

---

Main Slide

## 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

March 2, 2020

## Outline

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

Ok, start with a simple one, almost everybody knows about the navigation - path planning problem. Waze, Garmin, ...

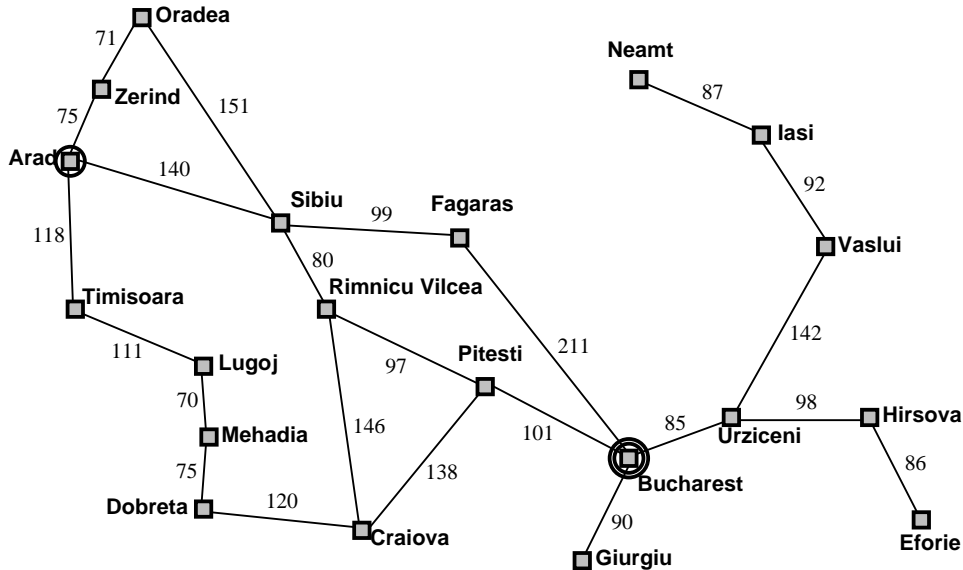
Can you think about more problems?

For example:

- Touring problems. Special case: Traveling salesperson problem – each city must be visited exactly once.
- Planning robot movements – mobile robot or manipulator.
- VLSI (chip) layout.
- ...

## Main Slide

### Example: Traveling in Romania



Classical problem from the Book [2], we use it, too.

## Main Slide

## Example: Map of Romania

Goal:

be in Bucharest

Problem formulation:

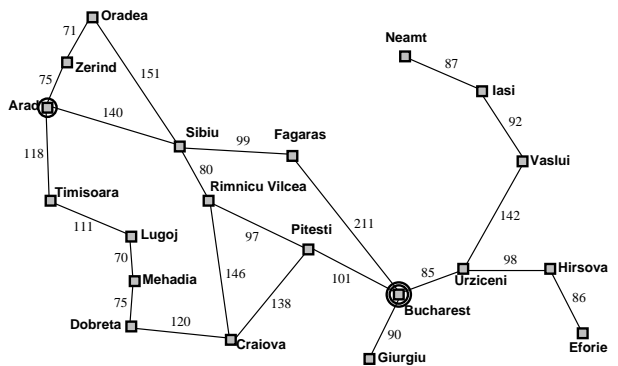
states: position in a city (cities)

actions: drive between cities

Solution:

Sequence of cities (path)

(action sequence [2])



Classical problem from the Book [2], we use it, too.

## Main Slide

## Example: Map of Romania

Goal:

be in Bucharest

Problem formulation:

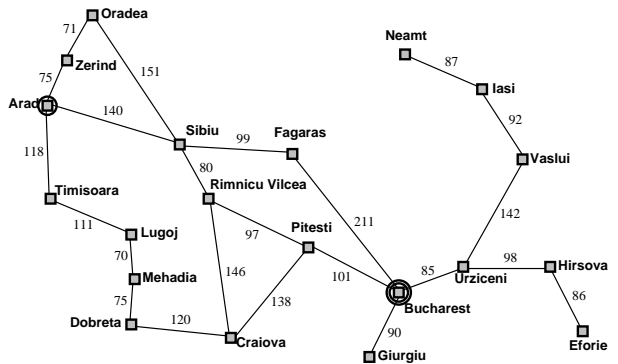
states: position in a city (cities)

actions: drive between cities

Solution:

Sequence of cities (path)

(action sequence [2])



Classical problem from the Book [2], we use it, too.

## Main Slide

## Example: Map of Romania

Goal:

be in Bucharest

Problem formulation:

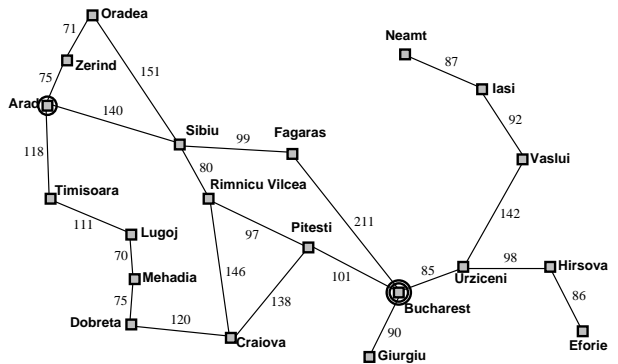
states: position in a city (cities)

actions: drive between cities

Solution:

Sequence of cities (path)

(action sequence [2])



Classical problem from the Book [2], we use it, too.

## Main Slide

## Example: Map of Romania

Goal:

be in Bucharest

Problem formulation:

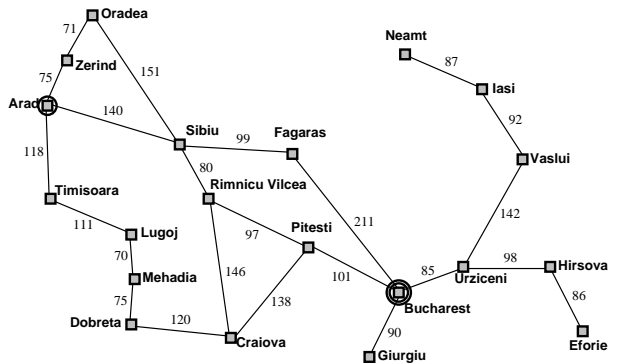
states: position in a city (cities)

actions: drive between cities

Solution:

Sequence of cities (path)

(action sequence [2])



Classical problem from the Book [2], we use it, too.

## Main Slide

### Example: Map of Romania

Goal:

be in Bucharest

Problem formulation:

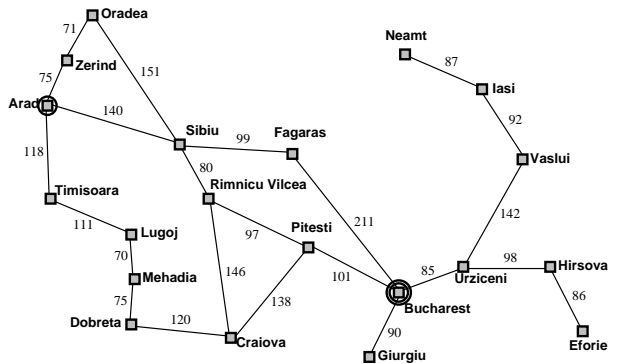
states: position in a city (cities)

actions: drive between cities

Solution:

Sequence of cities (path)

(action sequence [2])





Also known as  $n - 1$  puzzle.

- States: Location of each of the 8 tiles and the blank.
- Number of states: 9!
- Initial state: any state. (Note that any given goal state can be reached from exactly half of the initial states.)
- Actions: Movements of the blank space: Left, Right, Up, Down (or a subset of these)
- Solution / goal test: Check whether state matches the goal configuration.
- Path cost: nr. steps in the path (each step costs 1)

Toy problem (3.2.1) from [2].

## Main Slide

### Example: The 8-puzzle

7	2	4
5		6
8	3	1

Start State

1	2	3
4	5	6
7	8	

Goal State

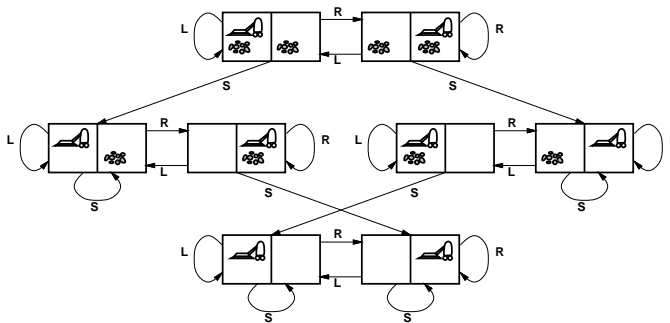
states?  
actions?  
solution?  
cost?

- States: Determined by agent location and dirt location. The agent is in one of two locations, each of which may or may not contain dirt.
- Number of states:  $2 \times 2^2$  (two possible choices for agent location; for every location, choice dirt vs. no dirt). For  $n$  locations:  $n \times 2^n$
- Initial state: any state
- Actions: Left, Right, Suck (larger envs. can have also Up and Down)
- Solution / goal test: Are all squares clean?
- Path cost: nr. steps in the path (each step costs 1)

Toy problem (3.2.1) from [2].

## Main Slide

### Example: Vacuum cleaner



states?  
actions?  
solution?  
cost?

We will use the terminology through the next 5-6 lectures; also for Markov (Sequential) Decision Processes, Reinforcement Learning

---

**Main Slide**

---

## 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?

We will use the terminology through the next 5-6 lectures; also for Markov (Sequential) Decision Processes, Reinforcement Learning

---

**Main Slide**

---

## 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?

We will use the terminology through the next 5-6 lectures; also for Markov (Sequential) Decision Processes, Reinforcement Learning

---

**Main Slide**

---

## 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?

We will use the terminology through the next 5-6 lectures; also for Markov (Sequential) Decision Processes, Reinforcement Learning

---

**Main Slide**

---

## 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?

Formalizing a real world problem – (creating) a state space graph – could be a problem in itself. I put creating into brackets as it may be also infinite.

---

**Main Slide**

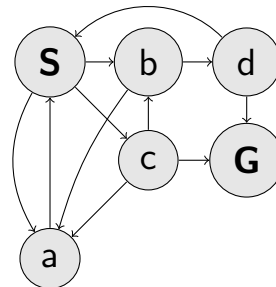
---

## 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

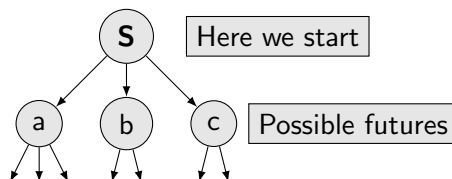
Each state occurs only *once* in a state (search) space.



- What if decision about an action, repeats . . .
- Nodes in the search tree are not the same as the nodes in the state space graph.

## Main Slide

## Search Trees



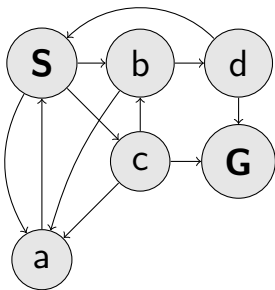
- ▶ A “what if” tree of plans and their outcomes
- ▶ Start node is the root
- ▶ Children are successors
- ▶ Nodes show/contains states, but correspond to *plans* that achieve those states



- 'S' denotes Start; 'G' denotes Goal.
- There could be multiple search trees, depending on the algorithm.
- When going through the unfolding of the *search tree* (on the right), one may already introduce that there are *leaf nodes* at the *frontier*; one of them always gets *expanded*.
- A search tree can be much bigger than the state space. (E.g., states 'S', 'a',... appear more than once in the search tree...)
- Note also that search does not have stop when 'G' is reached for the first time. We may need the shortest path...
- These properties will be discussed next.

## Main Slide

## State Space Graphs vs. Search Trees

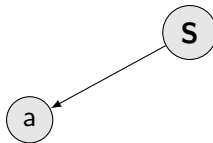
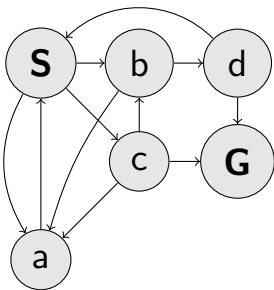


How big is the search tree?

- 'S' denotes Start; 'G' denotes Goal.
- There could be multiple search trees, depending on the algorithm.
- When going through the unfolding of the *search tree* (on the right), one may already introduce that there are *leaf nodes* at the *frontier*; one of them always gets *expanded*.
- A search tree can be much bigger than the state space. (E.g., states 'S', 'a',... appear more than once in the search tree...)
- Note also that search does not have stop when 'G' is reached for the first time. We may need the shortest path...
- These properties will be discussed next.

## Main Slide

## State Space Graphs vs. Search Trees

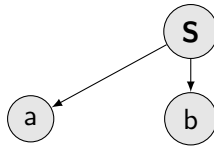
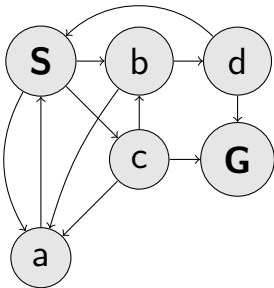


How big is the search tree?

- 'S' denotes Start; 'G' denotes Goal.
- There could be multiple search trees, depending on the algorithm.
- When going through the unfolding of the *search tree* (on the right), one may already introduce that there are *leaf nodes* at the *frontier*; one of them always gets *expanded*.
- A search tree can be much bigger than the state space. (E.g., states 'S', 'a',... appear more than once in the search tree...)
- Note also that search does not have stop when 'G' is reached for the first time. We may need the shortest path...
- These properties will be discussed next.

## Main Slide

## State Space Graphs vs. Search Trees

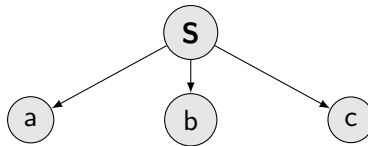
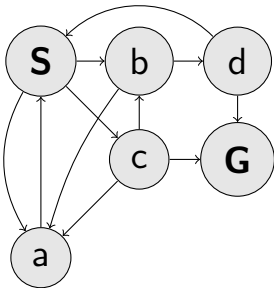


How big is the search tree?

- 'S' denotes Start; 'G' denotes Goal.
- There could be multiple search trees, depending on the algorithm.
- When going through the unfolding of the *search tree* (on the right), one may already introduce that there are *leaf nodes* at the *frontier*; one of them always gets *expanded*.
- A search tree can be much bigger than the state space. (E.g., states 'S', 'a',... appear more than once in the search tree...)
- Note also that search does not have stop when 'G' is reached for the first time. We may need the shortest path...
- These properties will be discussed next.

## Main Slide

## State Space Graphs vs. Search Trees

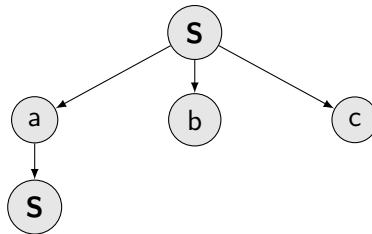
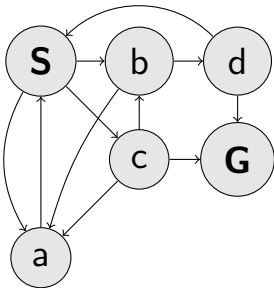


How big is the search tree?

- 'S' denotes Start; 'G' denotes Goal.
- There could be multiple search trees, depending on the algorithm.
- When going through the unfolding of the *search tree* (on the right), one may already introduce that there are *leaf nodes* at the *frontier*; one of them always gets *expanded*.
- A search tree can be much bigger than the state space. (E.g., states 'S', 'a',... appear more than once in the search tree...)
- Note also that search does not have stop when 'G' is reached for the first time. We may need the shortest path...
- These properties will be discussed next.

## Main Slide

## State Space Graphs vs. Search Trees

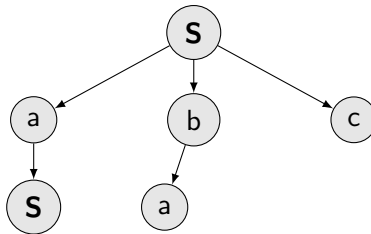
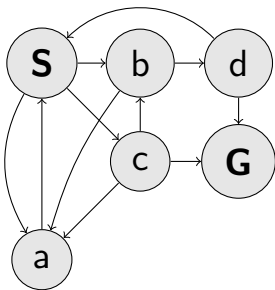


How big is the search tree?

- 'S' denotes Start; 'G' denotes Goal.
- There could be multiple search trees, depending on the algorithm.
- When going through the unfolding of the *search tree* (on the right), one may already introduce that there are *leaf nodes* at the *frontier*; one of them always gets *expanded*.
- A search tree can be much bigger than the state space. (E.g., states 'S', 'a',... appear more than once in the search tree...)
- Note also that search does not have stop when 'G' is reached for the first time. We may need the shortest path...
- These properties will be discussed next.

## Main Slide

## State Space Graphs vs. Search Trees

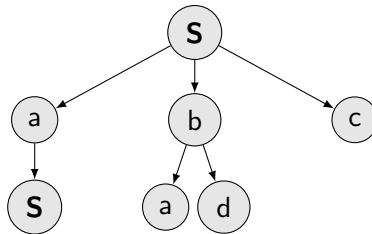
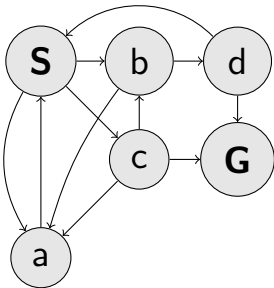


How big is the search tree?

