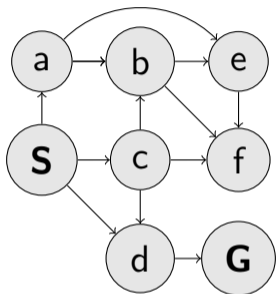
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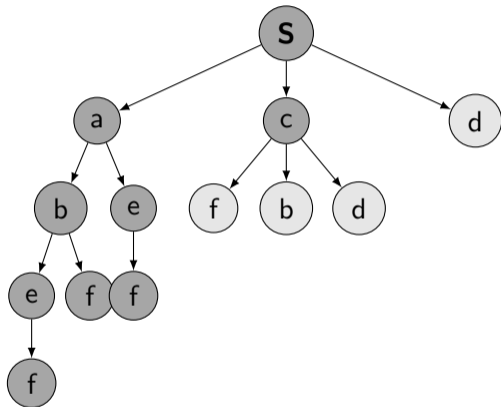
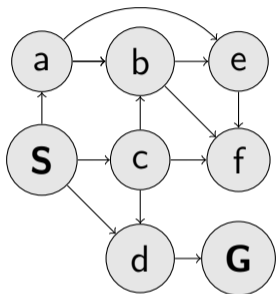
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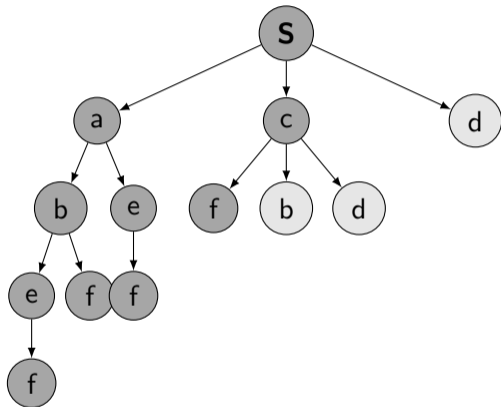
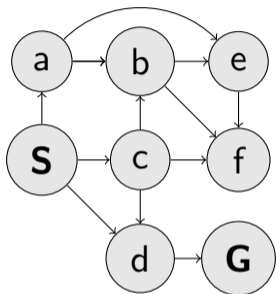
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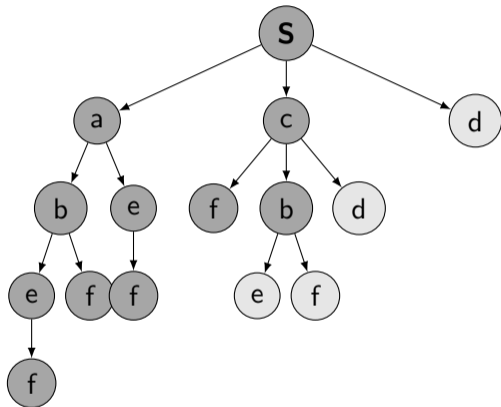
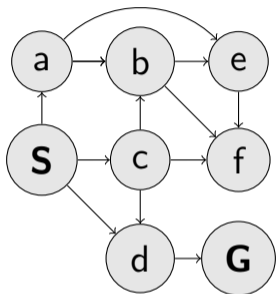
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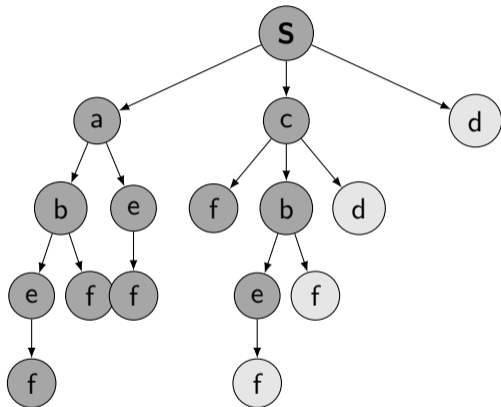
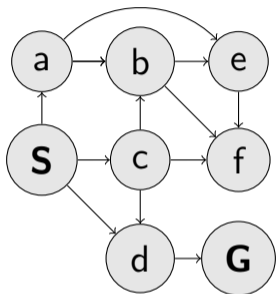
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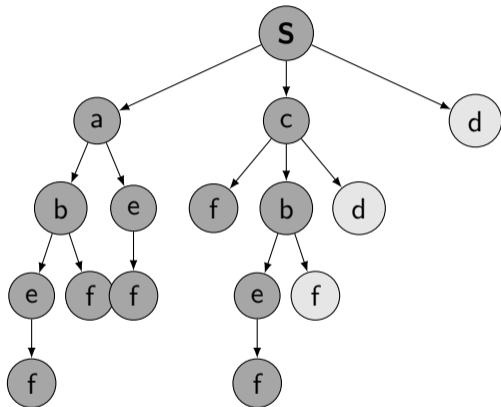
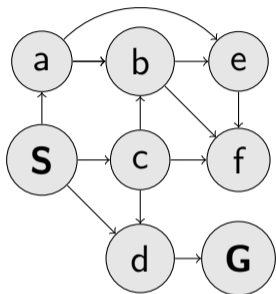
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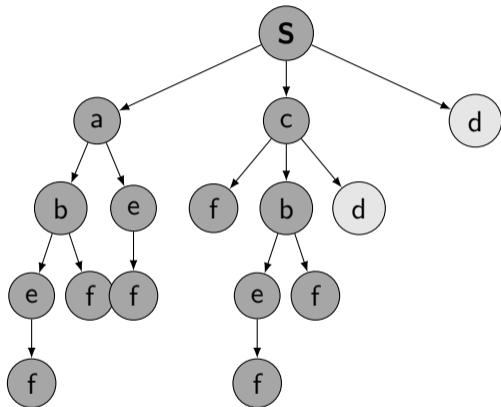
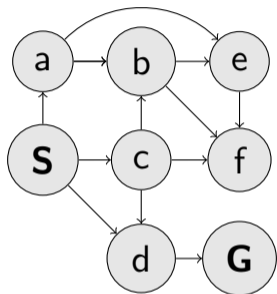
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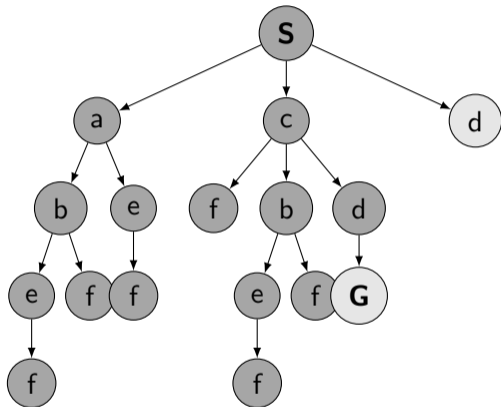
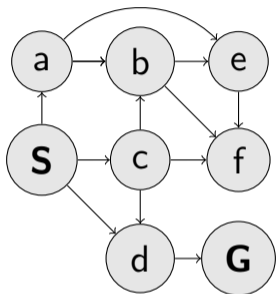
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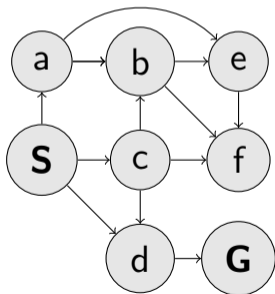
Depth-First Search (DFS)



What are the DFS properties (complete, optimal, time, space)?

