Fundamentals of Artificial Intelligence – Uninformed Search

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Organization

The content is covered in the AI book by the section "Solving Problems by Searching", Sec. 1-4.

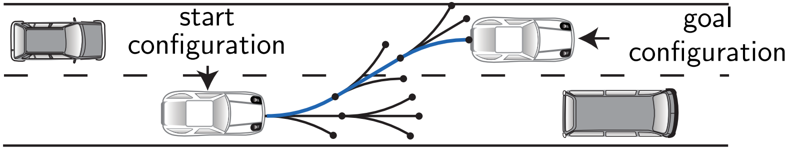
Learning Outcomes

- You can create formally defined search problems.
- You understand the complexity of search problems.
- You understand how real world problems can often be posed as a pure search problem.
- You understand the difference between tree search and graph search.
- You can apply the most important uninformed search techniques: Breadth-First Search, Uniform-Cost Search, Depth-First Search, Depth-Limited Search, Iterative Deepening Search.
- You can compare the advantages and disadvantages of uninformed search strategies.

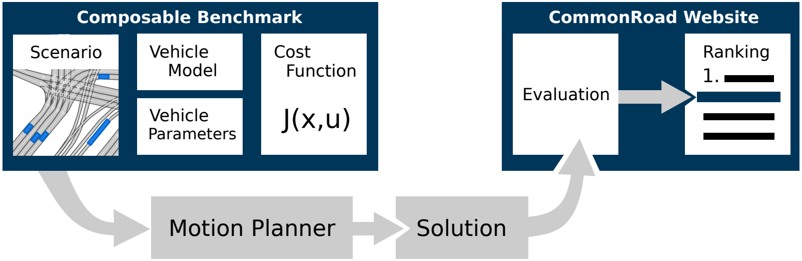
Motivation

One example how search is used in my research group:

- Automated vehicles have to search a collision-free path from a start to a goal configuration.
- Searching in continuous space is difficult.
- We discretize the search problem in space and time by offering only a finite number of possible actions at discrete time steps.
- This makes it possible to use classical search techniques as introduced in this lecture.



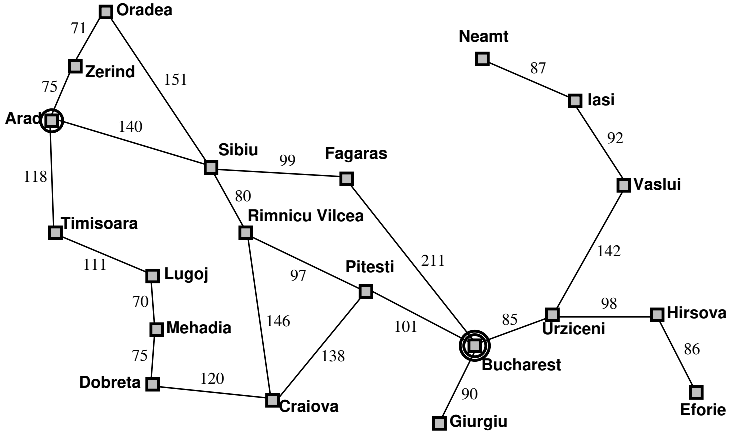
Introducing CommonRoad



Website: **https://commonroad.in.tum.de**

Another Example: Holiday in Romania

On holiday in Romania; currently in Arad. Flight leaves tomorrow from Bucharest.