- 'S' denotes Start; 'G' denotes Goal.
- There could be multiple search trees, depending on the algorithm.
- When going through the unfolding of the *search tree* (on the right), one may already introduce that there are *leaf nodes* at the *frontier*; one of them always gets *expanded*.
- A search tree can be much bigger than the state space. (E.g., states 'S', 'a',... appear more than once in the search tree...)
- Note also that search does not have stop when 'G' is reached for the first time. We may need the shortest path...
- These properties will be discussed next.

## Main Slide

## State Space Graphs vs. Search Trees

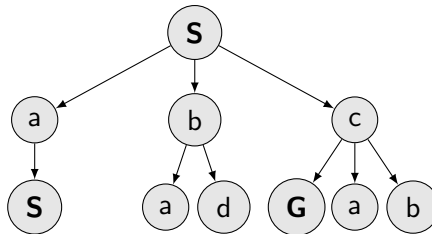
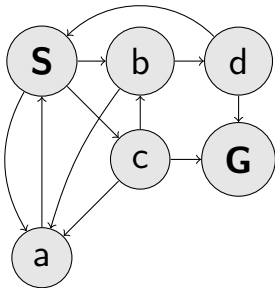


How big is the search tree?

- 'S' denotes Start; 'G' denotes Goal.
- There could be multiple search trees, depending on the algorithm.
- When going through the unfolding of the *search tree* (on the right), one may already introduce that there are *leaf nodes* at the *frontier*; one of them always gets *expanded*.
- A search tree can be much bigger than the state space. (E.g., states 'S', 'a',... appear more than once in the search tree...)
- Note also that search does not have stop when 'G' is reached for the first time. We may need the shortest path...
- These properties will be discussed next.

## Main Slide

## State Space Graphs vs. Search Trees



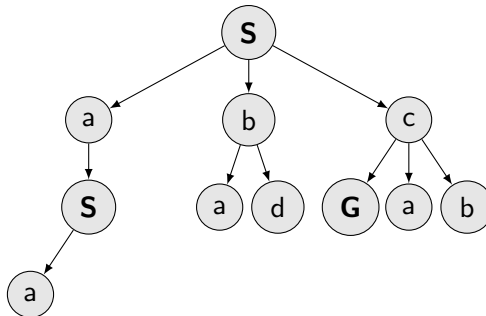
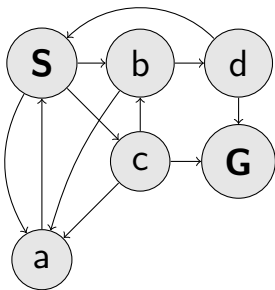
How big is the search tree?



- 'S' denotes Start; 'G' denotes Goal.
- There could be multiple search trees, depending on the algorithm.
- When going through the unfolding of the *search tree* (on the right), one may already introduce that there are *leaf nodes* at the *frontier*; one of them always gets *expanded*.
- A search tree can be much bigger than the state space. (E.g., states 'S', 'a',... appear more than once in the search tree...)
- Note also that search does not have stop when 'G' is reached for the first time. We may need the shortest path...
- These properties will be discussed next.

## Main Slide

## State Space Graphs vs. Search Trees

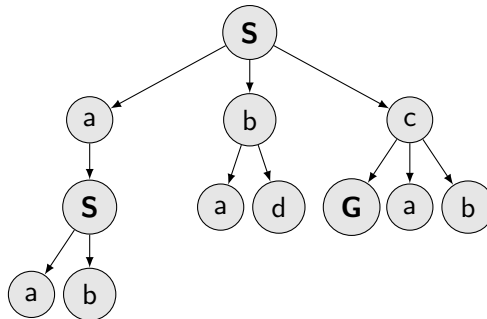
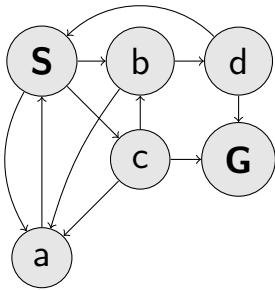


How big is the search tree?

- 'S' denotes Start; 'G' denotes Goal.
- There could be multiple search trees, depending on the algorithm.
- When going through the unfolding of the *search tree* (on the right), one may already introduce that there are *leaf nodes* at the *frontier*; one of them always gets *expanded*.
- A search tree can be much bigger than the state space. (E.g., states 'S', 'a',... appear more than once in the search tree...)
- Note also that search does not have stop when 'G' is reached for the first time. We may need the shortest path...
- These properties will be discussed next.

## Main Slide

## State Space Graphs vs. Search Trees

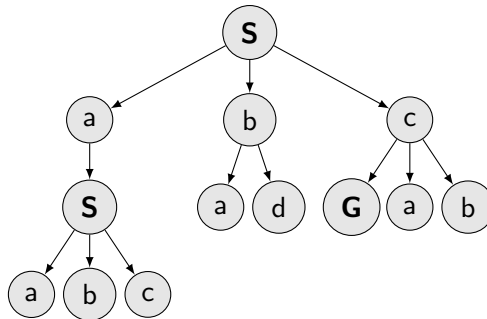
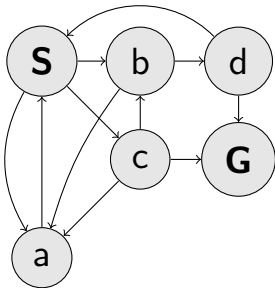


How big is the search tree?

- 'S' denotes Start; 'G' denotes Goal.
- There could be multiple search trees, depending on the algorithm.
- When going through the unfolding of the *search tree* (on the right), one may already introduce that there are *leaf nodes* at the *frontier*; one of them always gets *expanded*.
- A search tree can be much bigger than the state space. (E.g., states 'S', 'a',... appear more than once in the search tree...)
- Note also that search does not have stop when 'G' is reached for the first time. We may need the shortest path...
- These properties will be discussed next.

## Main Slide

## State Space Graphs vs. Search Trees

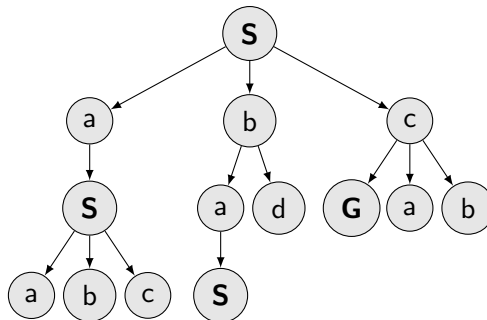
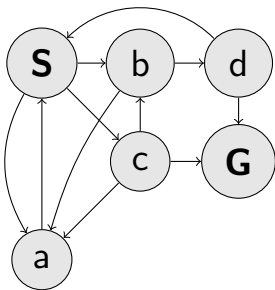


How big is the search tree?

- 'S' denotes Start; 'G' denotes Goal.
- There could be multiple search trees, depending on the algorithm.
- When going through the unfolding of the *search tree* (on the right), one may already introduce that there are *leaf nodes* at the *frontier*; one of them always gets *expanded*.
- A search tree can be much bigger than the state space. (E.g., states 'S', 'a',... appear more than once in the search tree...)
- Note also that search does not have stop when 'G' is reached for the first time. We may need the shortest path...
- These properties will be discussed next.

## Main Slide

## State Space Graphs vs. Search Trees

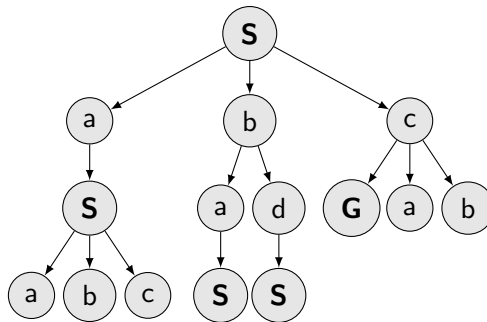
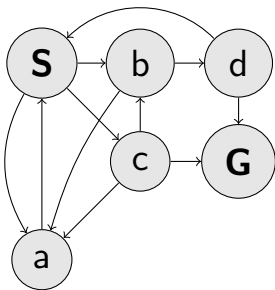


How big is the search tree?

- 'S' denotes Start; 'G' denotes Goal.
- There could be multiple search trees, depending on the algorithm.
- When going through the unfolding of the *search tree* (on the right), one may already introduce that there are *leaf nodes* at the *frontier*; one of them always gets *expanded*.
- A search tree can be much bigger than the state space. (E.g., states 'S', 'a',... appear more than once in the search tree...)
- Note also that search does not have stop when 'G' is reached for the first time. We may need the shortest path...
- These properties will be discussed next.

## Main Slide

## State Space Graphs vs. Search Trees

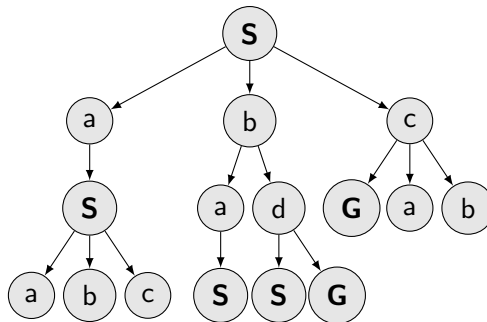
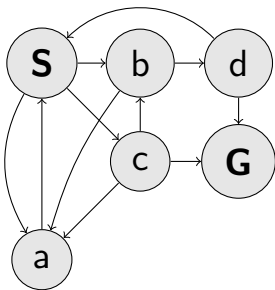


How big is the search tree?

- 'S' denotes Start; 'G' denotes Goal.
- There could be multiple search trees, depending on the algorithm.
- When going through the unfolding of the *search tree* (on the right), one may already introduce that there are *leaf nodes* at the *frontier*; one of them always gets *expanded*.
- A search tree can be much bigger than the state space. (E.g., states 'S', 'a',... appear more than once in the search tree...)
- Note also that search does not have stop when 'G' is reached for the first time. We may need the shortest path...
- These properties will be discussed next.

## Main Slide

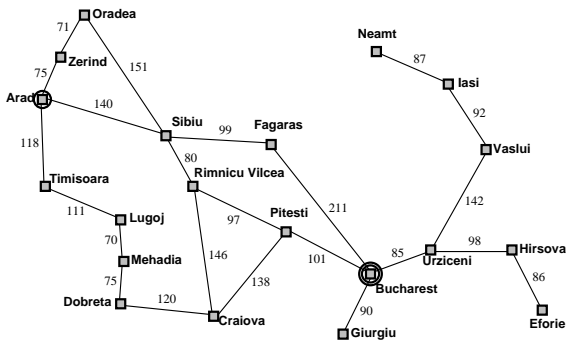
## State Space Graphs vs. Search Trees



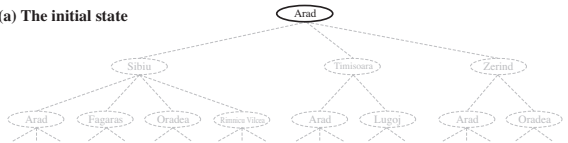
How big is the search tree?

## Main Slide

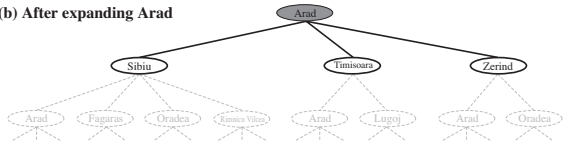
From problem/transition graph to search tree (Romania)



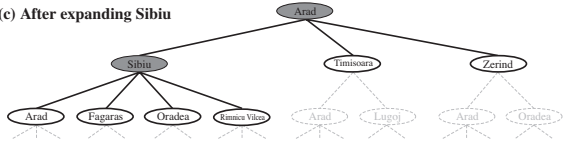
(a) The initial state



(b) After expanding Arad



(c) After expanding Sibiu



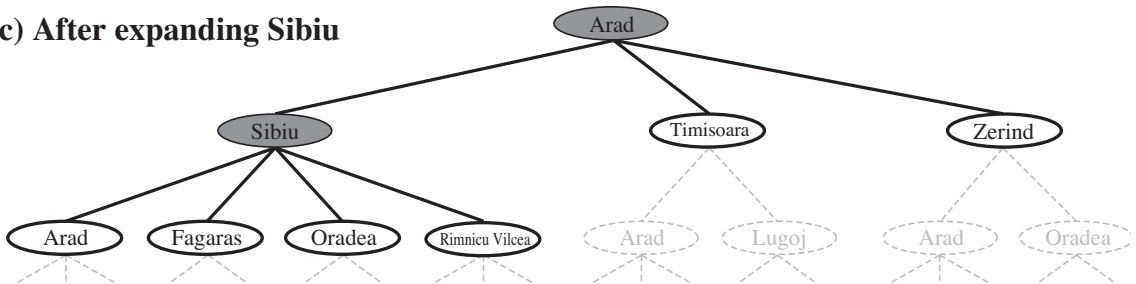
Problem/transition graph is revealed incrementally.

The revealing strategy can be visualized as a search tree.

## Main Slide

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(?)*.



A *general* tree search algorithm. Individual search algorithms vary primarily in how they choose which state to expand next – the “search strategy”.

## Main Slide

## 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

  end loop

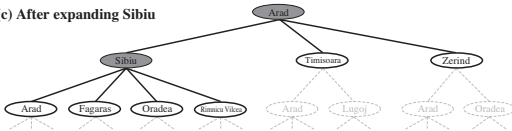
**end function**

A *general* tree search algorithm. Individual search algorithms vary primarily in how they choose which state to expand next – the “search strategy”.

## Main Slide

## 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

**end loop**

**end function**

A *general* tree search algorithm. Individual search algorithms vary primarily in how they choose which state to expand next – the “search strategy”.

## Main Slide

## 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

end loop

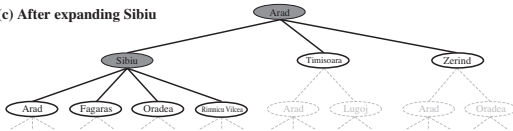
end function

A *general* tree search algorithm. Individual search algorithms vary primarily in how they choose which state to expand next – the “search strategy”.

## Main Slide

## 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

end loop

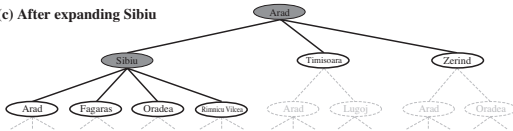
end function

A *general* tree search algorithm. Individual search algorithms vary primarily in how they choose which state to expand next – the “search strategy”.

## Main Slide

## 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

**end loop**

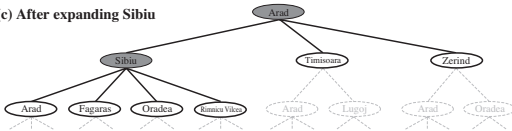
**end function**

A *general* tree search algorithm. Individual search algorithms vary primarily in how they choose which state to expand next – the “search strategy”.

## Main Slide

## Tree search algorithm

(c) After expanding Sibiu



```

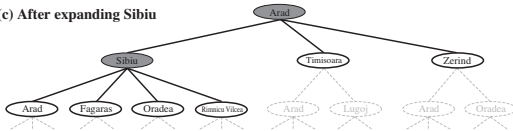
function TREE_SEARCH(problem) return a solution or failure
  initialize by using the initial state of the problem
  loop
    if no candidates for expansion then return failure
    else choose a leaf node for expansion
    end if
    if the node contains a goal state then return the solution
    end if
    Expand the node and add the resulting nodes to the tree
  end loop
end function
  
```

A *general* tree search algorithm. Individual search algorithms vary primarily in how they choose which state to expand next – the “search strategy”.

## Main Slide

## Tree search algorithm

(c) After expanding Sibiu



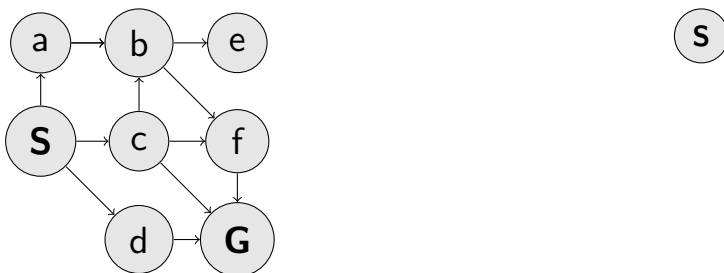
```

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
  end loop
end function
  
```

Before going to the next slide, think about algorithms. What properties of an algorithm would you want?

## Main Slide

## Example of a tree search



Which nodes to *explore*?

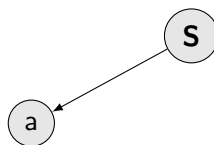
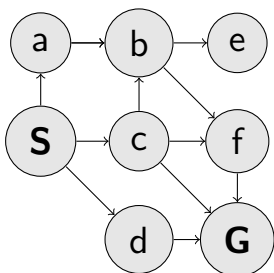
What are the properties of a strategy/algorithm?



Before going to the next slide, think about algorithms. What properties of an algorithm would you want?

## Main Slide

## Example of a tree search



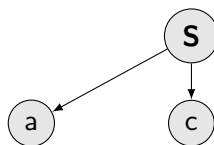
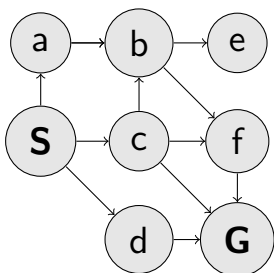
Which nodes to *explore*?

What are the properties of a strategy/algorithm?