DFS properties

- ▶ Time complexity?
- ▶ Space complexity?
- ▶ Complete?
- ▶ Optimal?



b, m, s , Time complexity?

A $\mathcal{O}(bm)$

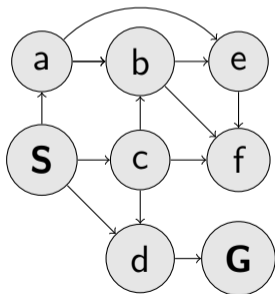
B $\mathcal{O}(b^m)$

C $\mathcal{O}(m^b)$

D ∞

DFS properties

- ▶ Time complexity?
- ▶ Space complexity?
- ▶ Complete?
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b, m, s , Space complexity?

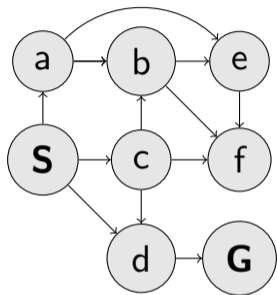
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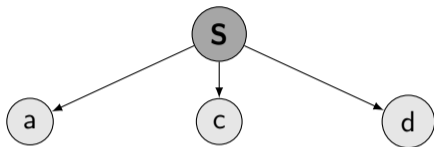
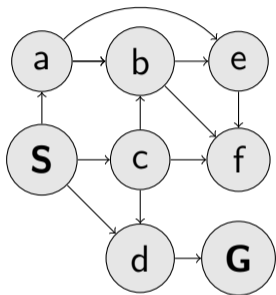
D ∞

Breadth-First Search (BFS)



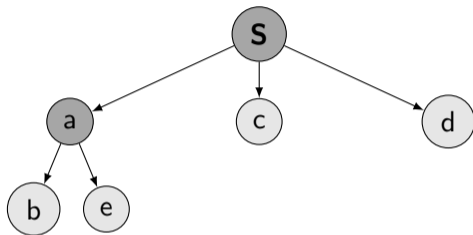
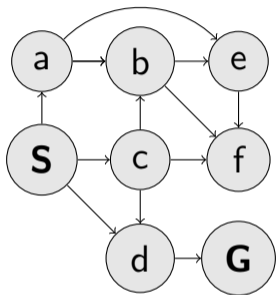
What are the BFS properties?

Breadth-First Search (BFS)



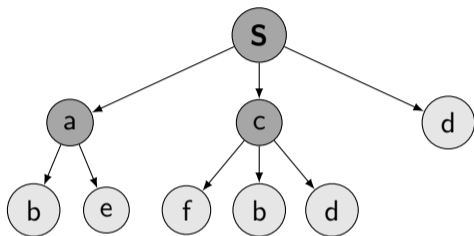
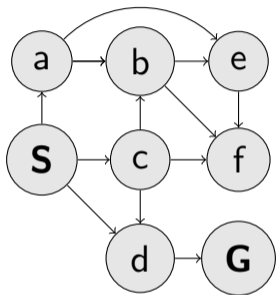
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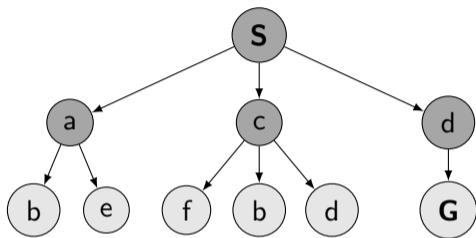
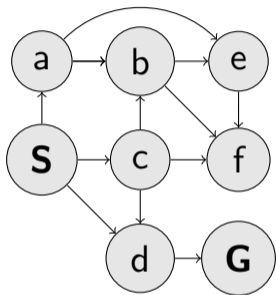
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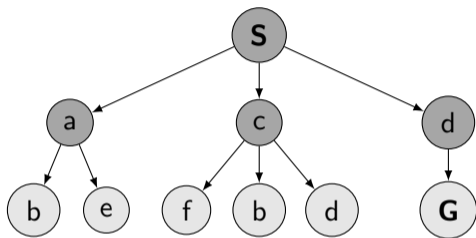
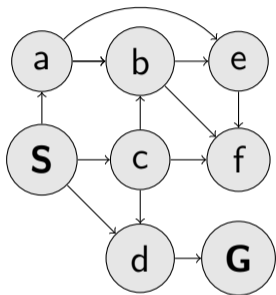
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What are the BFS properties?

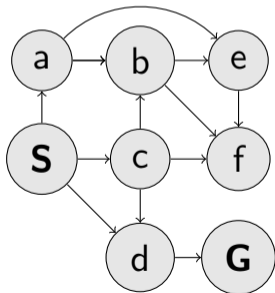
Breadth-First Search (BFS)



What are the BFS properties?

BFS properties

- ▶ Time complexity?
- ▶ Space complexity?
- ▶ Complete?
- ▶ Optimal?



b, m, s , Time complexity?

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B $\mathcal{O}(b^m)$

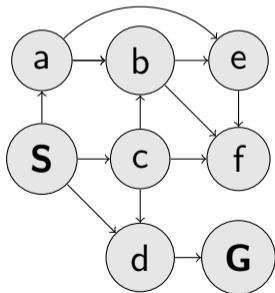
C $\mathcal{O}(m^b)$

D ∞

E $\mathcal{O}(b^s)$

BFS properties

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- ▶ Space complexity?
- ▶ Complete?
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b, m, s , Space complexity?

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B $\mathcal{O}(b^m)$

C $\mathcal{O}(m^b)$

D ∞

E $\mathcal{O}(b^s)$

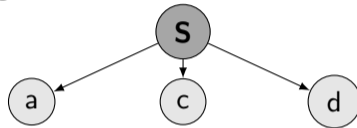
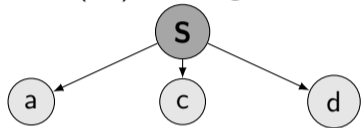
DFS vs BFS

What are (dis)advantages of the individual strategies?