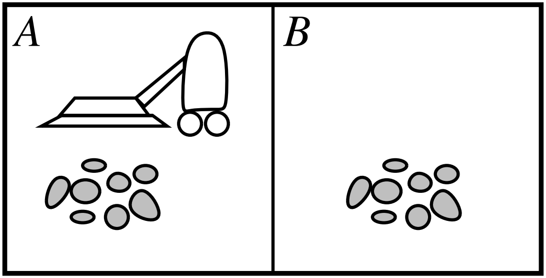


Well-defined problems

A problem can be formally defined by 5 components:

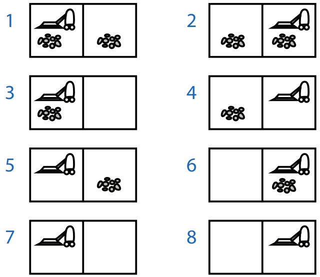
- The **initial state** the agent starts in.
  Example: initial state is `In(Arad)`.
- A description of the possible **actions**.
  Example: actions of `In(Arad)` are `Go(Sibiu)`, `Go(Timisoara)`, `Go(Zerind)`.
- A description of what each action does, which we refer to as the **transition model**.
  Example: `RESULT(In(Arad), Go(Zerind)) = In(Zerind)`.
- The **goal test**, which checks whether a given state is the goal state.
  Example: the goal state is `In(Bucharest)`.
- A **path cost** function assigning a numeric cost to each solution path.
  Example: traveled distance is a good path cost.

Vacuum-Cleaner World



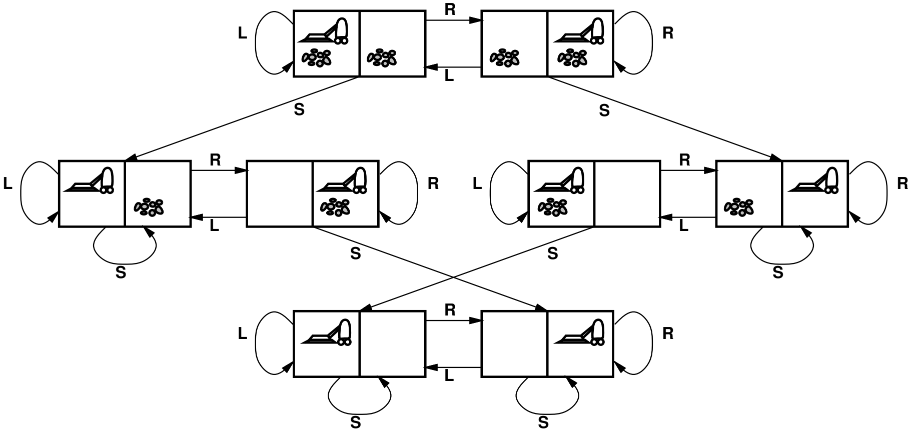
Percepts: location and contents, e.g., $[A, Dirty]$
Actions: *Left*, *Right*, *Suck*, *NoOp* (**No Op**eration)

Vacuum World (Toy Problem I)



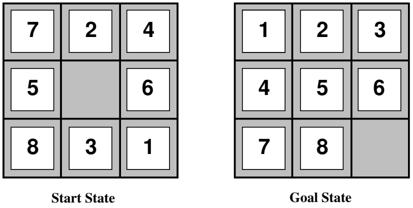
- **States**: Combination of cleaner and dirt locations: $2 \cdot 2^2 = 8$ states.
- **Initial state**: any state.
- **Actions**: `Left`, `Right`, and `Suck`.
- **Transition model**: see next slide.
- **Goal test**: checks whether all locations are clean.
- **Path cost**: Each step costs 1.

Vacuum World: Transition Model



The transition model can be stored as a directed graph, just like the Holiday-in-Romania-Problem. This is possible for all discrete problems.

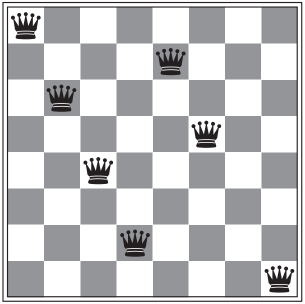
8-Puzzle (Toy Problem II)



Tiles can move to the blank space. How to reach the goal state?