Before going to the next slide, think about algorithms. What properties of an algorithm would you want?

## Main Slide

## Example of a tree search



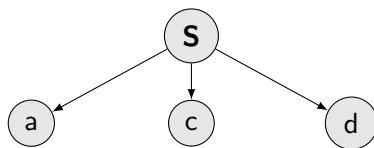
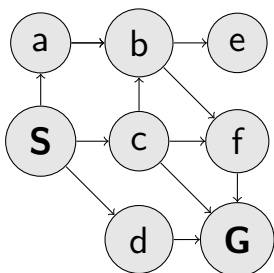
Which nodes to *explore*?

What are the properties of a strategy/algorithm?

Before going to the next slide, think about algorithms. What properties of an algorithm would you want?

## Main Slide

## Example of a tree search



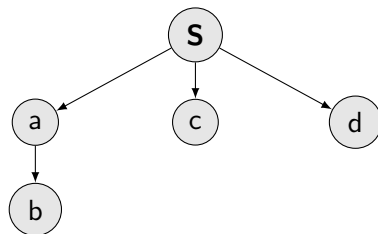
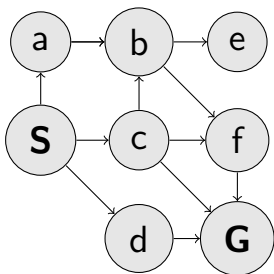
Which nodes to *explore*?

What are the properties of a strategy/algorithm?

Before going to the next slide, think about algorithms. What properties of an algorithm would you want?

## Main Slide

## Example of a tree search



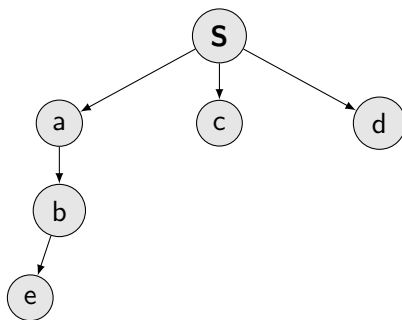
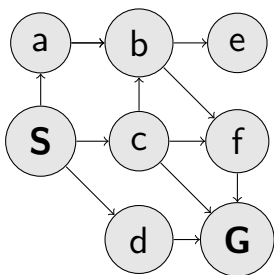
Which nodes to *explore*?

What are the properties of a strategy/algorithm?

Before going to the next slide, think about algorithms. What properties of an algorithm would you want?

## Main Slide

## Example of a tree search



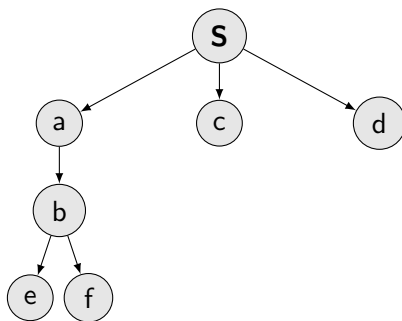
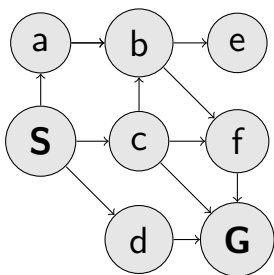
Which nodes to *explore*?

What are the properties of a strategy/algorithm?

Before going to the next slide, think about algorithms. What properties of an algorithm would you want?

## Main Slide

## Example of a tree search



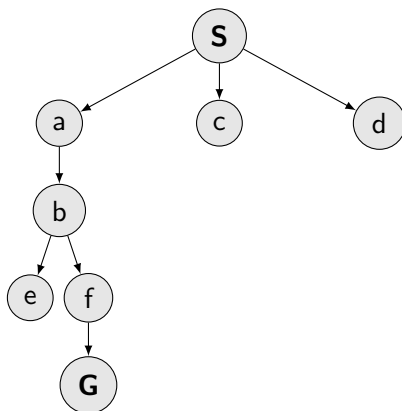
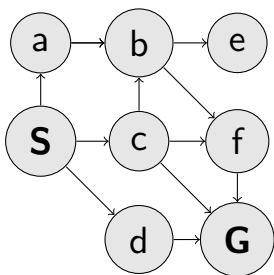
Which nodes to *explore*?

What are the properties of a strategy/algorithm?

Before going to the next slide, think about algorithms. What properties of an algorithm would you want?

## Main Slide

## Example of a tree search



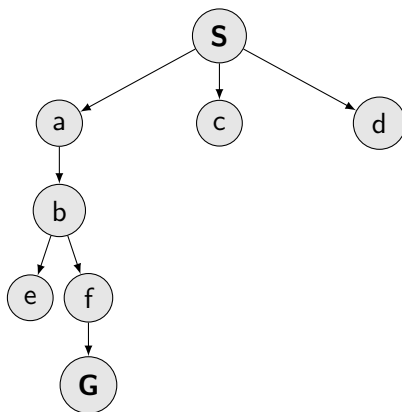
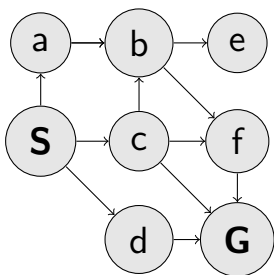
Which nodes to *explore*?

What are the properties of a strategy/algorithm?

Before going to the next slide, think about algorithms. What properties of an algorithm would you want?

## Main Slide

## Example of a tree search



Which nodes to *explore*?

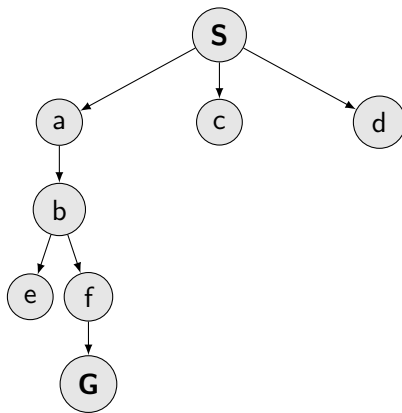
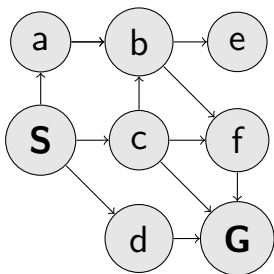
What are the properties of a strategy/algorithm?



Before going to the next slide, think about algorithms. What properties of an algorithm would you want?

## Main Slide

## Example of a tree search

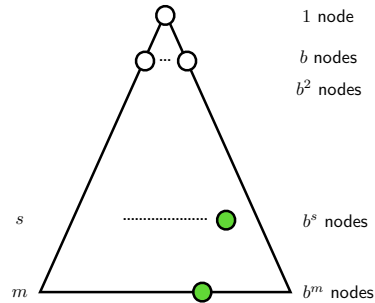


Which nodes to *explore*?

What are the properties of a strategy/algorithm?

Draw a (symbolic—think about a triangle) sketch of a (search) tree. It may grow upwards or downwards. How would you characterize/parametrize size of a tree.

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



## Main Slide

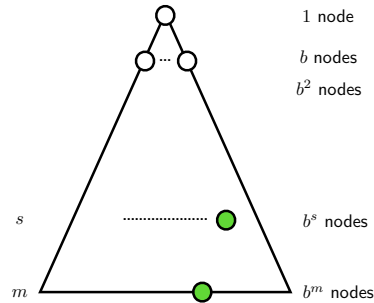
### Search (algorithm) properties

- ▶ 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?

Draw a (symbolic—think about a triangle) sketch of a (search) tree. It may grow upwards or downwards. How would you characterize/parametrize size of a tree.

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



## Main Slide

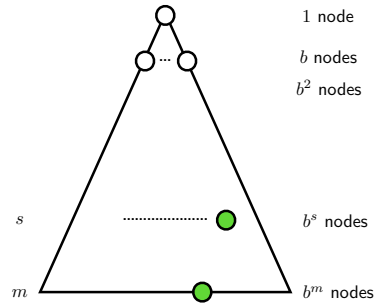
### Search (algorithm) properties

- ▶ 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?

Draw a (symbolic—think about a triangle) sketch of a (search) tree. It may grow upwards or downwards. How would you characterize/parametrize size of a tree.

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



## Main Slide

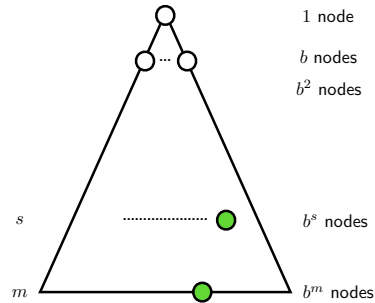
### Search (algorithm) properties

- ▶ 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?

Draw a (symbolic–think about a triangle) sketch of a (search) tree. It may grow upwards or downwards. How would you characterize/parametrize *size* of a tree.

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



## Main Slide

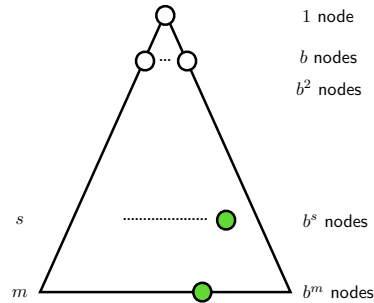
### Search (algorithm) properties

- ▶ 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?

Draw a (symbolic–think about a triangle) sketch of a (search) tree. It may grow upwards or downwards. How would you characterize/parametrize *size* of a tree.

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



## Main Slide

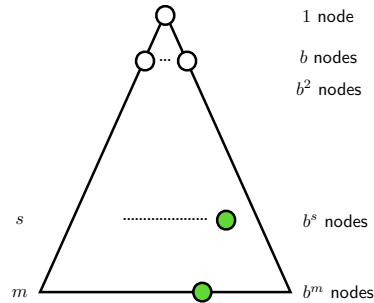
### Search (algorithm) properties

- ▶ 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?

Draw a (symbolic—think about a triangle) sketch of a (search) tree. It may grow upwards or downwards. How would you characterize/parametrize size of a tree.

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



## Main Slide

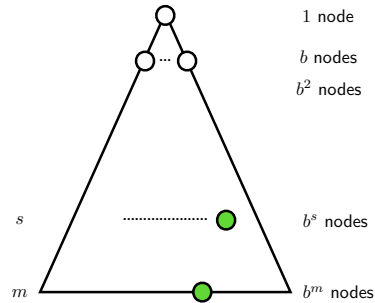
### Search (algorithm) properties

- ▶ 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?

Draw a (symbolic—think about a triangle) sketch of a (search) tree. It may grow upwards or downwards. How would you characterize/parametrize *size* of a tree.

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



## Main Slide

### Search (algorithm) properties

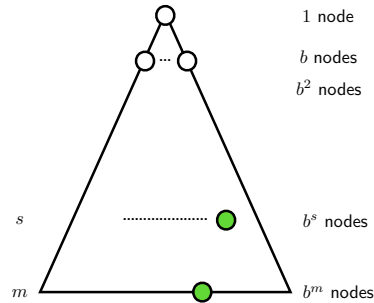
- ▶ Guaranteed to find a solution (if exists)? **Complete?**
- ▶ Guaranteed to find the least cost path? **Optimal?**
- ▶ How many steps - an operation with a node? **Time** complexity?
- ▶ How many nodes to remember? **Space/Memory** complexity?

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



Draw a (symbolic—think about a triangle) sketch of a (search) tree. It may grow upwards or downwards. How would you characterize/parametrize *size* of a tree.

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



## Main Slide

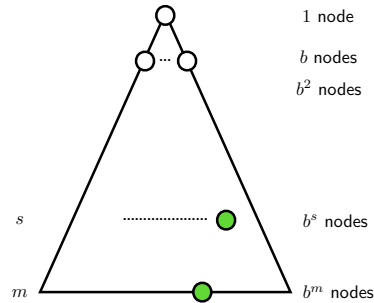
### Search (algorithm) properties

- ▶ 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?

Draw a (symbolic—think about a triangle) sketch of a (search) tree. It may grow upwards or downwards. How would you characterize/parametrize *size* of a tree.

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



## Main Slide

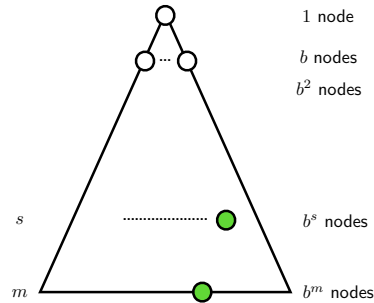
### Search (algorithm) properties

- ▶ 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?

Draw a (symbolic—think about a triangle) sketch of a (search) tree. It may grow upwards or downwards. How would you characterize/parametrize *size* of a tree.

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



## Main Slide

### 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?

It is perhaps worth to remember that the search tree is built as the algorithm goes. Or better said, the tree is a human friendly representation of the machine run.

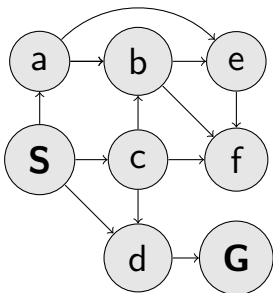
## Strategies

How to traverse/build a search tree?

- In animation, we will do the expansion step at once.
- What is the *frontier* - set of nodes, waiting to be expanded?
- When to stop the search?
- Thinking about optimality, what is the best solution we seek?

## Main Slide

## Depth-First Search (DFS)

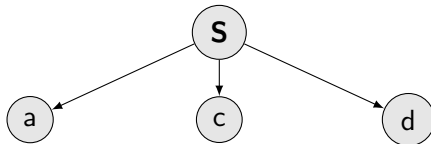
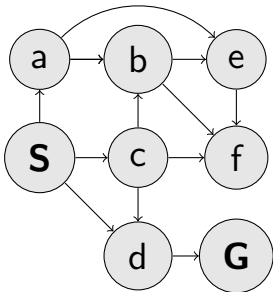


What are the DFS properties (complete, optimal, time, space)?

- In animation, we will do the expansion step at once.
- What is the *frontier* - set of nodes, waiting to be expanded?
- When to stop the search?
- Thinking about optimality, what is the best solution we seek?

## Main Slide

## Depth-First Search (DFS)

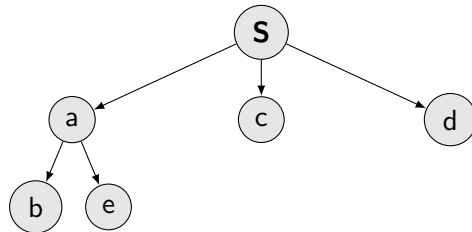
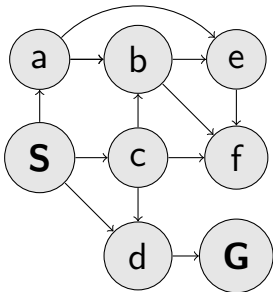


What are the DFS properties (complete, optimal, time, space)?

- In animation, we will do the expansion step at once.
- What is the *frontier* - set of nodes, waiting to be expanded?
- When to stop the search?
- Thinking about optimality, what is the best solution we seek?

## Main Slide

## Depth-First Search (DFS)

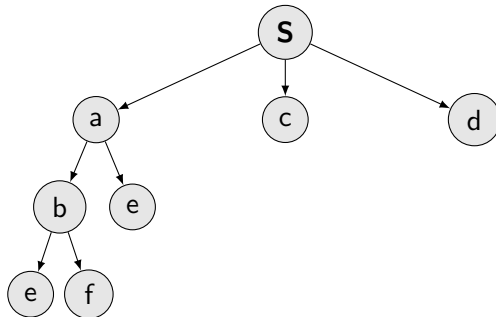
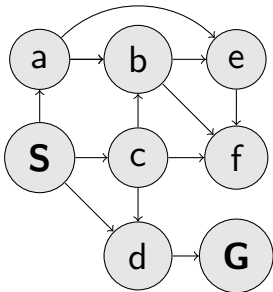


What are the DFS properties (complete, optimal, time, space)?

- In animation, we will do the expansion step at once.
- What is the *frontier* - set of nodes, waiting to be expanded?
- When to stop the search?
- Thinking about optimality, what is the best solution we seek?

## Main Slide

## Depth-First Search (DFS)



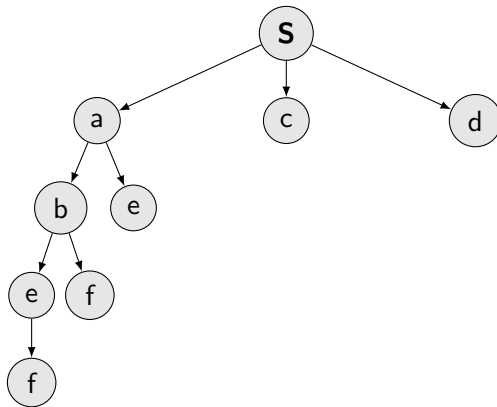
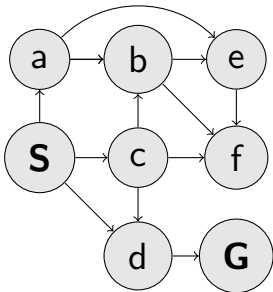
What are the DFS properties (complete, optimal, time, space)?



- In animation, we will do the expansion step at once.
- What is the *frontier* - set of nodes, waiting to be expanded?
- When to stop the search?
- Thinking about optimality, what is the best solution we seek?