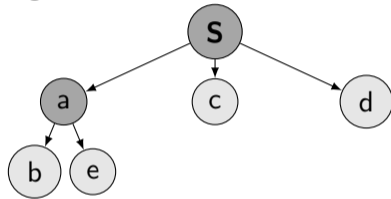
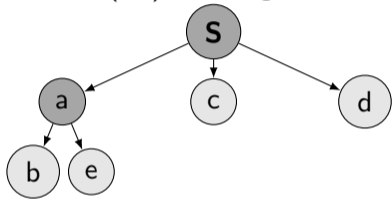
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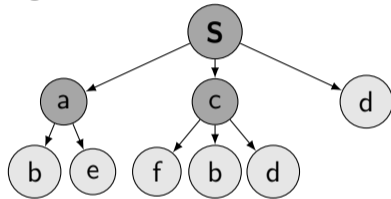
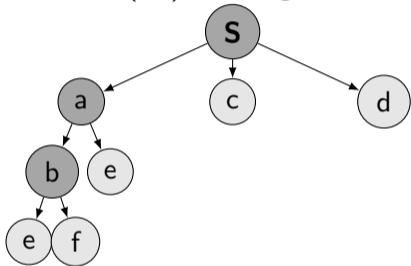
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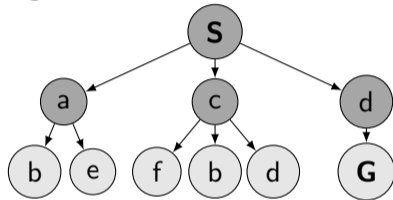
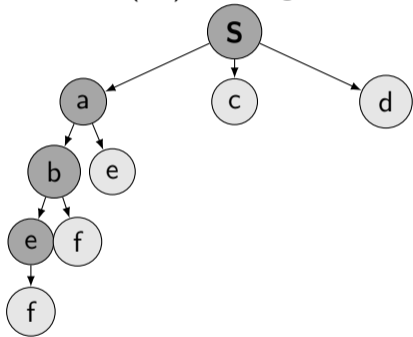
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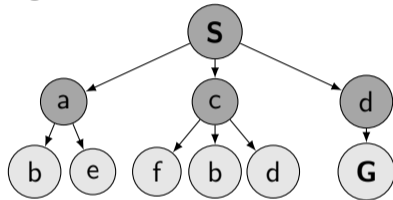
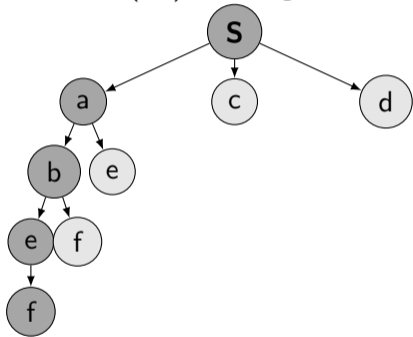
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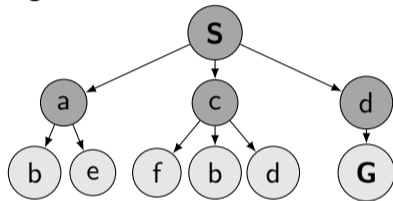
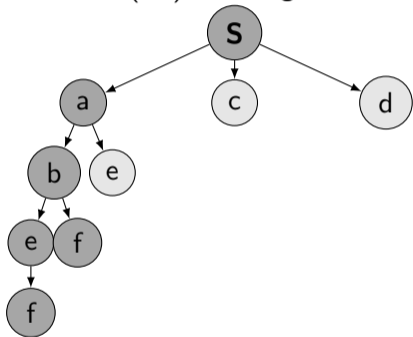
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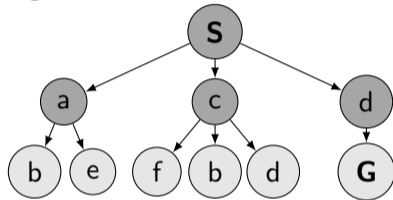
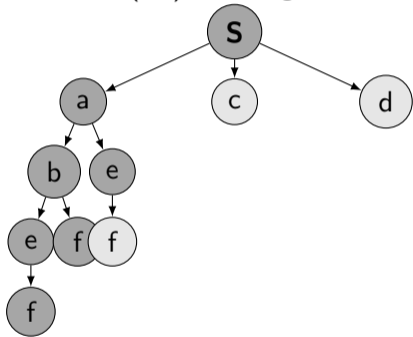
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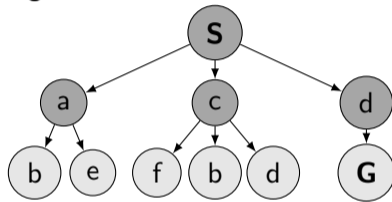
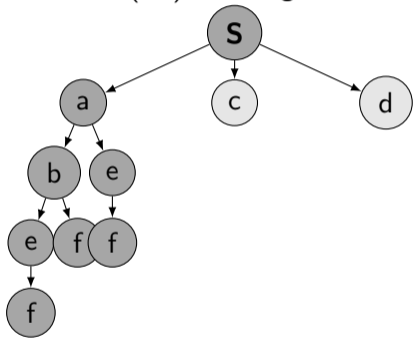
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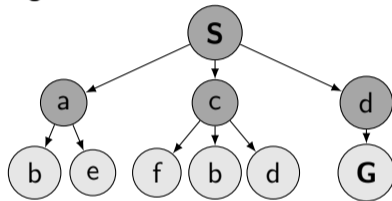
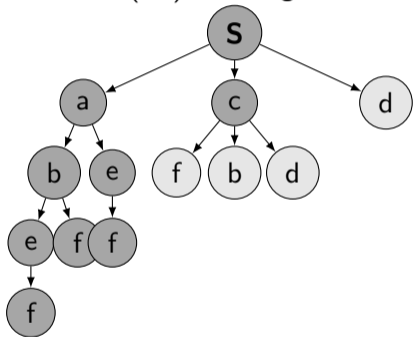
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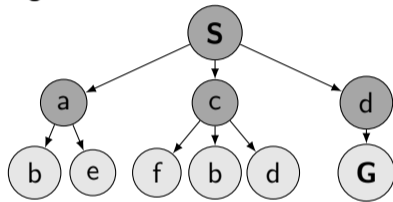
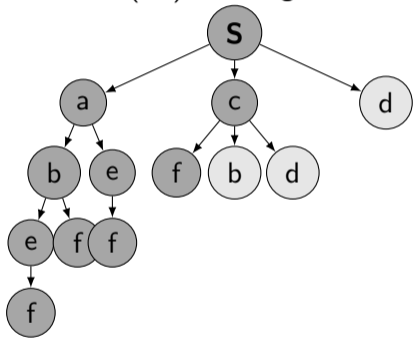
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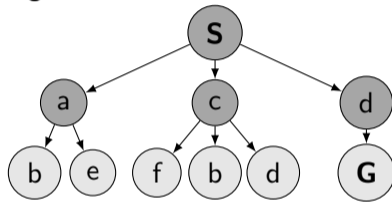
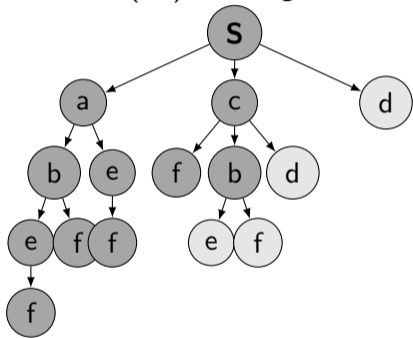
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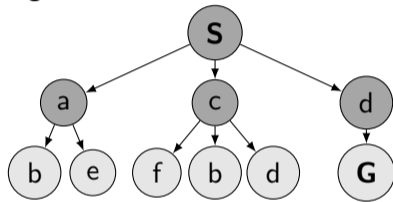
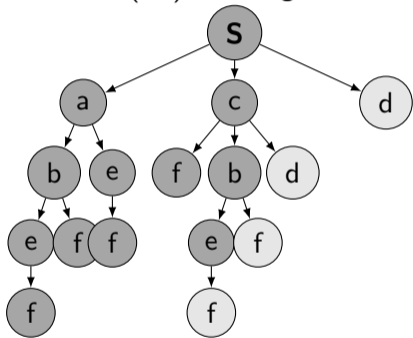
DFS vs BFS

What are (dis)advantages of the individual strategies?