- **States**: Specify the location of each tile and the blank space: $9!/2 = 181440$ states (only half of possible initial states can be moved to the goal state; see Moodle attachment).
- **Initial state**: Any state.
- **Actions**: Movement of the blank space: `Left`, `Right`, `Up`, and `Down`.
- **Transition model**: Huge, but trivial e.g., if `Left` applied to start state: '5' and 'blank' are switched.
- **Goal test**: Checks whether the goal configuration is reached.
- **Path cost**: Each step costs 1.

8-Queens Problem (Toy Problem III)



- Place 8 queens on a chessboard such that no queens attack each other (A queen attacks any piece in the same row, column or diagonal).
- Is the above figure a feasible solution?
- Two formulations:
  - **Incremental formulation**: Start with an empty chessboard and add a queen at a time.
  - **Complete-state formulation**: Start with 8 queens and move them.

8-Queens Problem Description

We try the following **incremental formulation**:

- **States**: Any arrangement of $0 - 8$ queens:
  $64 \cdot 63 \cdot \ldots \cdot 57 \approx 1.8 \cdot 10^{14}$ states.
- **Initial state**: No queens on the board.
- **Actions**: Add a queen to any empty square.
- **Transition model**: Returns the board with a queen added to the specified square.
- **Goal test**: 8 queens on the board, none attacked.
- **Path cost**: Does not apply.

Improvement to reduce complexity: Do not place a queen on a square that is already attacked.

- **States***: Any arrangement of 0-8 queens with no queens attacking each other in the n leftmost columns (now only 2057 states).
- **Actions***: Add a queen to any empty square in the leftmost empty column such that it is not attacked by any other queen.

Examples of Real-World Problems

Not relevant for the exam

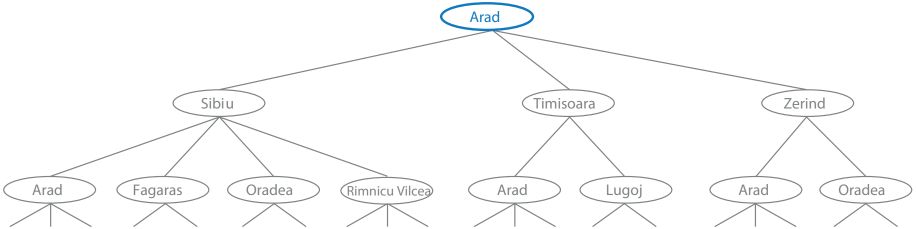
- **Route-Finding problem**: Airline travel planning, video streams in computer networks, etc.
- **Touring problem**: How to best visit a number of places, e.g., in the map of Romania?
- **Layout of digital circuits**: How to best place components and their connections on a circuit board?
- **Robot navigation**: Similar to the route-finding problem, but in a continuous space.
- **Automatic assembly sequencing**: In which order should a product be assembled?
- **Protein design**: What sequence of amino acids will fold into a three-dimensional protein?

Generating a Search Tree (1)

We are searching for an action sequence to a goal state. The possible actions from the initial state form the **search tree**:

- **Root**: Initial state.
- **Branches**: Actions.
- **Nodes**: Reached states.
- **Leaves**: Unexpanded nodes.

A search tree is expanded by applying all possible actions to each parent node. Example:

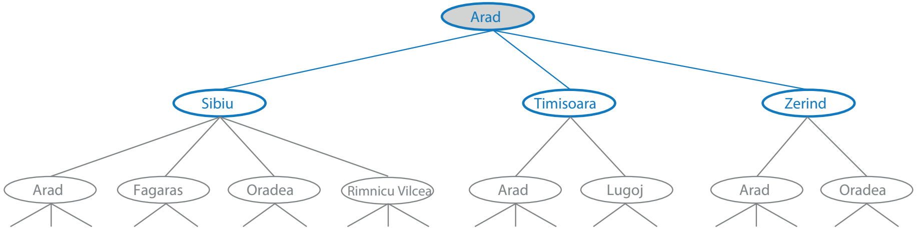


Generating a Search Tree (2)

We are searching for an action sequence to a goal state. The possible actions from the initial state form the **search tree**:

- **Root**: Initial state.
- **Branches**: Actions.
- **Nodes**: Reached states.
- **Leaves**: Unexpanded nodes.