## Main Slide

## Depth-First Search (DFS)

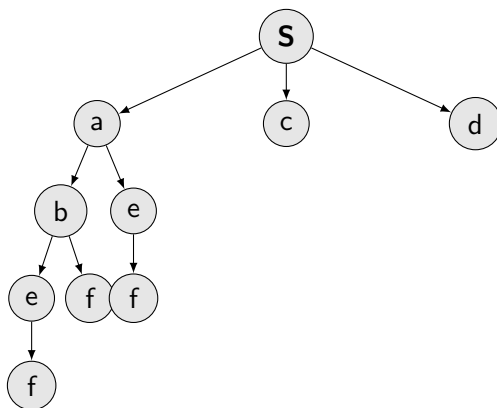
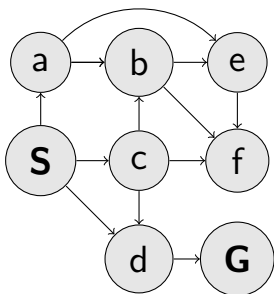


What are the DFS properties (complete, optimal, time, space)?

- In animation, we will do the expansion step at once.
- What is the *frontier* - set of nodes, waiting to be expanded?
- When to stop the search?
- Thinking about optimality, what is the best solution we seek?

## Main Slide

## Depth-First Search (DFS)

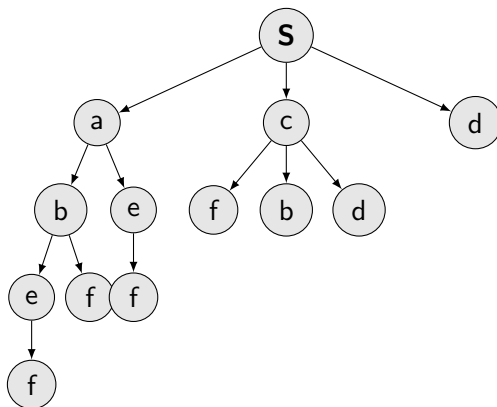
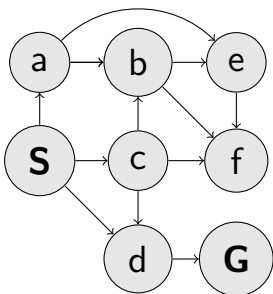


What are the DFS properties (complete, optimal, time, space)?

- In animation, we will do the expansion step at once.
- What is the *frontier* - set of nodes, waiting to be expanded?
- When to stop the search?
- Thinking about optimality, what is the best solution we seek?

## Main Slide

## Depth-First Search (DFS)

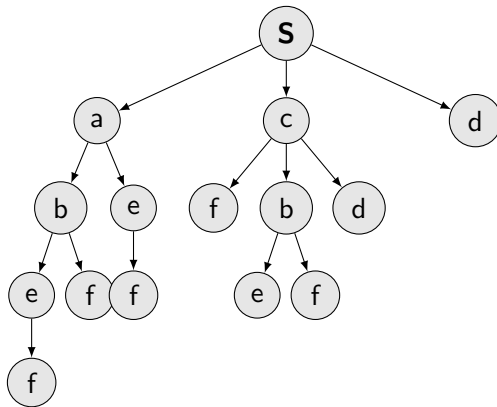
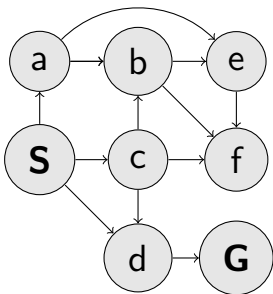


What are the DFS properties (complete, optimal, time, space)?

- In animation, we will do the expansion step at once.
- What is the *frontier* - set of nodes, waiting to be expanded?
- When to stop the search?
- Thinking about optimality, what is the best solution we seek?

## Main Slide

## Depth-First Search (DFS)

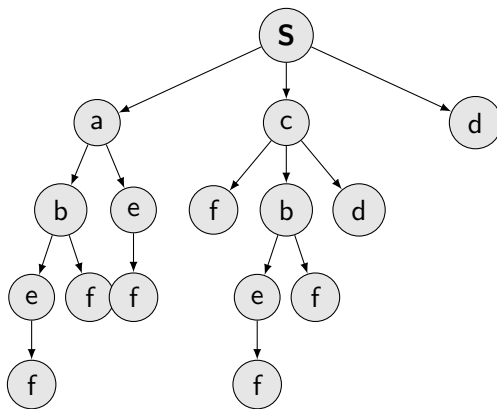
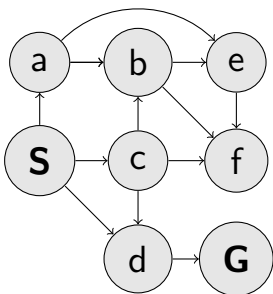


What are the DFS properties (complete, optimal, time, space)?

- In animation, we will do the expansion step at once.
- What is the *frontier* - set of nodes, waiting to be expanded?
- When to stop the search?
- Thinking about optimality, what is the best solution we seek?

## Main Slide

## Depth-First Search (DFS)

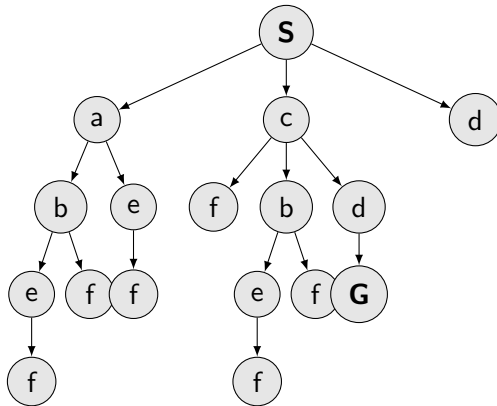
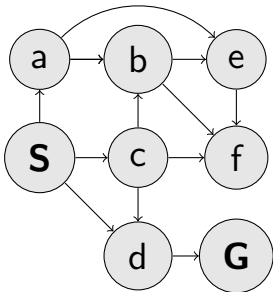


What are the DFS properties (complete, optimal, time, space)?

- In animation, we will do the expansion step at once.
- What is the *frontier* - set of nodes, waiting to be expanded?
- When to stop the search?
- Thinking about optimality, what is the best solution we seek?

## Main Slide

## Depth-First Search (DFS)

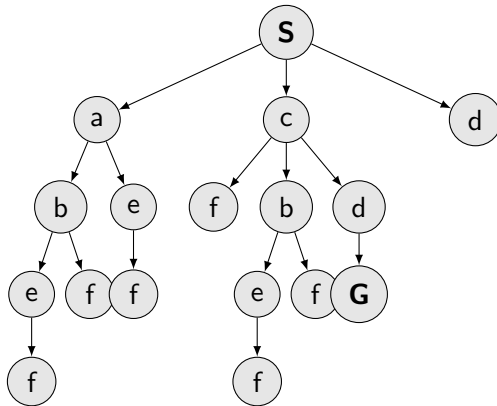
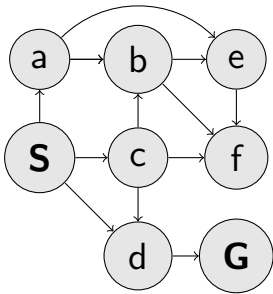


What are the DFS properties (complete, optimal, time, space)?

- In animation, we will do the expansion step at once.
- What is the *frontier* - set of nodes, waiting to be expanded?
- When to stop the search?
- Thinking about optimality, what is the best solution we seek?

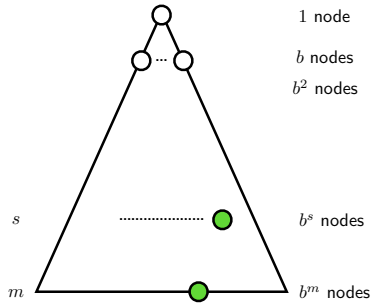
## Main Slide

## Depth-First Search (DFS)



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

- Time, can process the whole tree:  $b^m$
- Space, only the path so far:  $bm$  (a path from root to leaf ( $m$ ), plus siblings on the path are also on the frontier ( $b \times m$  ) )
- Completeness:  $m$  may be  $\infty$  hence, not in general
- Optimality: No! It just takes the first solution found.

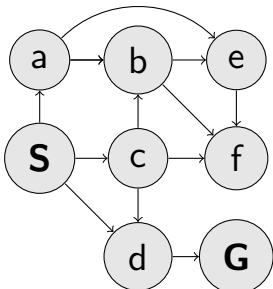


Main Slide

DFS properties

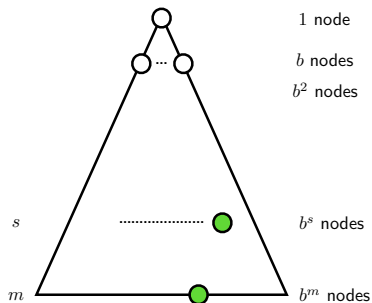


- ▶ Time complexity?
- ▶ Space complexity?
- ▶ Complete?
- ▶ Optimal?





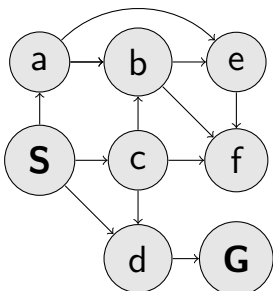
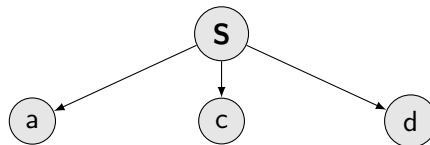
- Time, can process the whole tree:  $b^m$
- Space, only the path so far:  $bm$  (a path from root to leaf ( $m$ ), plus siblings on the path are also on the frontier ( $b \times m$  ) )
- Completeness:  $m$  may be  $\infty$  hence, not in general
- Optimality: No! It just takes the first solution found.



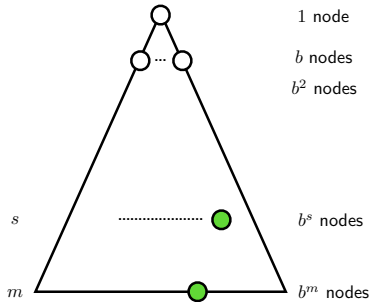
Main Slide

DFS properties

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



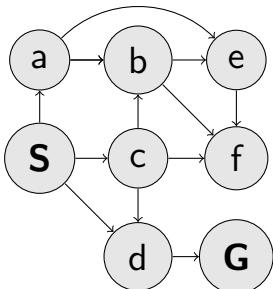
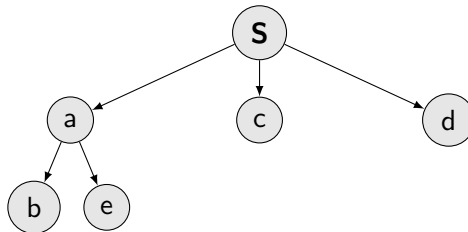
- Time, can process the whole tree:  $b^m$
- Space, only the path so far:  $bm$  (a path from root to leaf ( $m$ ), plus siblings on the path are also on the frontier ( $b \times m$ ))
- Completeness:  $m$  may be  $\infty$  hence, not in general
- Optimality: No! It just takes the first solution found.



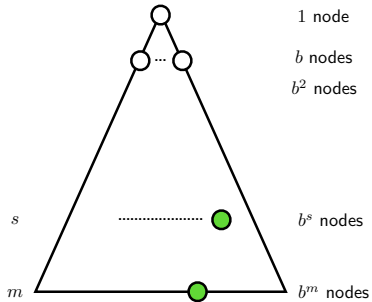
## Main Slide

## DFS properties

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



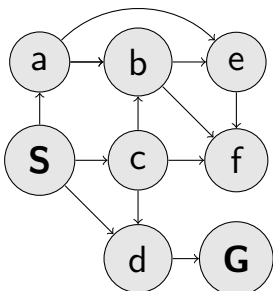
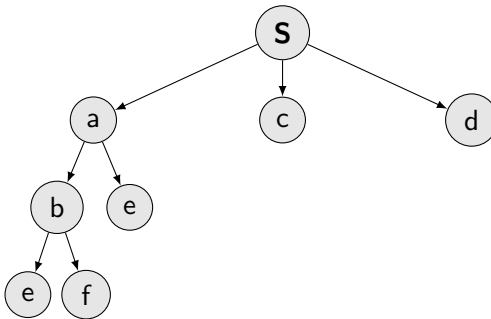
- Time, can process the whole tree:  $b^m$
- Space, only the path so far:  $bm$  (a path from root to leaf ( $m$ ), plus siblings on the path are also on the frontier ( $b \times m$  ) )
- Completeness:  $m$  may be  $\infty$  hence, not in general
- Optimality: No! It just takes the first solution found.



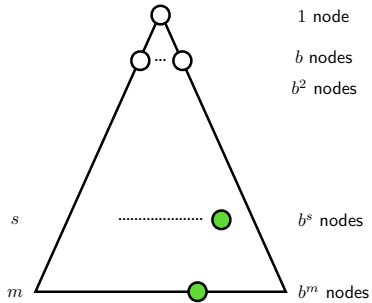
## Main Slide

## DFS properties

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



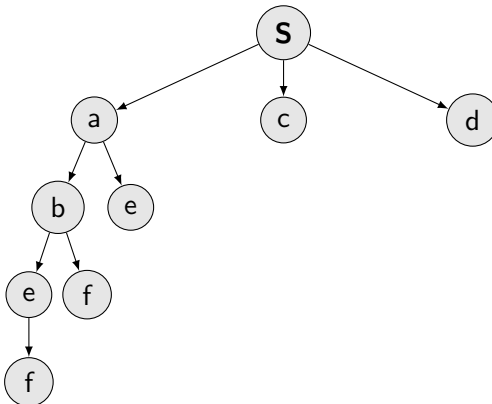
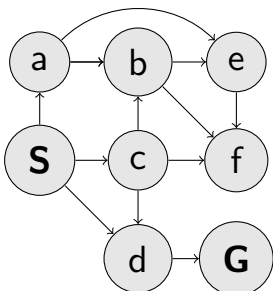
- Time, can process the whole tree:  $b^m$
- Space, only the path so far:  $bm$  (a path from root to leaf ( $m$ ), plus siblings on the path are also on the frontier ( $b \times m$  ) )
- Completeness:  $m$  may be  $\infty$  hence, not in general
- Optimality: No! It just takes the first solution found.



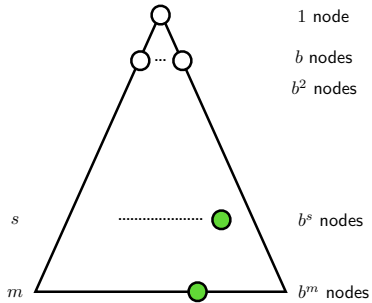
## Main Slide

## DFS properties

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



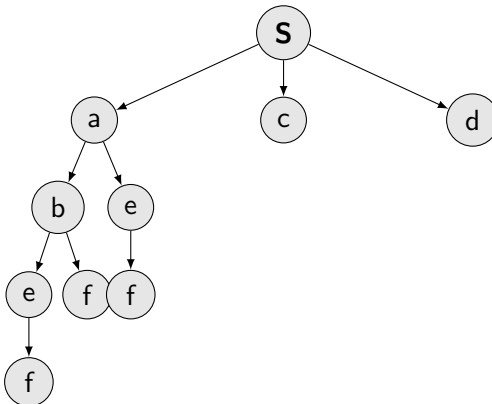
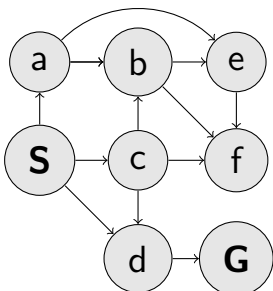
- Time, can process the whole tree:  $b^m$
- Space, only the path so far:  $bm$  (a path from root to leaf ( $m$ ), plus siblings on the path are also on the frontier ( $b \times m$  ) )
- Completeness:  $m$  may be  $\infty$  hence, not in general
- Optimality: No! It just takes the first solution found.



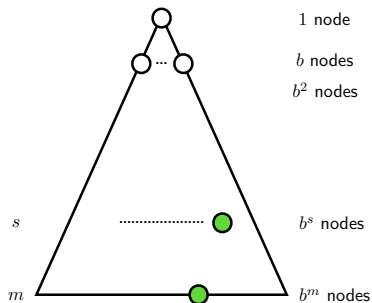
## Main Slide

## DFS properties

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



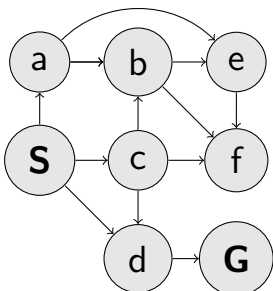
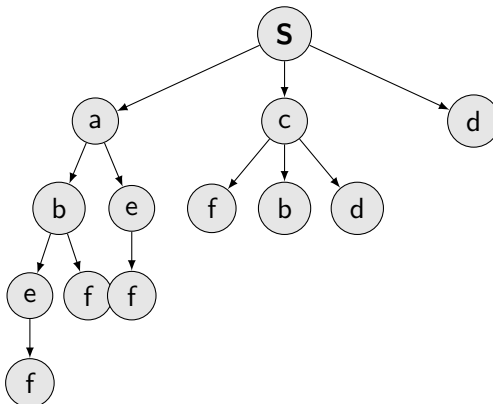
- Time, can process the whole tree:  $b^m$
- Space, only the path so far:  $bm$  (a path from root to leaf ( $m$ ), plus siblings on the path are also on the frontier ( $b \times m$  ) )
- Completeness:  $m$  may be  $\infty$  hence, not in general
- Optimality: No! It just takes the first solution found.