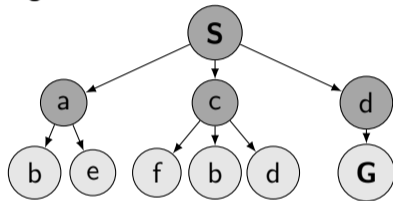
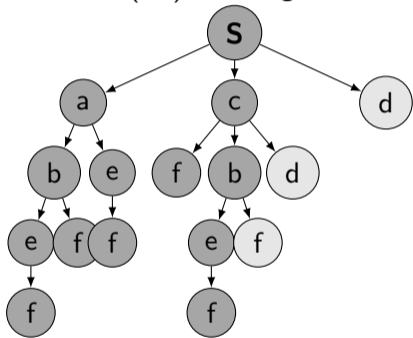
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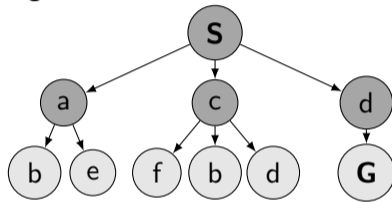
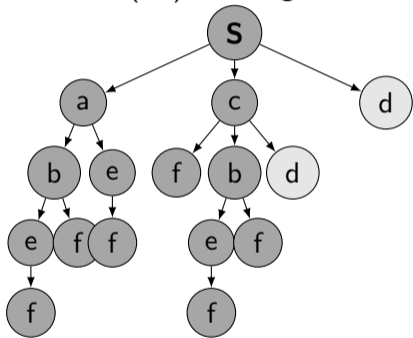
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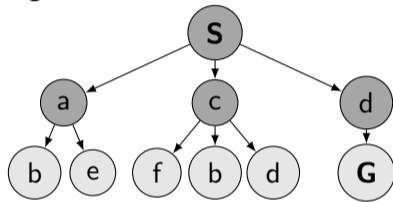
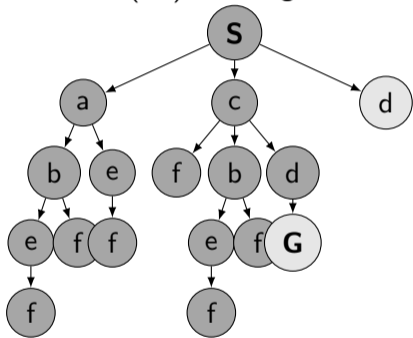
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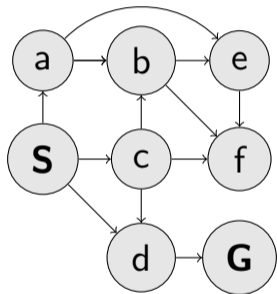
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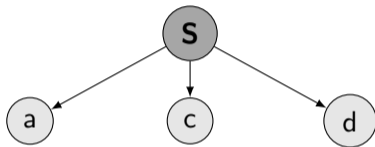
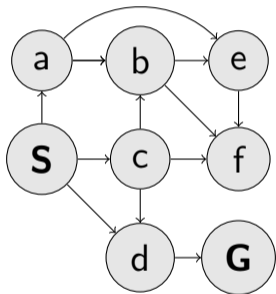
DFS with limited depth, maxdepth=2