A search tree is expanded by applying all possible actions to each parent node. Example:

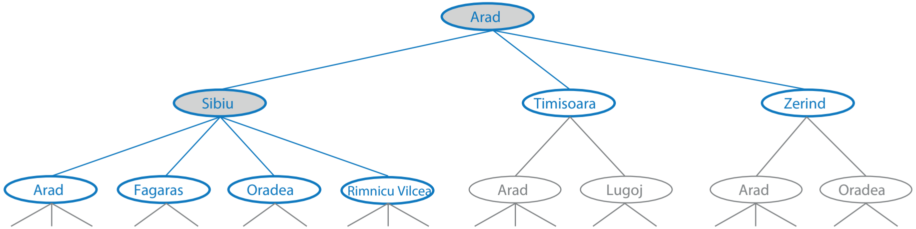


Generating a Search Tree (3)

We are searching for an action sequence to a goal state. The possible actions from the initial state form the **search tree**:

- **Root**: Initial state.
- **Branches**: Actions.
- **Nodes**: Reached states.
- **Leaves**: Unexpanded nodes.

A search tree is expanded by applying all possible actions to each parent node. Example:



Tree Search Algorithm

The basic principle of expanding leaves until a goal is found can be implemented by the subsequent pseudo code.

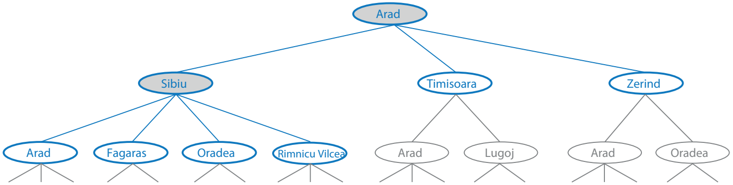
```
function Tree-Search (problem) returns a solution or failure
initialize the frontier using the initial state of problem
loop do
    if the frontier is empty then return failure
    choose a leaf node and remove it from the frontier
    if the node contains a goal state then return the corresponding solution
    expand the chosen node, adding the resulting nodes to the frontier
```

Tweedback Questions

- Does tree search always find a solution if one exists?
- Is the search tree of a finite graph also finite?

Avoiding Loops in the Search Tree

- The set of leaves is now referred to as the **frontier** or **open list**.
- In the previous example, we went back to Arad from Sibiu: Expanding from Arad only contains repetitions of previous possibilities.



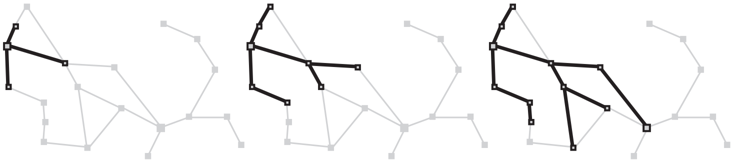
- **Solution**: Only expand nodes that have not been visited before. Visited states are stored in an **explored set** or **closed list**.
- This idea is referred to as graph search (see next slide).

Graph Search Algorithm

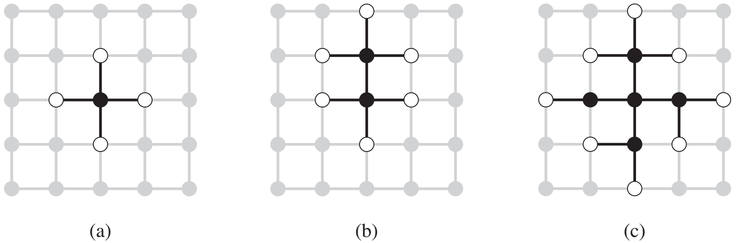
Differences to the tree search are highlighted in orange.

```
function Graph-Search (problem) returns a solution or failure
initialize the frontier using the initial state of problem
initialize the explored set to be empty
loop do
    if the frontier is empty then return failure
    choose a leaf node and remove it from the frontier
    if the node contains a goal state then return the corresponding solution
    add the node to the explored set
    expand the chosen node, adding the resulting nodes to the frontier only if not
                in frontier or explored set
```

Graph Search Algorithm: Illustrations



A sequence of search trees generated by graph search. The northernmost city (Oradea) has become a dead end; this would not have happened with tree search.