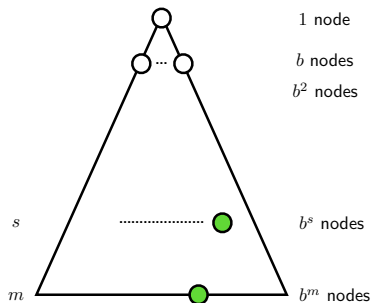
Main Slide

DFS properties

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



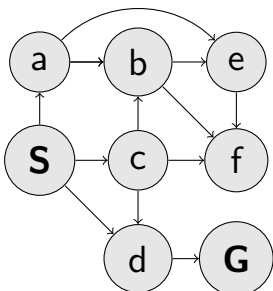
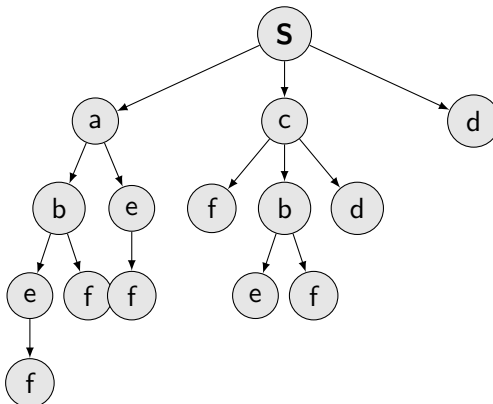
- Time, can process the whole tree:  $b^m$
- Space, only the path so far:  $bm$  (a path from root to leaf ( $m$ ), plus siblings on the path are also on the frontier ( $b \times m$  ) )
- Completeness:  $m$  may be  $\infty$  hence, not in general
- Optimality: No! It just takes the first solution found.



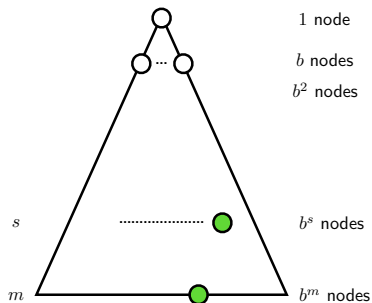
Main Slide

DFS properties

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



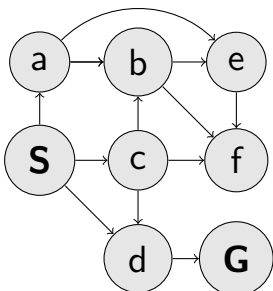
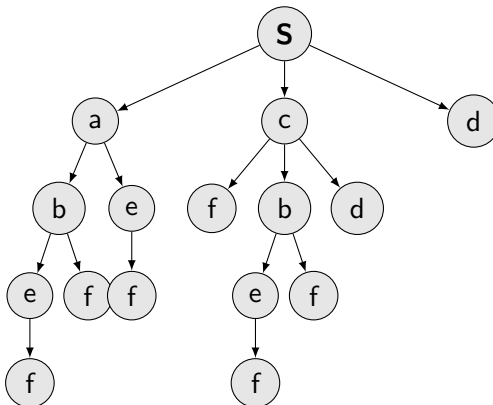
- Time, can process the whole tree:  $b^m$
- Space, only the path so far:  $bm$  (a path from root to leaf ( $m$ ), plus siblings on the path are also on the frontier ( $b \times m$  ) )
- Completeness:  $m$  may be  $\infty$  hence, not in general
- Optimality: No! It just takes the first solution found.



Main Slide

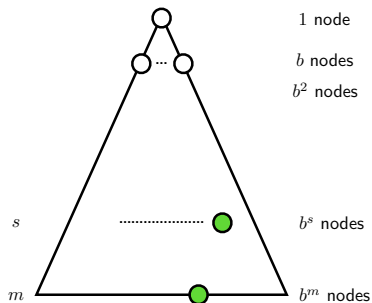
DFS properties

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





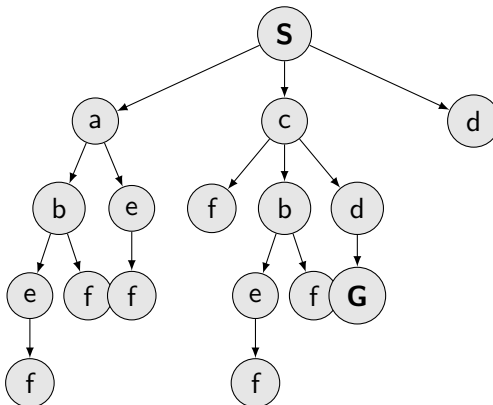
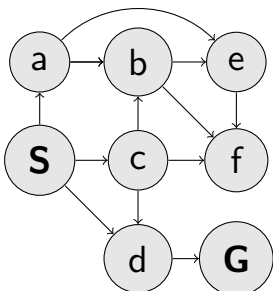
- Time, can process the whole tree:  $b^m$
- Space, only the path so far:  $bm$  (a path from root to leaf ( $m$ ), plus siblings on the path are also on the frontier ( $b \times m$  ) )
- Completeness:  $m$  may be  $\infty$  hence, not in general
- Optimality: No! It just takes the first solution found.



Main Slide

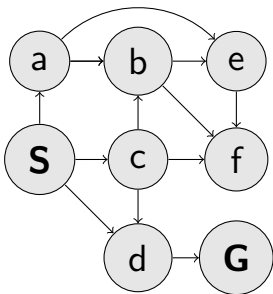
DFS properties

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



## Main Slide

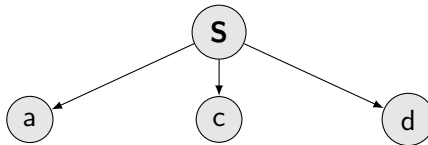
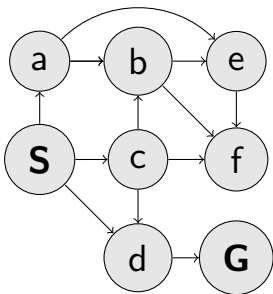
## Breadth-First Search (BFS)



What are the BFS properties?

## Main Slide

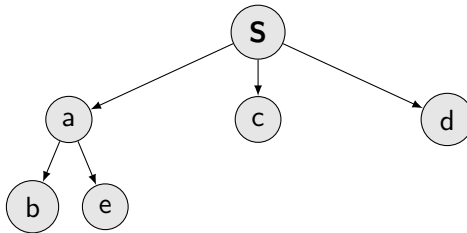
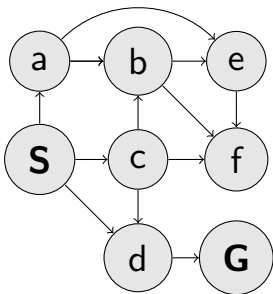
## Breadth-First Search (BFS)



What are the BFS properties?

## Main Slide

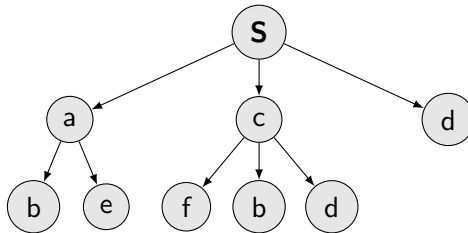
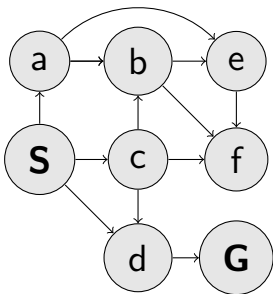
## Breadth-First Search (BFS)



What are the BFS properties?

## Main Slide

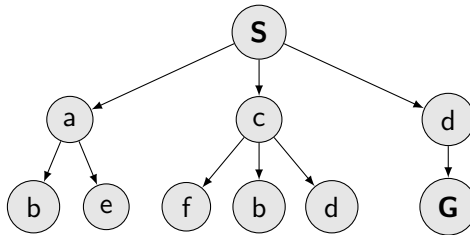
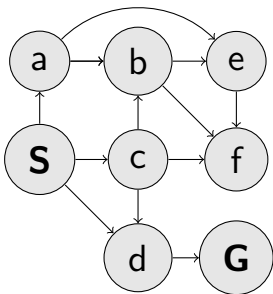
## Breadth-First Search (BFS)



What are the BFS properties?

## Main Slide

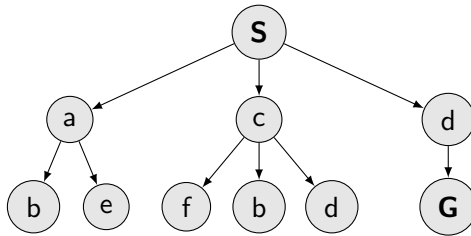
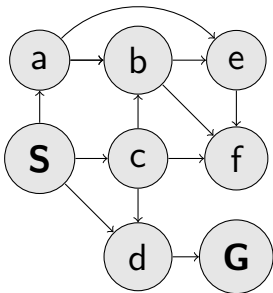
## Breadth-First Search (BFS)



What are the BFS properties?

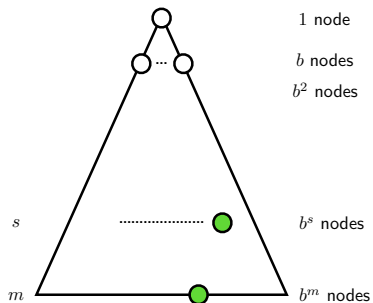
## Main Slide

## Breadth-First Search (BFS)



What are the BFS properties?

- Time, can process the whole tree until  $s: b^s$ , well actually  $b + b^2 + b^3 + \dots + b^s$  but the last layer vastly dominates. Try some calculations for various  $b$ .
- Space, all the frontier:  $b^s$
- Completeness: Yes!
- Optimality, it does not miss the shallowest solution, hence if all the transition costs are 1: Yes!

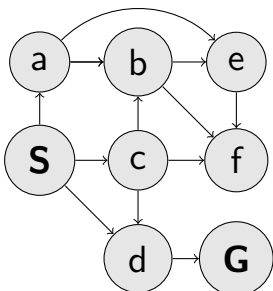


## Main Slide

## BFS properties

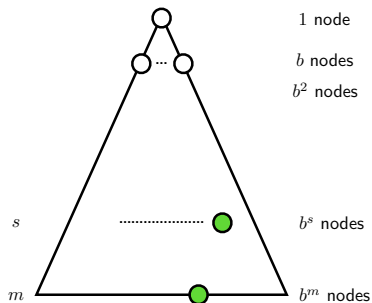
S

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





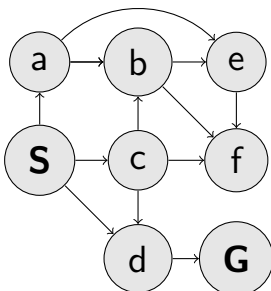
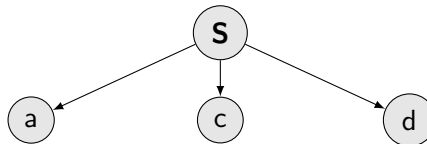
- Time, can process the whole tree until  $s$ :  $b^s$ , well actually  $b + b^2 + b^3 + \dots + b^s$  but the last layer vastly dominates. Try some calculations for various  $b$ .
- Space, all the frontier:  $b^s$
- Completeness: Yes!
- Optimality, it does not miss the shallowest solution, hence if all the transition costs are 1: Yes!



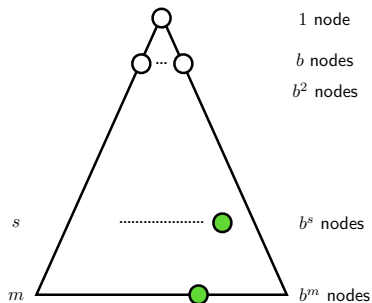
Main Slide

BFS properties

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



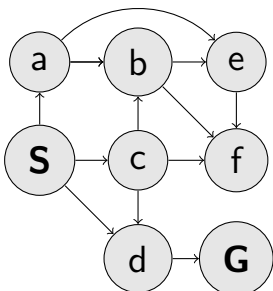
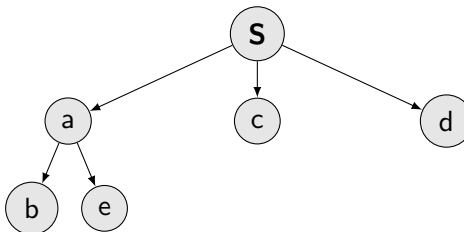
- Time, can process the whole tree until  $s$ :  $b^s$ , well actually  $b + b^2 + b^3 + \dots + b^s$  but the last layer vastly dominates. Try some calculations for various  $b$ .
- Space, all the frontier:  $b^s$
- Completeness: Yes!
- Optimality, it does not miss the shallowest solution, hence if all the transition costs are 1: Yes!



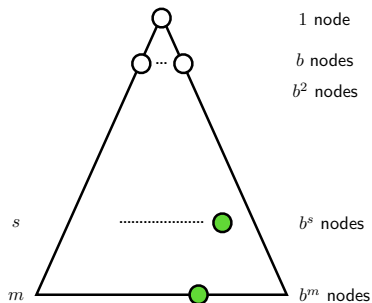
Main Slide

BFS properties

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



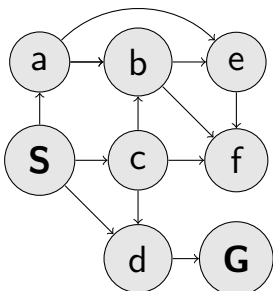
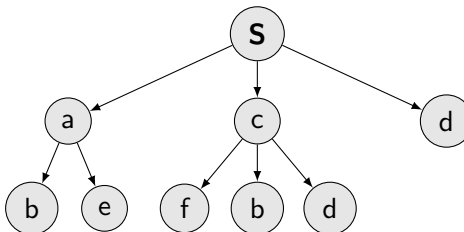
- Time, can process the whole tree until  $s$ :  $b^s$ , well actually  $b + b^2 + b^3 + \dots + b^s$  but the last layer vastly dominates. Try some calculations for various  $b$ .
- Space, all the frontier:  $b^s$
- Completeness: Yes!
- Optimality, it does not miss the shallowest solution, hence if all the transition costs are 1: Yes!



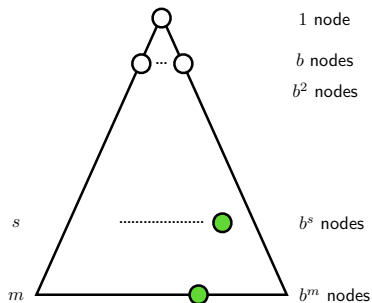
Main Slide

BFS properties

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



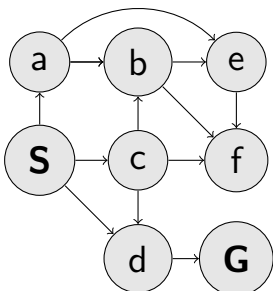
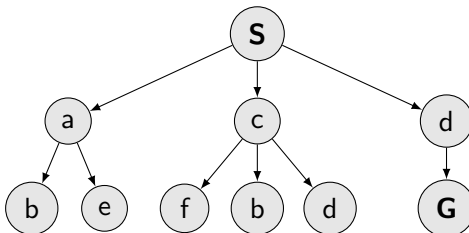
- Time, can process the whole tree until  $s$ :  $b^s$ , well actually  $b + b^2 + b^3 + \dots + b^s$  but the last layer vastly dominates. Try some calculations for various  $b$ .
- Space, all the frontier:  $b^s$
- Completeness: Yes!
- Optimality, it does not miss the shallowest solution, hence if all the transition costs are 1: Yes!



Main Slide

BFS properties

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



What is the impression from the animation? BFS seems better.

- However, let's not jump to conclusions!
- Draw for yourself a different graph and construct appropriate trees.
- Not everything is visible from the animations.
- Draw a comparison table.

	Complete	Optimal	Time	Space
DFS	N (Y if no cycles)	N	$O(b^m)$	$O(mb)$
BFS	Y	Y	$O(b^m)$	$O(b^m)$

- Exponential complexity is scary.
- Practically, space complexity is even more critical. It is not about “waiting longer” but “memory overflow” ...
- This motivates the algorithm modification we look at next.

## Main Slide

### DFS vs BFS

What are (dis)advantages of the individual strategies?



What is the impression from the animation? BFS seems better.

- However, let's not jump to conclusions!
- Draw for yourself a different graph and construct appropriate trees.
- Not everything is visible from the animations.
- Draw a comparison table.

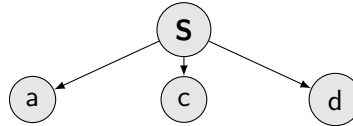
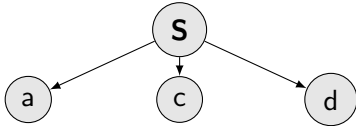
	Complete	Optimal	Time	Space
DFS	N (Y if no cycles)	N	$O(b^m)$	$O(mb)$
BFS	Y	Y	$O(b^m)$	$O(b^m)$

- Exponential complexity is scary.
- Practically, space complexity is even more critical. It is not about “waiting longer” but “memory overflow” ...
- This motivates the algorithm modification we look at next.

## Main Slide

### DFS vs BFS

What are (dis)advantages of the individual strategies?



What is the impression from the animation? BFS seems better.

- However, let's not jump to conclusions!
- Draw for yourself a different graph and construct appropriate trees.
- Not everything is visible from the animations.
- Draw a comparison table.