Do not follow nodes with depth $>$ maxdepth



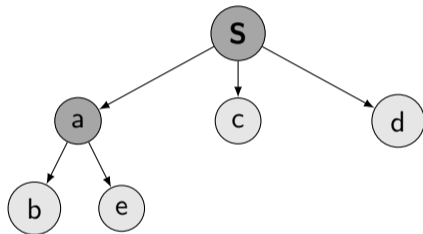
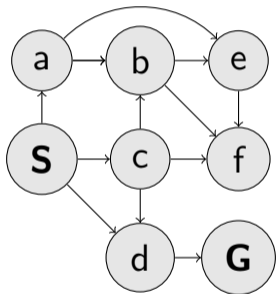
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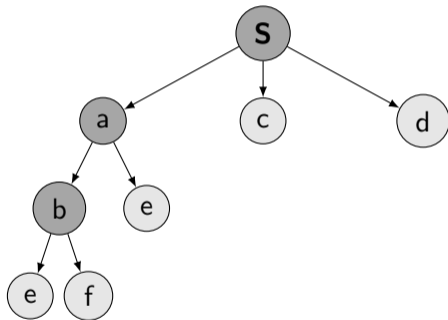
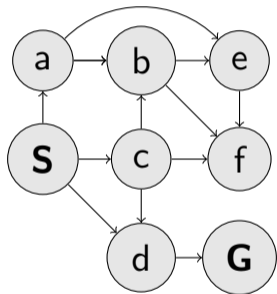
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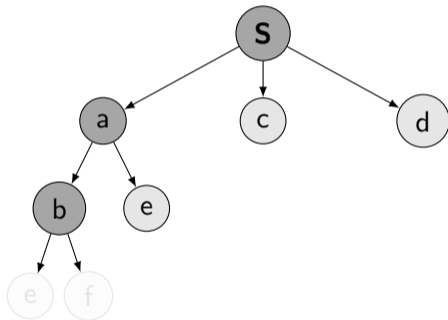
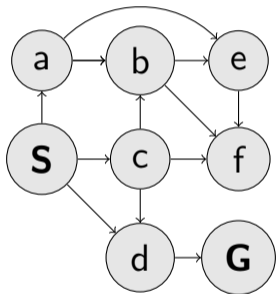
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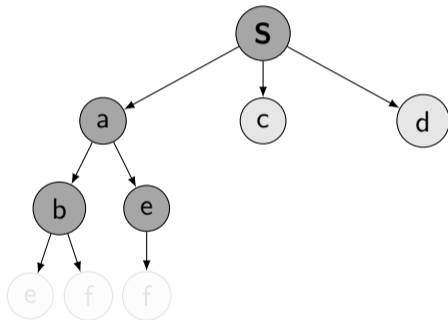
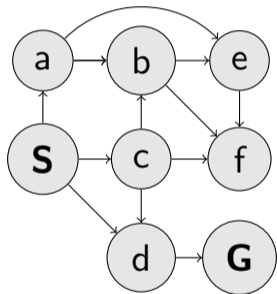
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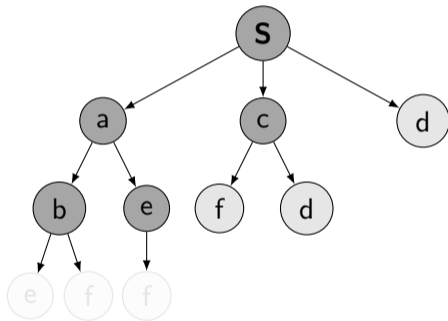
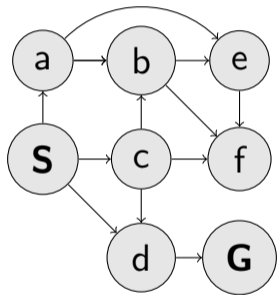
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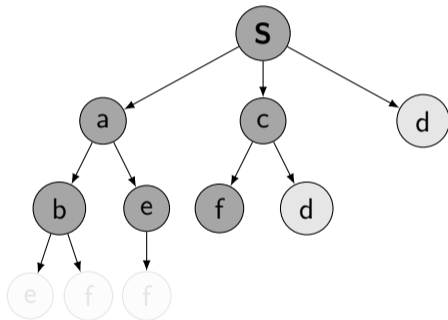
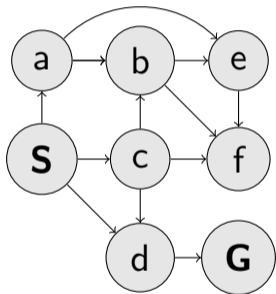
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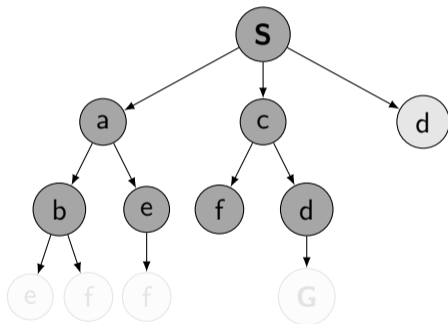
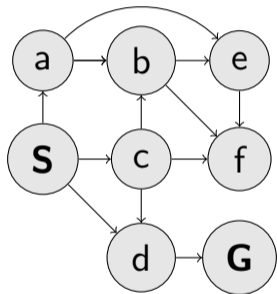
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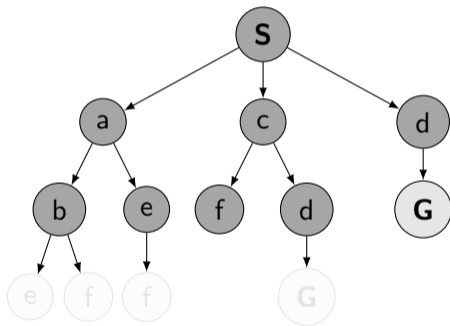
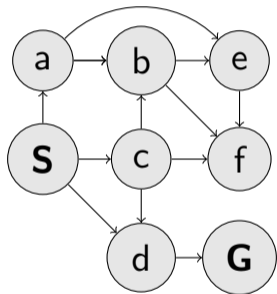
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Iterative deepening DFS (ID-DFS)

- ▶ Start with `maxdepth = 1`
 - ▶ Perform DFS with limited depth. Report success or failure.
 - ▶ If failure, forget everything, increase `maxdepth` and repeat DFS

Is it not a terrible waste to forget everything between steps?

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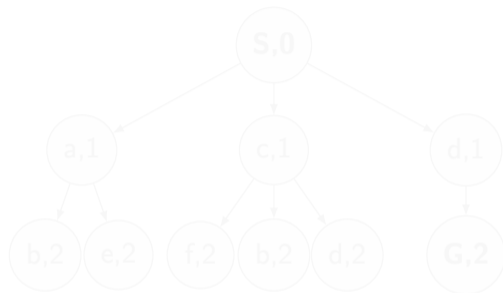
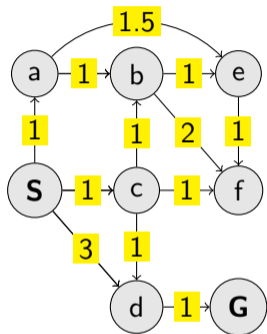
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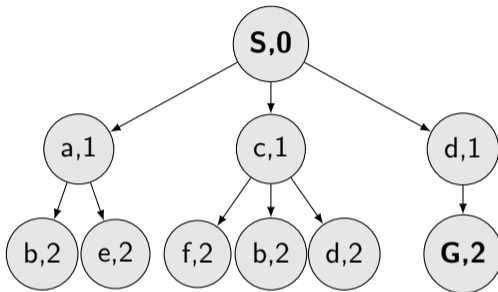
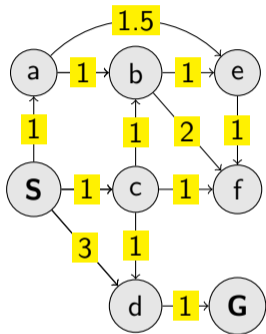
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Cost sensitive search



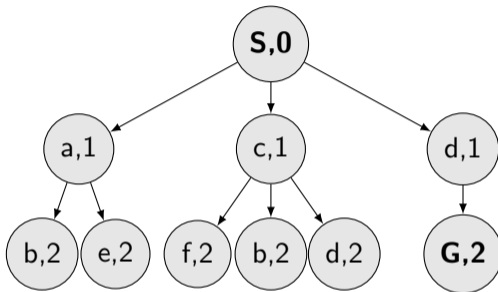
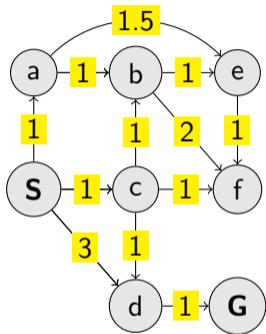
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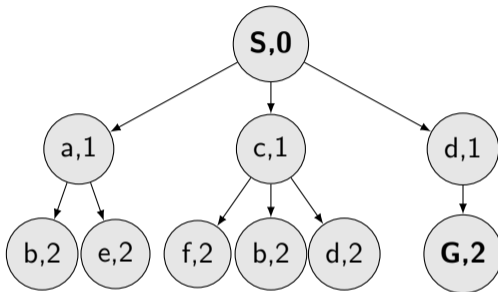
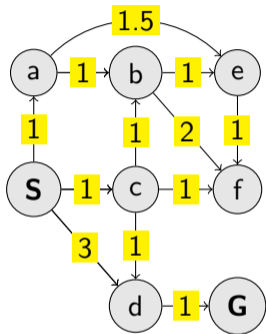
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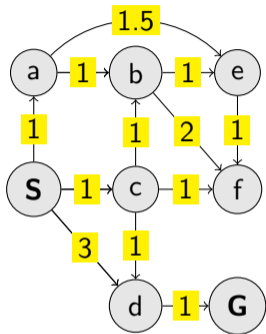
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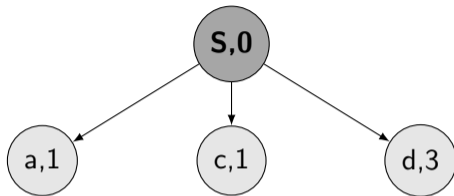
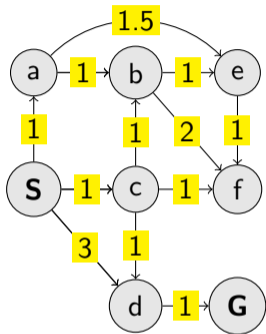
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Uniform Cost Search (UCS)



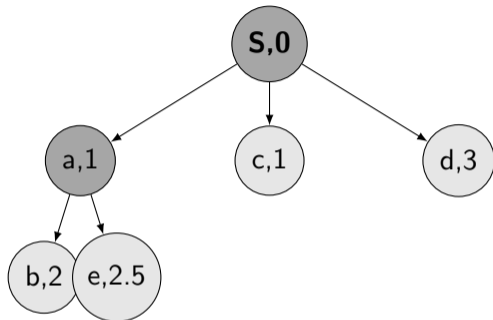
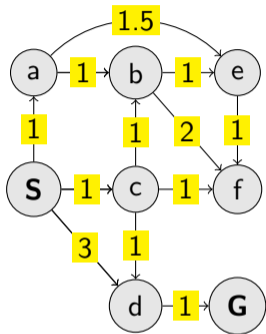
When to check the goal (and stop) the search? When visiting or expanding the node?

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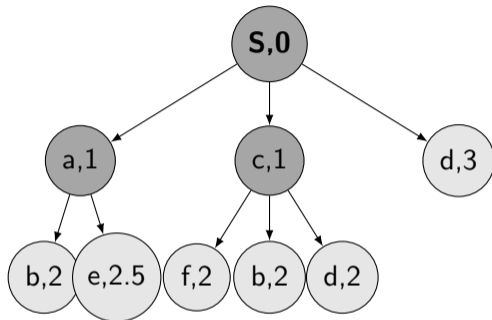
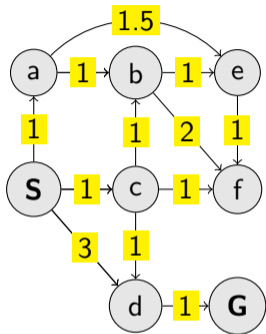
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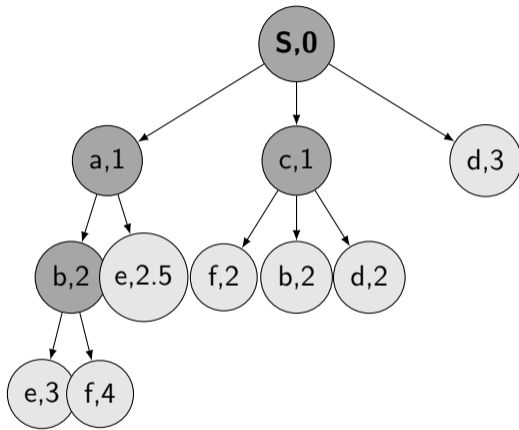
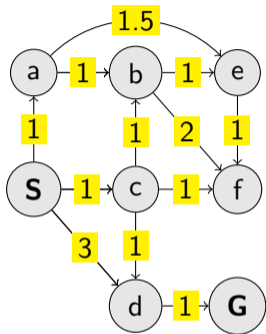
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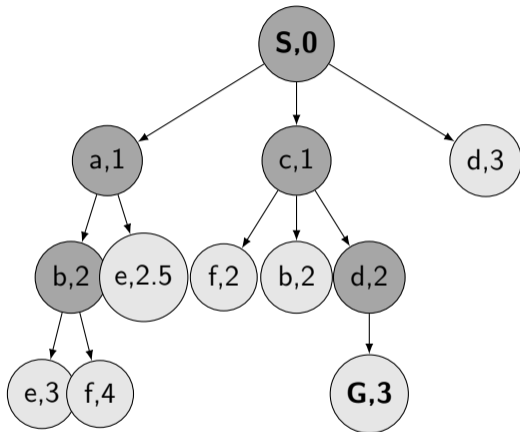
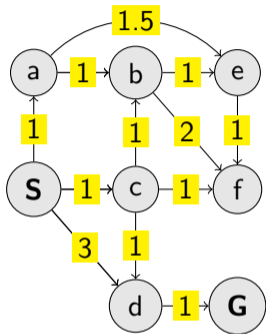
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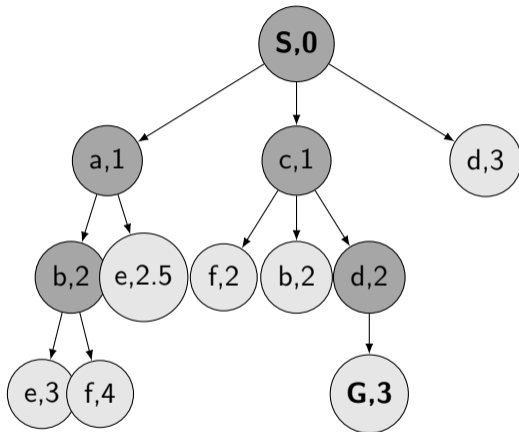
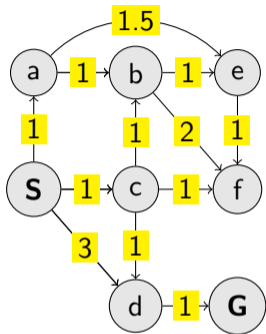
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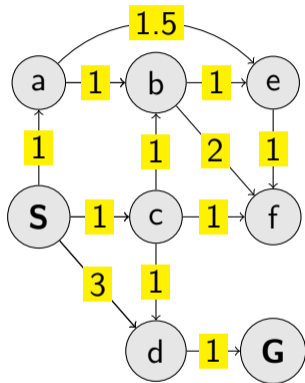
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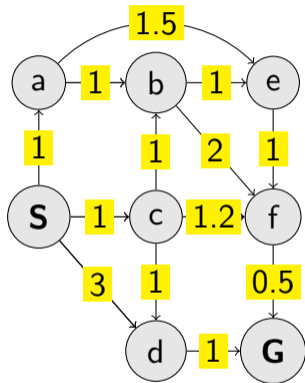