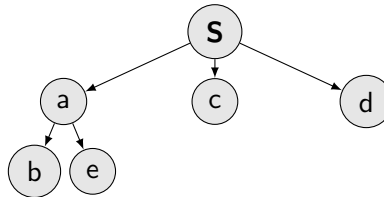
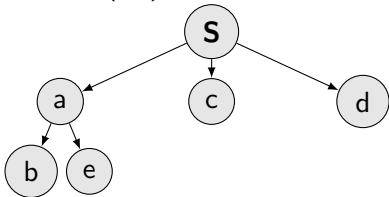
	Complete	Optimal	Time	Space
DFS	N (Y if no cycles)	N	$O(b^m)$	$O(mb)$
BFS	Y	Y	$O(b^m)$	$O(b^m)$

- Exponential complexity is scary.
- Practically, space complexity is even more critical. It is not about “waiting longer” but “memory overflow” ...
- This motivates the algorithm modification we look at next.

## Main Slide

### DFS vs BFS

What are (dis)advantages of the individual strategies?



What is the impression from the animation? BFS seems better.

- However, let's not jump to conclusions!
- Draw for yourself a different graph and construct appropriate trees.
- Not everything is visible from the animations.
- Draw a comparison table.

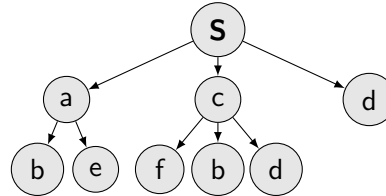
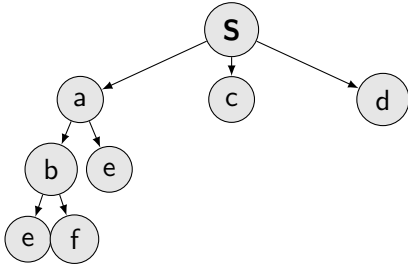
	Complete	Optimal	Time	Space
DFS	N (Y if no cycles)	N	$O(b^m)$	$O(mb)$
BFS	Y	Y	$O(b^m)$	$O(b^m)$

- Exponential complexity is scary.
- Practically, space complexity is even more critical. It is not about “waiting longer” but “memory overflow” ...
- This motivates the algorithm modification we look at next.

## Main Slide

### DFS vs BFS

What are (dis)advantages of the individual strategies?





What is the impression from the animation? BFS seems better.

- However, let's not jump to conclusions!
- Draw for yourself a different graph and construct appropriate trees.
- Not everything is visible from the animations.
- Draw a comparison table.

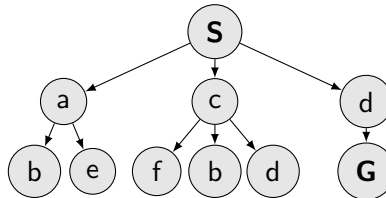
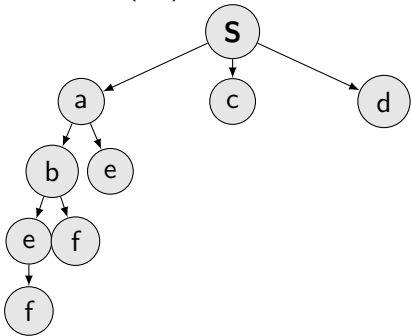
	Complete	Optimal	Time	Space
DFS	N (Y if no cycles)	N	$O(b^m)$	$O(mb)$
BFS	Y	Y	$O(b^m)$	$O(b^m)$

- Exponential complexity is scary.
- Practically, space complexity is even more critical. It is not about “waiting longer” but “memory overflow” ...
- This motivates the algorithm modification we look at next.

## Main Slide

### DFS vs BFS

What are (dis)advantages of the individual strategies?



What is the impression from the animation? BFS seems better.

- However, let's not jump to conclusions!
- Draw for yourself a different graph and construct appropriate trees.
- Not everything is visible from the animations.
- Draw a comparison table.

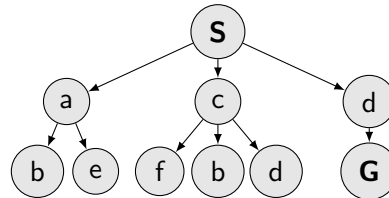
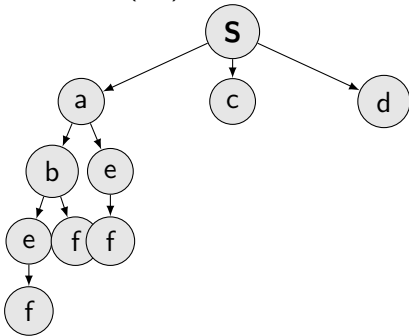
	Complete	Optimal	Time	Space
DFS	N (Y if no cycles)	N	$O(b^m)$	$O(mb)$
BFS	Y	Y	$O(b^m)$	$O(b^m)$

- Exponential complexity is scary.
- Practically, space complexity is even more critical. It is not about “waiting longer” but “memory overflow” ...
- This motivates the algorithm modification we look at next.

## Main Slide

### DFS vs BFS

What are (dis)advantages of the individual strategies?



What is the impression from the animation? BFS seems better.

- However, let's not jump to conclusions!
- Draw for yourself a different graph and construct appropriate trees.
- Not everything is visible from the animations.
- Draw a comparison table.

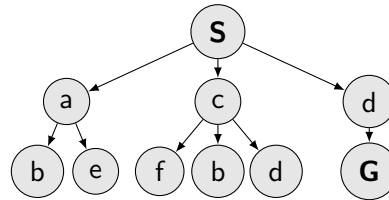
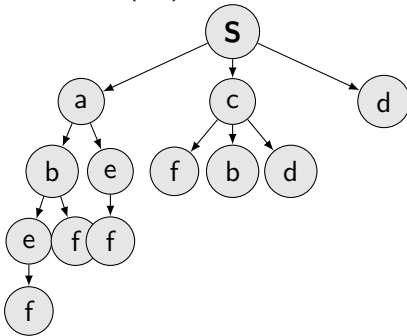
	Complete	Optimal	Time	Space
DFS	N (Y if no cycles)	N	$O(b^m)$	$O(mb)$
BFS	Y	Y	$O(b^m)$	$O(b^m)$

- Exponential complexity is scary.
- Practically, space complexity is even more critical. It is not about “waiting longer” but “memory overflow” ...
- This motivates the algorithm modification we look at next.

## Main Slide

### DFS vs BFS

What are (dis)advantages of the individual strategies?



What is the impression from the animation? BFS seems better.

- However, let's not jump to conclusions!
- Draw for yourself a different graph and construct appropriate trees.
- Not everything is visible from the animations.
- Draw a comparison table.

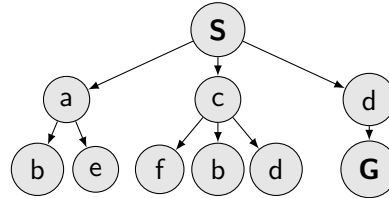
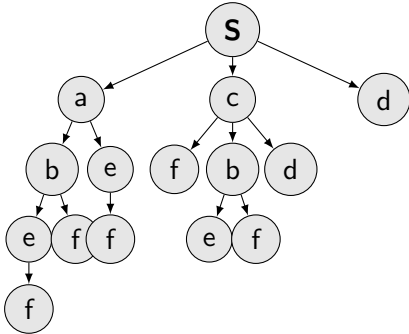
	Complete	Optimal	Time	Space
DFS	N (Y if no cycles)	N	$O(b^m)$	$O(mb)$
BFS	Y	Y	$O(b^m)$	$O(b^m)$

- Exponential complexity is scary.
- Practically, space complexity is even more critical. It is not about “waiting longer” but “memory overflow” ...
- This motivates the algorithm modification we look at next.

## Main Slide

### DFS vs BFS

What are (dis)advantages of the individual strategies?



What is the impression from the animation? BFS seems better.

- However, let's not jump to conclusions!
- Draw for yourself a different graph and construct appropriate trees.
- Not everything is visible from the animations.
- Draw a comparison table.

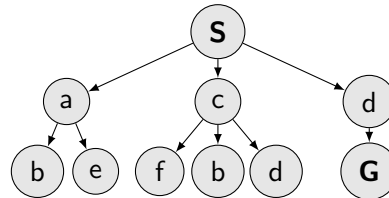
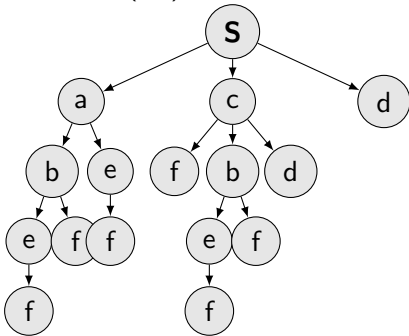
	Complete	Optimal	Time	Space
DFS	N (Y if no cycles)	N	$O(b^m)$	$O(mb)$
BFS	Y	Y	$O(b^m)$	$O(b^m)$

- Exponential complexity is scary.
- Practically, space complexity is even more critical. It is not about “waiting longer” but “memory overflow” ...
- This motivates the algorithm modification we look at next.

## Main Slide

### DFS vs BFS

What are (dis)advantages of the individual strategies?



What is the impression from the animation? BFS seems better.

- However, let's not jump to conclusions!
- Draw for yourself a different graph and construct appropriate trees.
- Not everything is visible from the animations.
- Draw a comparison table.

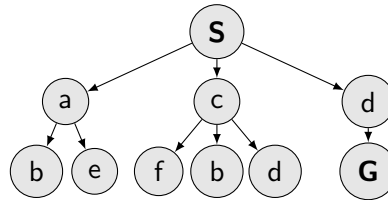
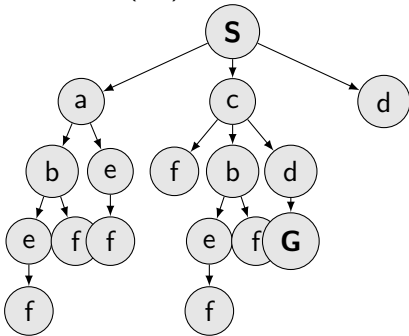
	Complete	Optimal	Time	Space
DFS	N (Y if no cycles)	N	$O(b^m)$	$O(mb)$
BFS	Y	Y	$O(b^m)$	$O(b^m)$

- Exponential complexity is scary.
- Practically, space complexity is even more critical. It is not about “waiting longer” but “memory overflow” ...
- This motivates the algorithm modification we look at next.

## Main Slide

### DFS vs BFS

What are (dis)advantages of the individual strategies?

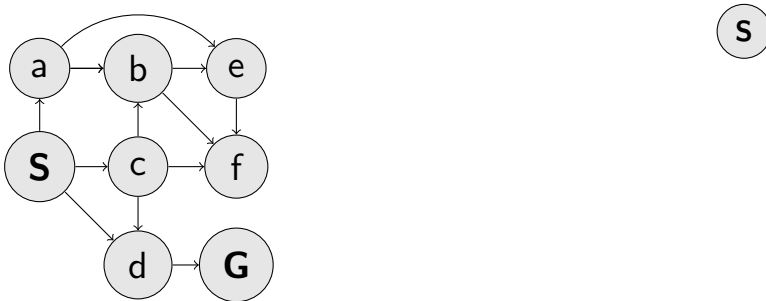


- Remedy to DFS failing in infinite state spaces.
- Supplying a predetermined max depth – nodes at this depth are treated as if they had no successors.
- However, an additional source of algorithm *incompleteness*. Solution can obviously be deeper than *maxdepth* – unless we know something about the problem. Think about our map of Romania. There are 20 cities. Hence, *maxdepth* = 19 is a possible choice. Taking a closer look, any city can be reached from any other city in max. 9 steps (*state space diameter*), giving a more strict and hence better limit.

## Main Slide

DFS with limited depth,  $\text{maxdepth}=2$ 

Do not follow nodes with  $\text{depth} > \text{maxdepth}$

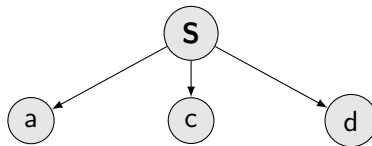
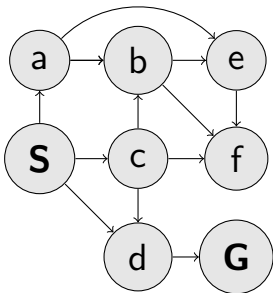


- Remedy to DFS failing in infinite state spaces.
- Supplying a predetermined max depth – nodes at this depth are treated as if they had no successors.
- However, an additional source of algorithm *incompleteness*. Solution can obviously be deeper than *maxdepth* – unless we know something about the problem. Think about our map of Romania. There are 20 cities. Hence, *maxdepth* = 19 is a possible choice. Taking a closer look, any city can be reached from any other city in max. 9 steps (*state space diameter*), giving a more strict and hence better limit.

## Main Slide

DFS with limited depth,  $\text{maxdepth}=2$ 

Do not follow nodes with  $\text{depth} > \text{maxdepth}$



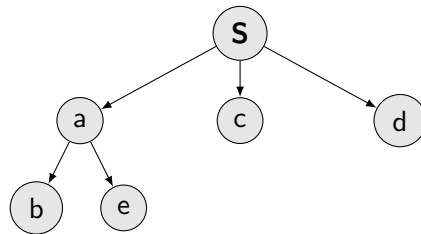
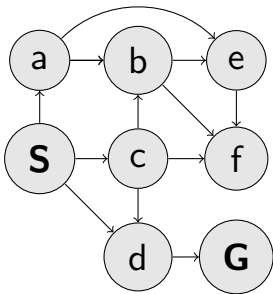


- Remedy to DFS failing in infinite state spaces.
- Supplying a predetermined max depth – nodes at this depth are treated as if they had no successors.
- However, an additional source of algorithm *incompleteness*. Solution can obviously be deeper than *maxdepth* – unless we know something about the problem. Think about our map of Romania. There are 20 cities. Hence, *maxdepth* = 19 is a possible choice. Taking a closer look, any city can be reached from any other city in max. 9 steps (*state space diameter*), giving a more strict and hence better limit.

## Main Slide

DFS with limited depth,  $\text{maxdepth}=2$ 

Do not follow nodes with  $\text{depth} > \text{maxdepth}$

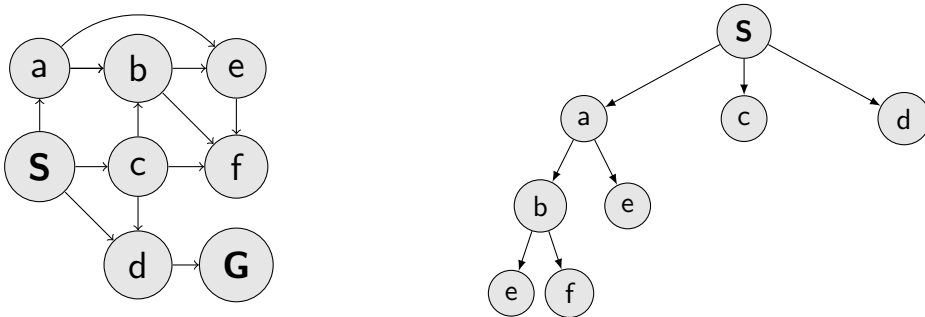


- Remedy to DFS failing in infinite state spaces.
- Supplying a predetermined max depth – nodes at this depth are treated as if they had no successors.
- However, an additional source of algorithm *incompleteness*. Solution can obviously be deeper than *maxdepth* – unless we know something about the problem. Think about our map of Romania. There are 20 cities. Hence, *maxdepth* = 19 is a possible choice. Taking a closer look, any city can be reached from any other city in max. 9 steps (*state space diameter*), giving a more strict and hence better limit.

## Main Slide

DFS with limited depth,  $\text{maxdepth}=2$ 

Do not follow nodes with  $\text{depth} > \text{maxdepth}$

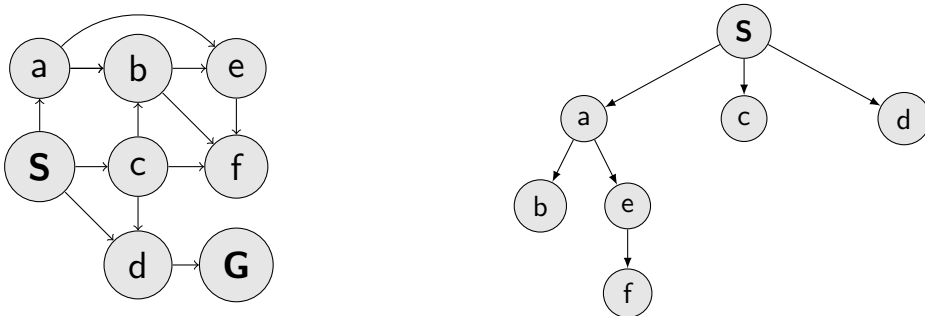


- Remedy to DFS failing in infinite state spaces.
- Supplying a predetermined max depth – nodes at this depth are treated as if they had no successors.
- However, an additional source of algorithm *incompleteness*. Solution can obviously be deeper than *maxdepth* – unless we know something about the problem. Think about our map of Romania. There are 20 cities. Hence, *maxdepth* = 19 is a possible choice. Taking a closer look, any city can be reached from any other city in max. 9 steps (*state space diameter*), giving a more strict and hence better limit.