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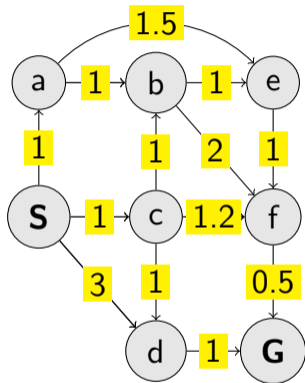
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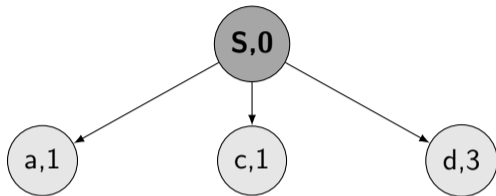
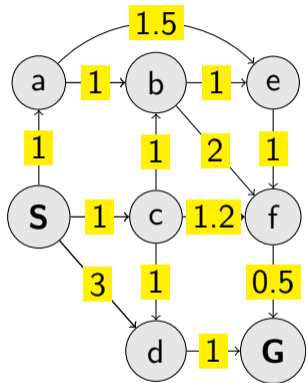
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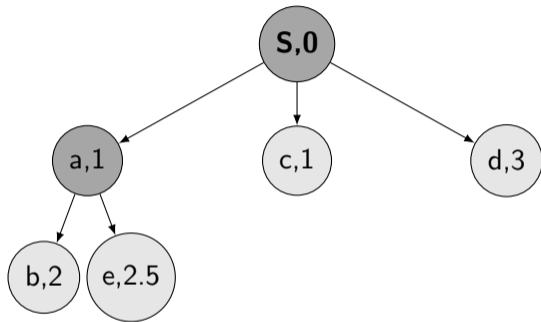
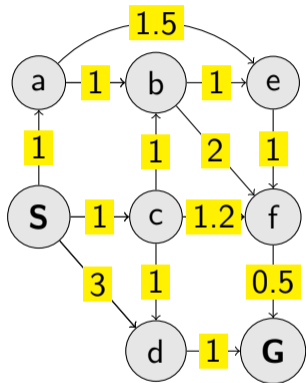
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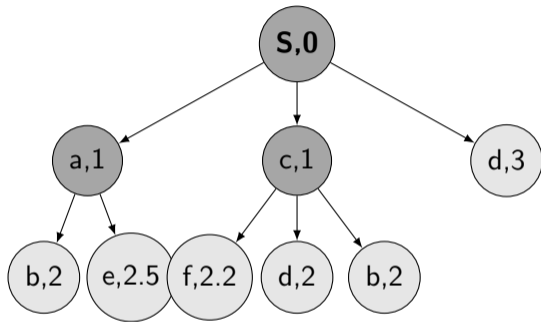
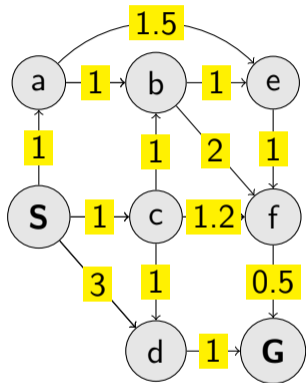
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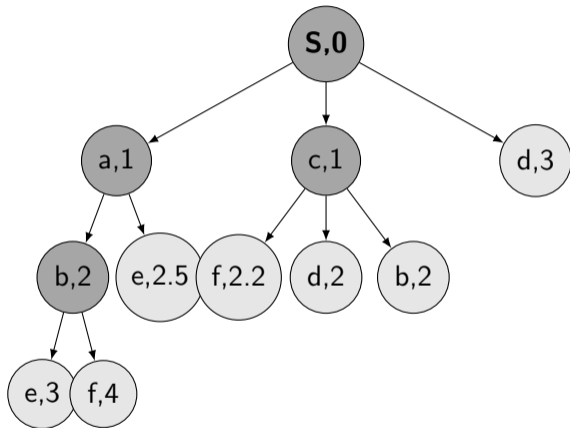
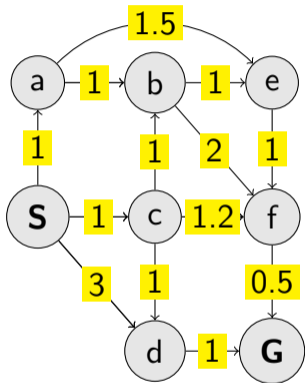
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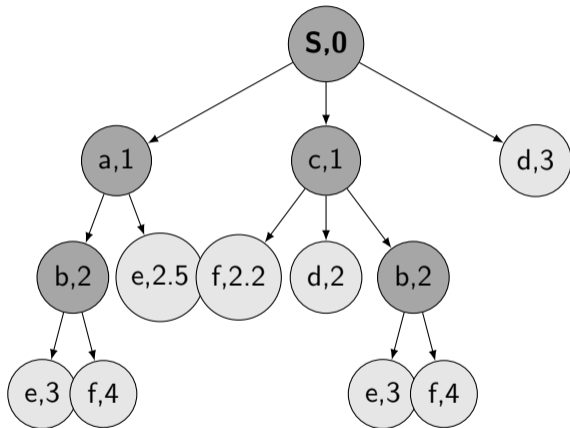
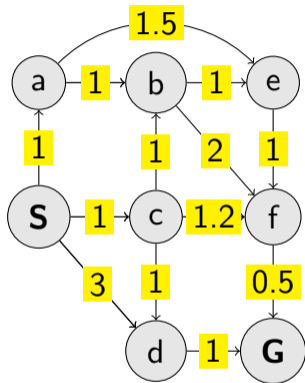
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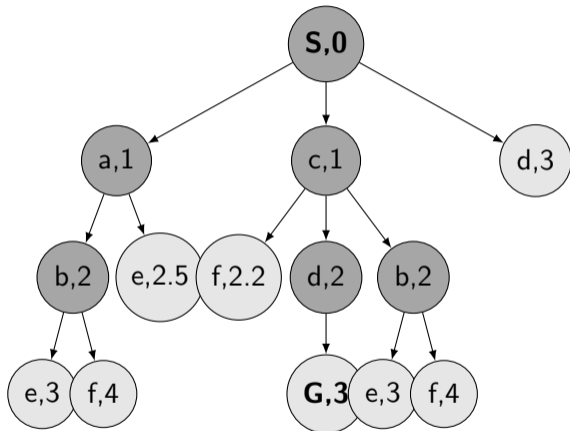
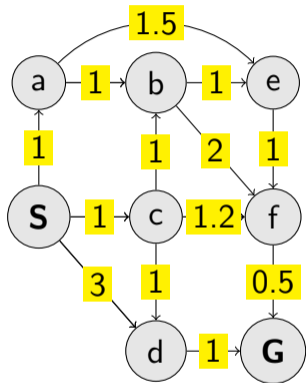
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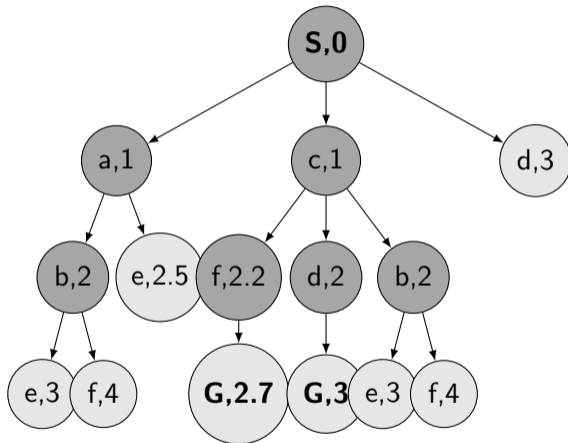
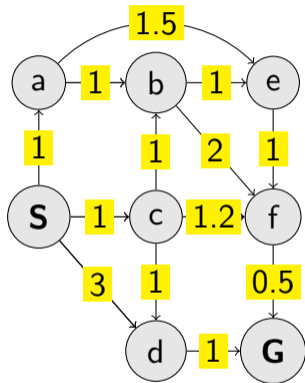
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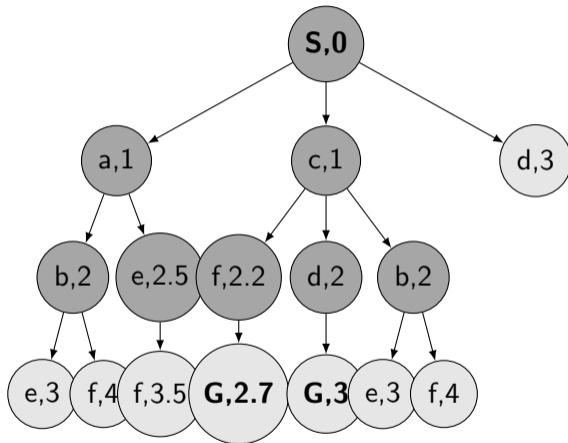
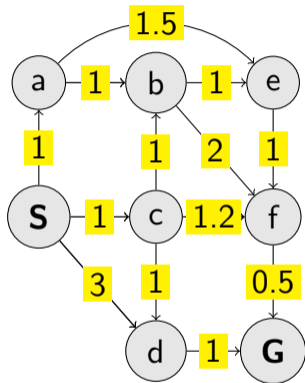
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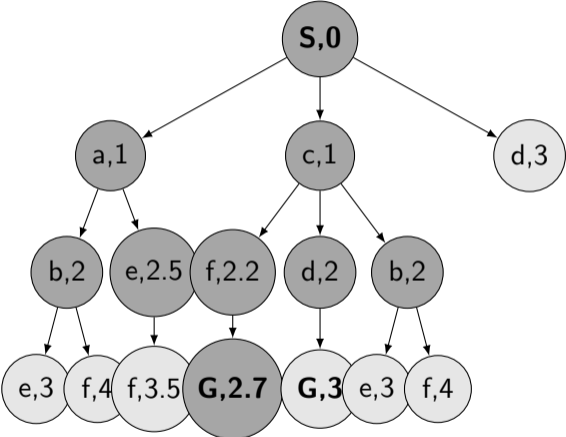
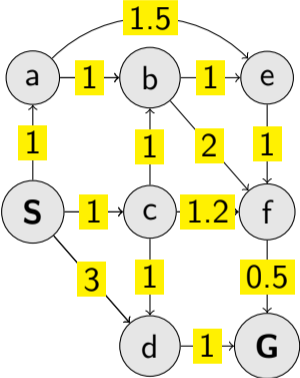
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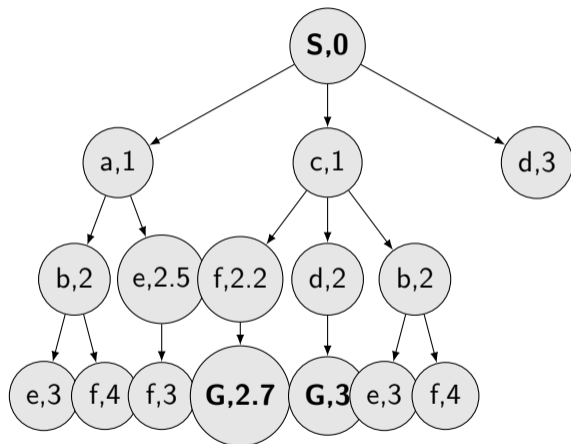


UCS properties

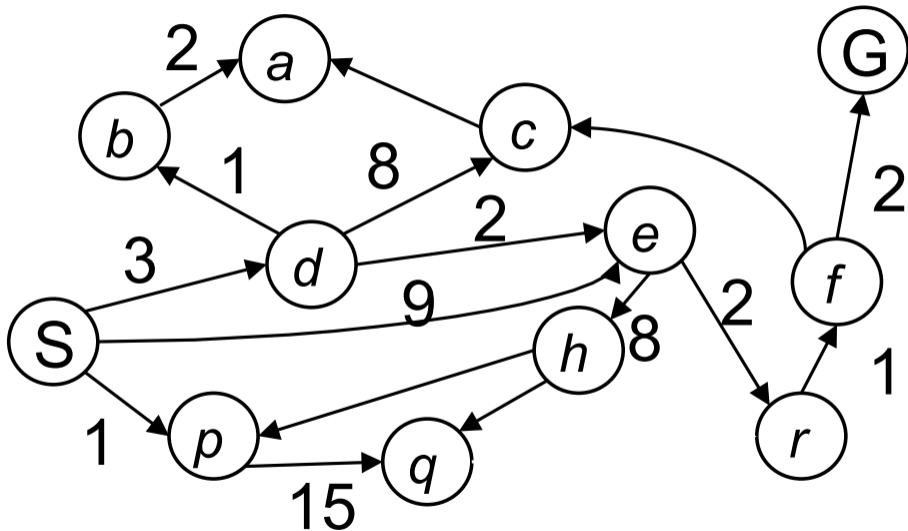
- ▶ Time complexity?
- ▶ Space complexity?
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Example: Graph with costs



Infrastructure for (tree) search algorithms

What should a **tree node** `n` know?

- ▶ `n.state`
- ▶ `n.parent`
- ▶ `n.pathcost`

Perhaps we may add something later, if needed ...

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How to organize nodes?

The Python examples are just suggestions, ...

- ▶ A dynamically linked structure (`list()`).
- ▶ Add a node (`list.insert(node)`).
- ▶ Take a node and remove from the structure (`node=list.pop()`).
- ▶ Check the Python modules `heapq`¹ and `queue`² for inspiration.

¹<https://docs.python.org/3.5/library/heapq.html>

²<https://docs.python.org/3.5/library/queue.html>

What is the solution?

- ▶ We stop when **Goal** is reached.
- ▶ How do we construct the **path**?

References, further reading

Some figures if from [2]. Chapter 2 in [1] provides a compact/dense intro into search algorithms.

[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.

<http://aima.cs.berkeley.edu/>.