## Main Slide

DFS with limited depth,  $\text{maxdepth}=2$ 

Do not follow nodes with  $\text{depth} > \text{maxdepth}$

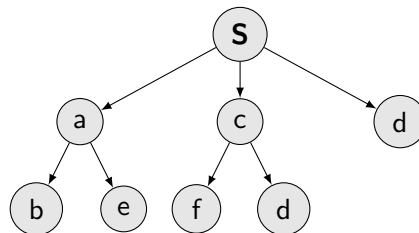
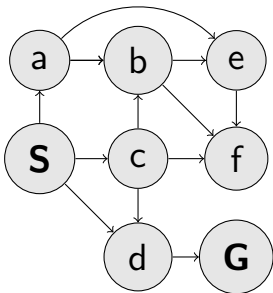


- Remedy to DFS failing in infinite state spaces.
- Supplying a predetermined max depth – nodes at this depth are treated as if they had no successors.
- However, an additional source of algorithm *incompleteness*. Solution can obviously be deeper than *maxdepth* – unless we know something about the problem. Think about our map of Romania. There are 20 cities. Hence, *maxdepth* = 19 is a possible choice. Taking a closer look, any city can be reached from any other city in max. 9 steps (*state space diameter*), giving a more strict and hence better limit.

## Main Slide

DFS with limited depth,  $\text{maxdepth}=2$ 

Do not follow nodes with  $\text{depth} > \text{maxdepth}$

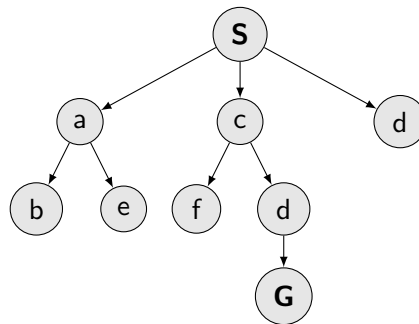
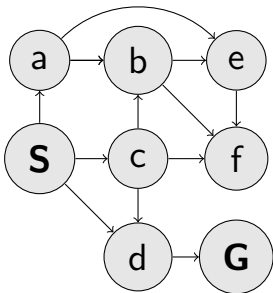


- Remedy to DFS failing in infinite state spaces.
- Supplying a predetermined max depth – nodes at this depth are treated as if they had no successors.
- However, an additional source of algorithm *incompleteness*. Solution can obviously be deeper than *maxdepth* – unless we know something about the problem. Think about our map of Romania. There are 20 cities. Hence, *maxdepth* = 19 is a possible choice. Taking a closer look, any city can be reached from any other city in max. 9 steps (*state space diameter*), giving a more strict and hence better limit.

## Main Slide

DFS with limited depth,  $\text{maxdepth}=2$ 

Do not follow nodes with  $\text{depth} > \text{maxdepth}$

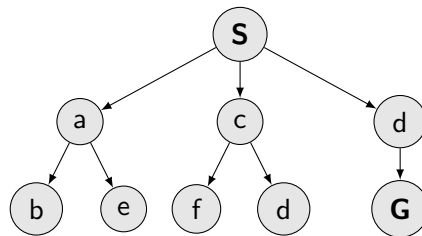
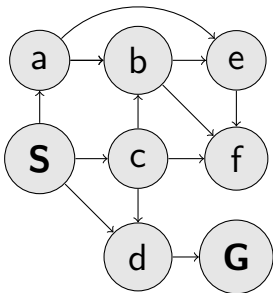


- Remedy to DFS failing in infinite state spaces.
- Supplying a predetermined max depth – nodes at this depth are treated as if they had no successors.
- However, an additional source of algorithm *incompleteness*. Solution can obviously be deeper than *maxdepth* – unless we know something about the problem. Think about our map of Romania. There are 20 cities. Hence, *maxdepth* = 19 is a possible choice. Taking a closer look, any city can be reached from any other city in max. 9 steps (*state space diameter*), giving a more strict and hence better limit.

## Main Slide

DFS with limited depth,  $\text{maxdepth}=2$ 

Do not follow nodes with  $\text{depth} > \text{maxdepth}$



Really, how much do we repeat/waste? The “upper levels”, close to the root, are repeated many times. However, in a tree, most nodes are the bottom levels and nr. nodes traversed is what counts. More specifically, for a solution at depth  $s$ , the nodes on the bottom level are generated only once, those on the next-to-bottom level  $2x$  ... children of the root are generated  $s \times$ . Compare the number of nodes generated ID-DFS vs. BFS:

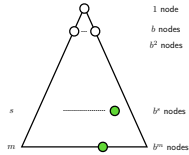
$$N(\text{ID-DFS}) = (s)b + (s-1)b^2 + (s-2)b^3 + \dots + (1)b^s$$

$$N(\text{BFS}) = b + b^2 + b^3 + \dots + b^s$$

Try some calculations for various  $s$  and  $b$ . For  $b = 10$  and  $d = 5$ :

$$N(\text{ID-DFS}) = 50 + 400 + 3000 + 20000 + 100000 = 123450$$

$$N(\text{BFS}) = 10 + 100 + 1000 + 10000 + 100000 = 111110$$



(Example from [2].)

## Main Slide

### 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?

Really, how much do we repeat/waste? The “upper levels”, close to the root, are repeated many times. However, in a tree, most nodes are the bottom levels and nr. nodes traversed is what counts. More specifically, for a solution at depth  $s$ , the nodes on the bottom level are generated only once, those on the next-to-bottom level  $2x$  ... children of the root are generated  $s \times$ . Compare the number of nodes generated ID-DFS vs. BFS:

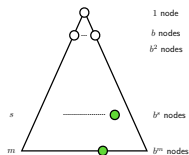
$$N(\text{ID-DFS}) = (s)b + (s-1)b^2 + (s-2)b^3 + \dots + (1)b^s$$

$$N(\text{BFS}) = b + b^2 + b^3 + \dots + b^s$$

Try some calculations for various  $s$  and  $b$ . For  $b = 10$  and  $d = 5$ :

$$N(\text{ID-DFS}) = 50 + 400 + 3000 + 20000 + 100000 = 123450$$

$$N(\text{BFS}) = 10 + 100 + 1000 + 10000 + 100000 = 111110$$



(Example from [2].)

## Main Slide

### 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?



Really, how much do we repeat/waste? The “upper levels”, close to the root, are repeated many times. However, in a tree, most nodes are the bottom levels and nr. nodes traversed is what counts. More specifically, for a solution at depth  $s$ , the nodes on the bottom level are generated only once, those on the next-to-bottom level  $2x$  ... children of the root are generated  $s \times$ . Compare the number of nodes generated ID-DFS vs. BFS:

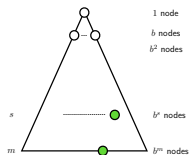
$$N(\text{ID-DFS}) = (s)b + (s-1)b^2 + (s-2)b^3 + \dots + (1)b^s$$

$$N(\text{BFS}) = b + b^2 + b^3 + \dots + b^s$$

Try some calculations for various  $s$  and  $b$ . For  $b = 10$  and  $d = 5$ :

$$N(\text{ID-DFS}) = 50 + 400 + 3000 + 20000 + 100000 = 123450$$

$$N(\text{BFS}) = 10 + 100 + 1000 + 10000 + 100000 = 111110$$



(Example from [2].)

## Main Slide

### 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?

Really, how much do we repeat/waste? The “upper levels”, close to the root, are repeated many times. However, in a tree, most nodes are the bottom levels and nr. nodes traversed is what counts. More specifically, for a solution at depth  $s$ , the nodes on the bottm level are generated only once, those on the next-to-bottom level  $2x$  ... children of the root are generated  $s \times$ . Compare the number of nodes generated ID-DFS vs. BFS:

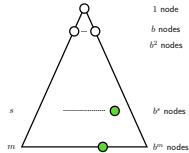
$$N(\text{ID-DFS}) = (s)b + (s-1)b^2 + (s-2)b^3 + \dots + (1)b^s$$

$$N(\text{BFS}) = b + b^2 + b^3 + \dots + b^s$$

Try some calculations for various  $s$  and  $b$ . For  $b = 10$  and  $d = 5$ :

$$N(\text{ID-DFS}) = 50 + 400 + 3000 + 20000 + 100000 = 123450$$

$$N(\text{BFS}) = 10 + 100 + 1000 + 10000 + 100000 = 111110$$



(Example from [2].)

## Main Slide

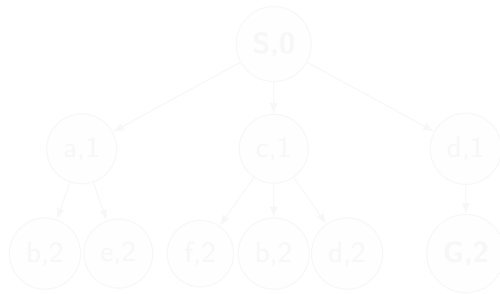
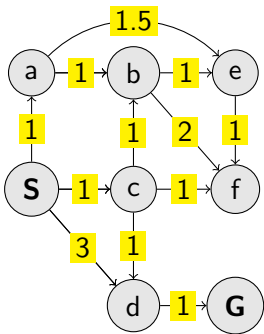
### Iterative deepening DFS (ID-DFS)

- ▶ 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?

## Main Slide

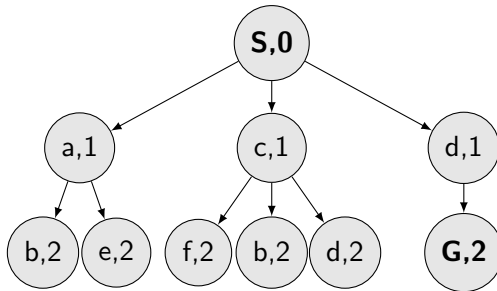
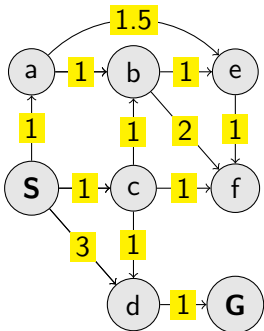
## Cost sensitive search



- ▶ In BFS, DFS, node  $\pm$ depth was the node-value.
- ▶ How was the depth actually computed?
- ▶ How to evaluate nodes with path cost?

## Main Slide

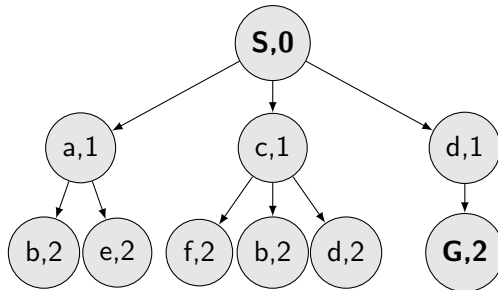
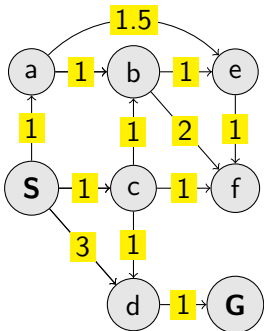
## Cost sensitive search



- ▶ In BFS, DFS, node  $\pm$ depth was the node-value.
- ▶ How was the depth actually computed?
- ▶ How to evaluate nodes with path cost?

## Main Slide

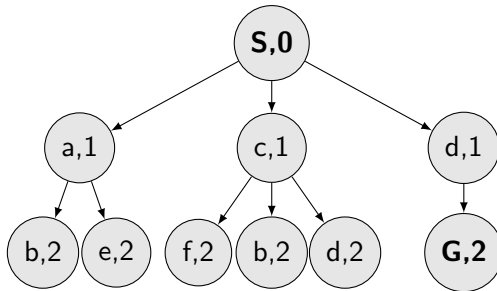
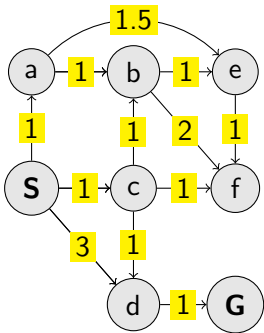
## Cost sensitive search



- ▶ In BFS, DFS, node  $\pm$ depth was the node-value.
- ▶ How was the depth actually computed?
- ▶ How to evaluate nodes with path cost?

## Main Slide

## Cost sensitive search



- ▶ In BFS, DFS, node  $\pm$ depth was the node-value.
- ▶ How was the depth actually computed?
- ▶ How to evaluate nodes with path cost?

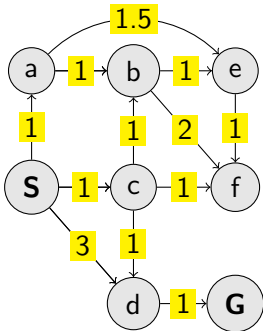
Simple extension of BFS. Instead of expanding shallowest node, the node with smallest path cost so far is expanded.

Two differences:

- Goal test applied to a node when *selected for expansion* – not when first generated. (First goal generated may be on a suboptimal path.)
- Test is added in case a better path is found to a node currently on the frontier.

## Main Slide

## Uniform Cost Search (UCS)



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

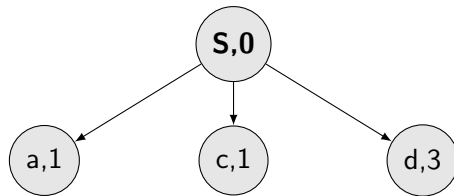
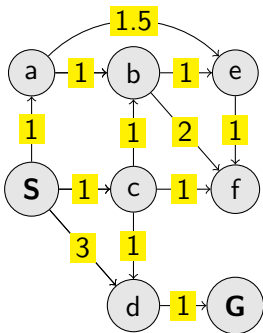
Simple extension of BFS. Instead of expanding shallowest node, the node with smallest path cost so far is expanded.

Two differences:

- Goal test applied to a node when *selected for expansion* – not when first generated. (First goal generated may be on a suboptimal path.)
- Test is added in case a better path is found to a node currently on the frontier.

## Main Slide

## Uniform Cost Search (UCS)



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



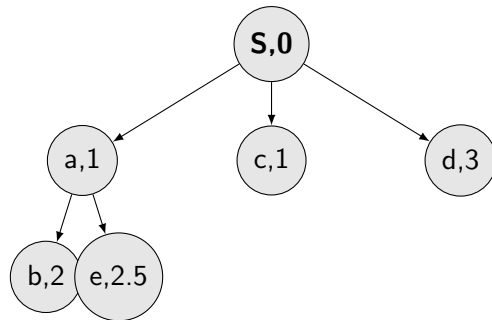
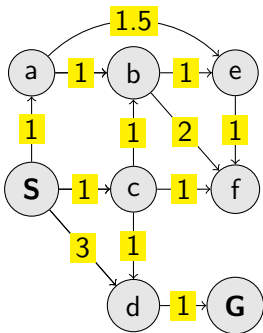
Simple extension of BFS. Instead of expanding shallowest node, the node with smallest path cost so far is expanded.

Two differences:

- Goal test applied to a node when *selected for expansion* – not when first generated. (First goal generated may be on a suboptimal path.)
- Test is added in case a better path is found to a node currently on the frontier.

## Main Slide

## Uniform Cost Search (UCS)



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

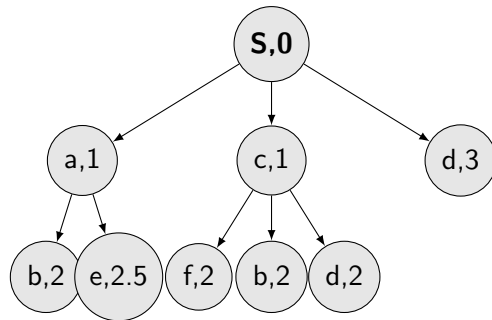
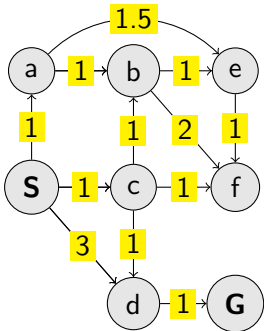
Simple extension of BFS. Instead of expanding shallowest node, the node with smallest path cost so far is expanded.

Two differences:

- Goal test applied to a node when *selected for expansion* – not when first generated. (First goal generated may be on a suboptimal path.)
- Test is added in case a better path is found to a node currently on the frontier.

## Main Slide

## Uniform Cost Search (UCS)



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

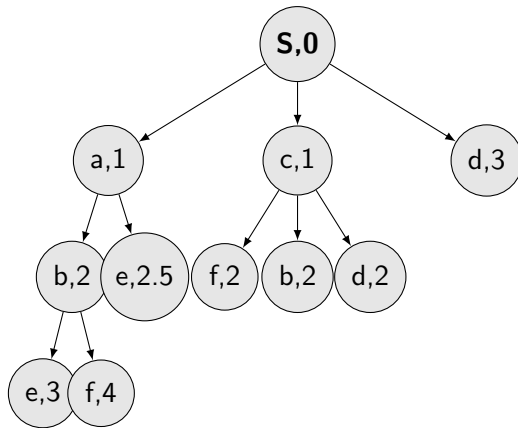
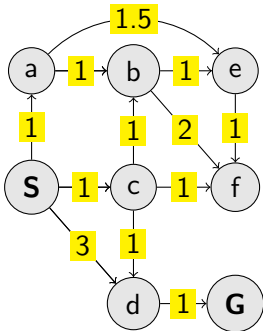
Simple extension of BFS. Instead of expanding shallowest node, the node with smallest path cost so far is expanded.

Two differences:

- Goal test applied to a node when *selected for expansion* – not when first generated. (First goal generated may be on a suboptimal path.)
- Test is added in case a better path is found to a node currently on the frontier.

## Main Slide

## Uniform Cost Search (UCS)



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

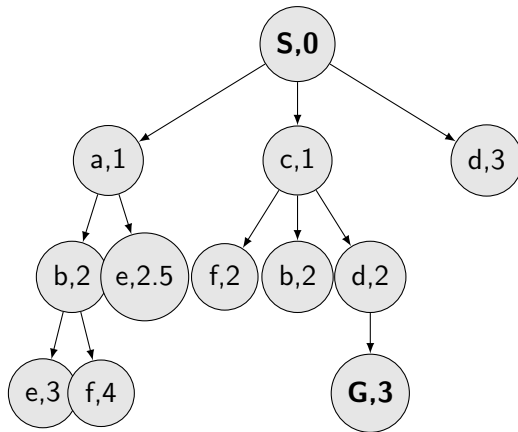
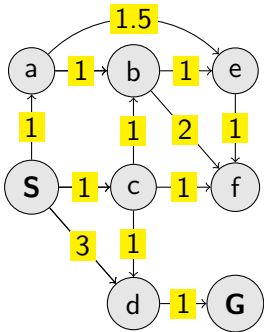
Simple extension of BFS. Instead of expanding shallowest node, the node with smallest path cost so far is expanded.

Two differences:

- Goal test applied to a node when *selected for expansion* – not when first generated. (First goal generated may be on a suboptimal path.)
- Test is added in case a better path is found to a node currently on the frontier.

## Main Slide

## Uniform Cost Search (UCS)



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

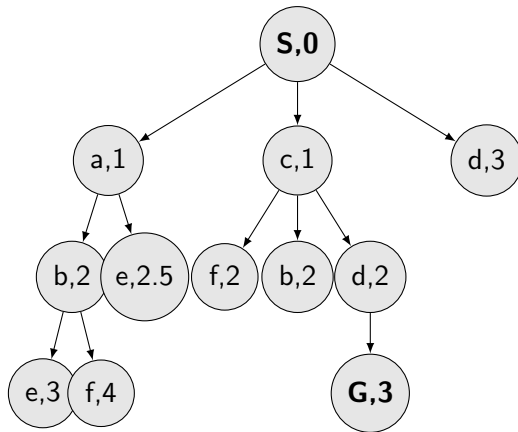
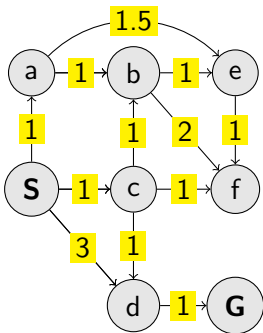
Simple extension of BFS. Instead of expanding shallowest node, the node with smallest path cost so far is expanded.

Two differences:

- Goal test applied to a node when *selected for expansion* – not when first generated. (First goal generated may be on a suboptimal path.)
- Test is added in case a better path is found to a node currently on the frontier.

## Main Slide

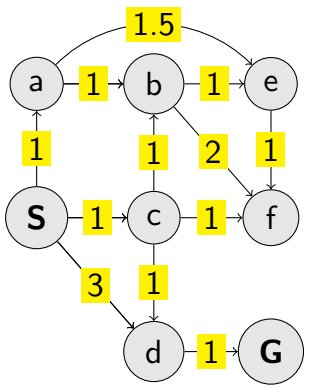
## Uniform Cost Search (UCS)



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

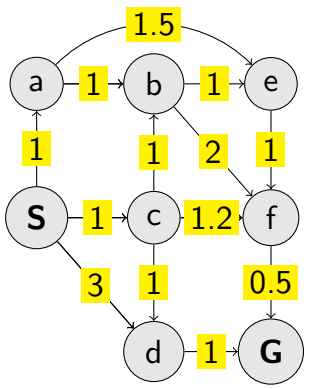
Main Slide

When to stop, when visiting or expanding?



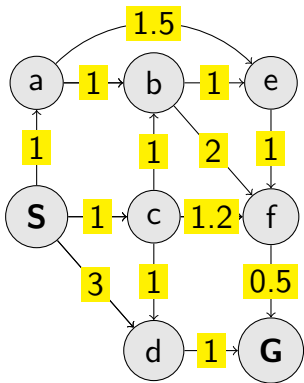
Main Slide

When to stop, when visiting or expanding?



Main Slide

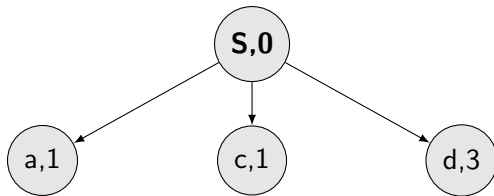
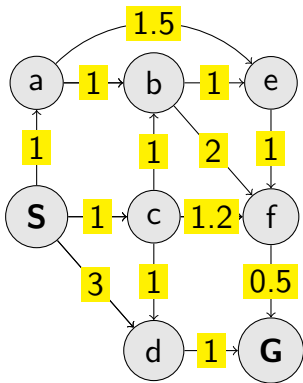
When to stop, when visiting or expanding?





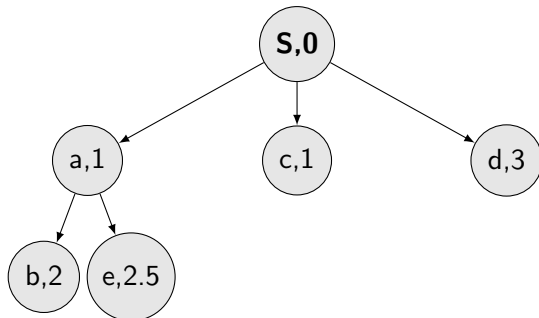
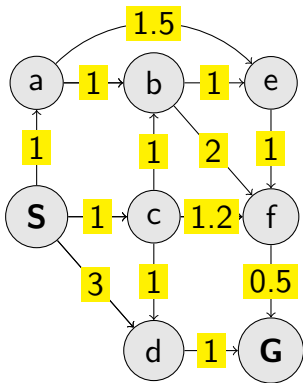
## Main Slide

When to stop, when visiting or expanding?



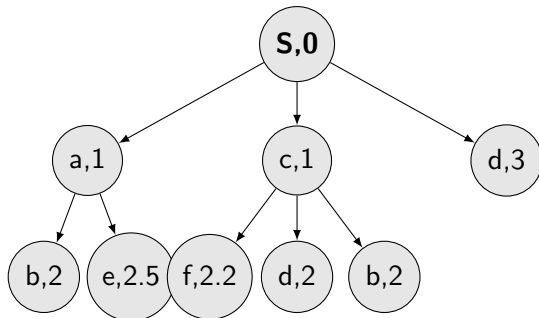
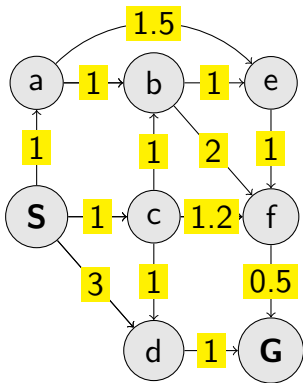
## Main Slide

When to stop, when visiting or expanding?



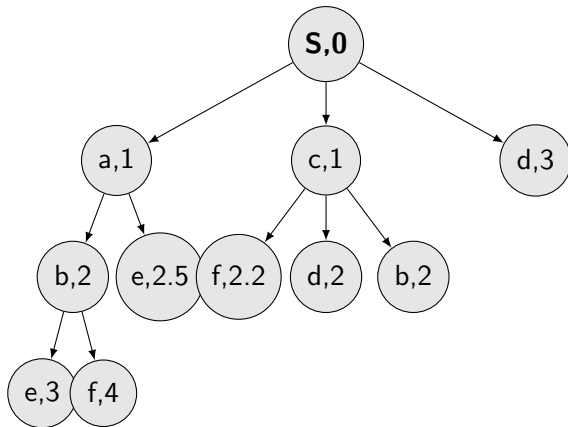
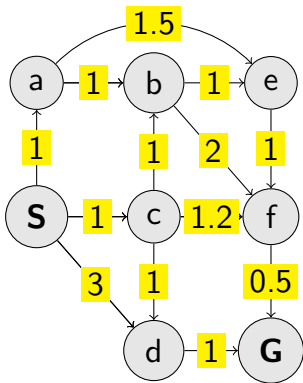
## Main Slide

When to stop, when visiting or expanding?



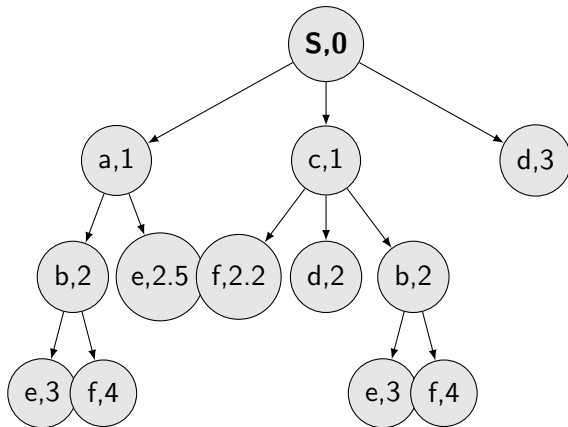
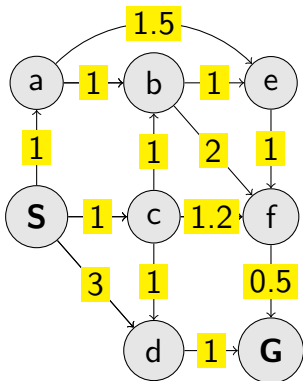
## Main Slide

When to stop, when visiting or expanding?



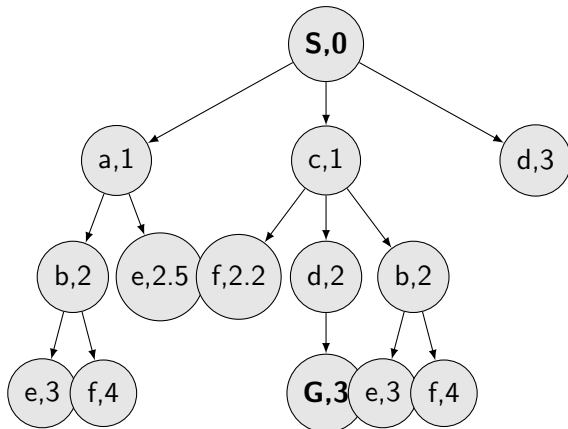
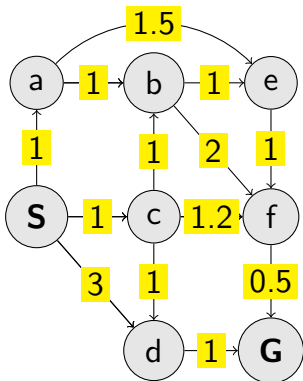
## Main Slide

When to stop, when visiting or expanding?



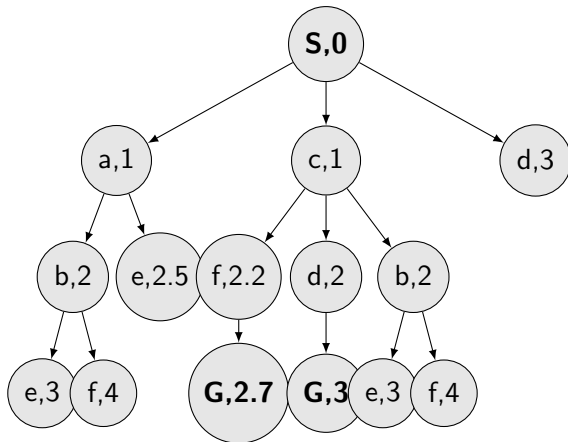
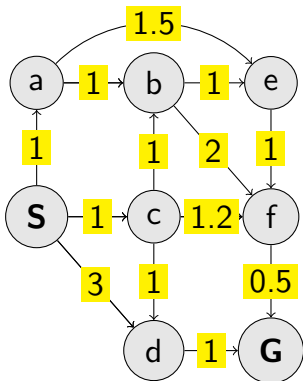
## Main Slide

When to stop, when visiting or expanding?



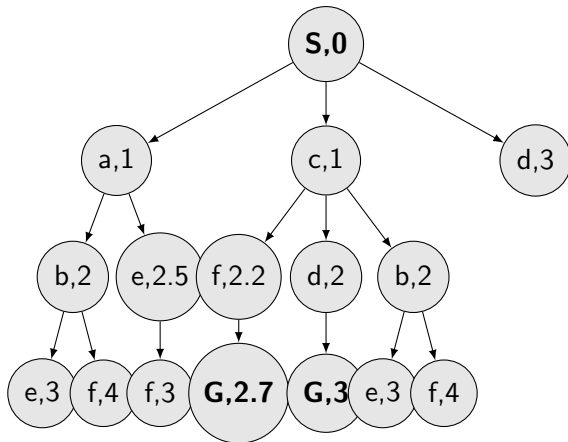
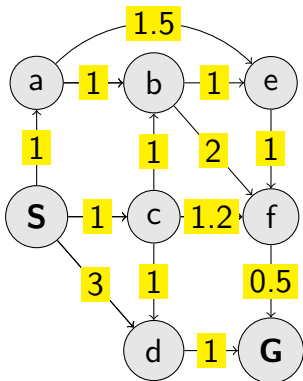
## Main Slide

When to stop, when visiting or expanding?



## Main Slide

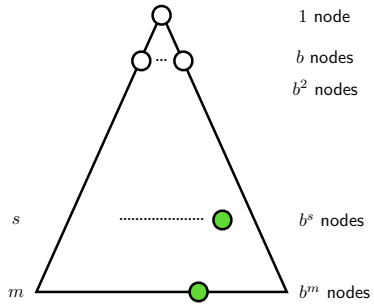
When to stop, when visiting or expanding?





Solution cost  $C^*$ , transition cost at least  $\epsilon$ . Effective depth, roughly  $C^*/\epsilon$ .

- Time:  $b^{C^*/\epsilon}$
- Space:  $b^{C^*/\epsilon}$
- Completeness: Yes!
- Optimality: Yes! Why?



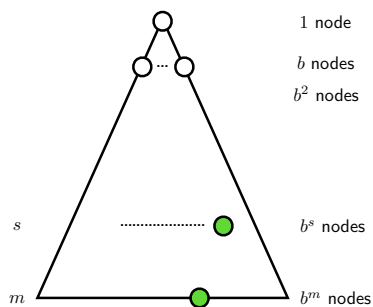
## Main Slide

### UCS properties

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

Solution cost  $C^*$ , transition cost at least  $\epsilon$ . Effective depth, roughly  $C^*/\epsilon$ .

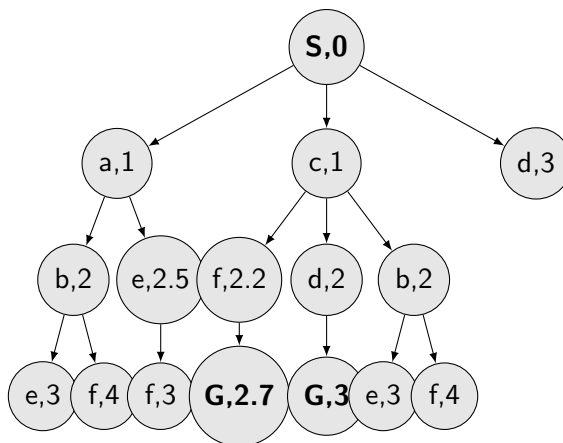
- Time:  $b^{C^*/\epsilon}$
- Space:  $b^{C^*/\epsilon}$
- Completeness: Yes!
- Optimality: Yes! Why?



Main Slide

UCS properties

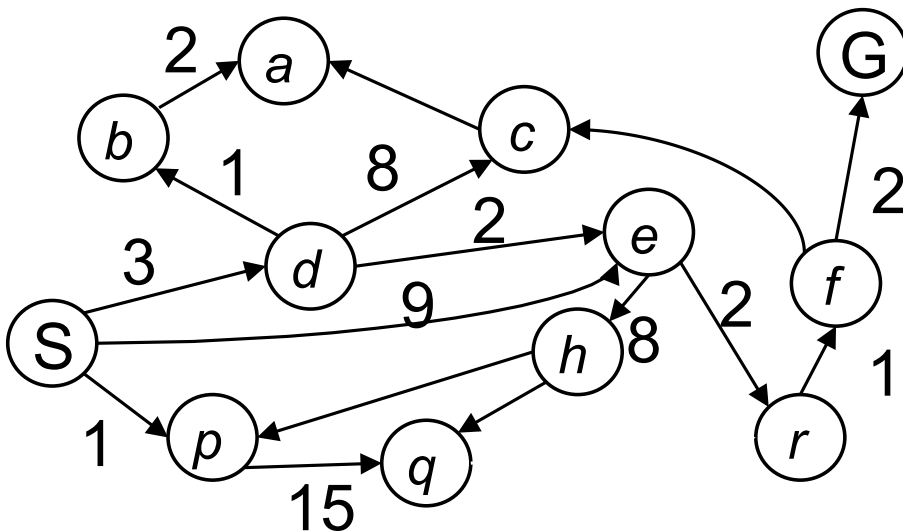
- ▶ Time complexity?
- ▶ Space complexity?
- ▶ Complete?
- ▶ Optimal?



Try it on paper, mark which nodes are in frontier, mark lines of equal cost.

## Main Slide

Example: Graph with costs



# Programming a Tree Search

## Main Slide

## Infrastructure for (tree) search algorithms

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

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

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

## Main Slide

## Infrastructure for (tree) search algorithms

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

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

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

## Main Slide

## 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`<sup>1</sup> and `queue`<sup>2</sup> for inspiration.

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

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

---

Main Slide

What is the solution?

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



## Main Slide

## 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/>.