The frontier (white nodes) separates the explored nodes (black nodes) from the unexplored ones (gray nodes). Nodes are not expanded to previously visited ones.

Tweedback Questions

- Is it possible that graph search is slower than tree search?
- What is the maximum number of steps required in graph search (according to slide 21)?
  - A The shortest number of edges from the initial state to the goal state.
  - B The number of edges of the graph.
  - C The number of nodes of the graph minus one.

Measuring Problem-Solving Performance

We can evaluate the performance of a search algorithm using the following criteria:

- **Completeness**: Is it guaranteed that the algorithm finds a solution if one exists?
- **Optimality**: Does the strategy find the optimal solution (minimum costs)?
- **Time complexity**: How long does it take to find a solution?
- **Space complexity**: How much memory is needed to perform the search?

Infrastructure for Search Algorithms

Structure of a node `n`

- `n.STATE`: The state in the state space to which the node corresponds;
- `n.PARENT`: The node in the search tree that generated this node;
- `n.ACTION`: The action that was applied to the parent to generate the node;
- `n.PATH-COST`: The cost, traditionally denoted by $g(n)$, of the path from the initial state to the node.

Operations on a queue (list of elements)

- `Empty`(queue): Returns true if queue is empty;
- `Pop`(queue): Removes the first element of the queue and returns it;
- `Insert`(element, queue): Inserts an element and returns the resulting queue.

Uninformed Search vs. Informed Search

Uninformed search

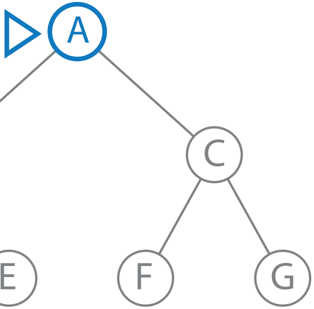
- No additional information besides the problem statement (states, initial state, actions, transition model, goal test) is provided.
- Uninformed search can only produce next states and check whether it is a goal state.

Informed search

- Strategies know whether a state is more promising than another to reach a goal.
- Informed search uses measures to indicate the distance to a goal.

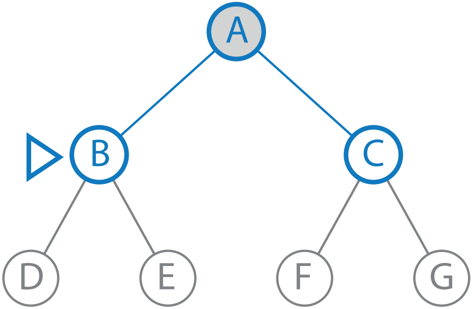
Breadth-First Search: Idea (1)

Special instance of the graph-search algorithm (slide 21): All nodes are expanded at a given depth in the search tree before any nodes at the next level are expanded:



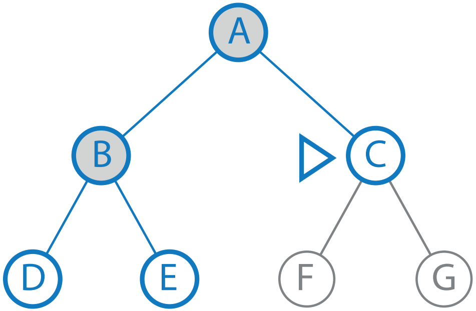
Breadth-First Search: Idea (2)

Special instance of the graph-search algorithm (slide 21): All nodes are expanded at a given depth in the search tree before any nodes at the next level are expanded:



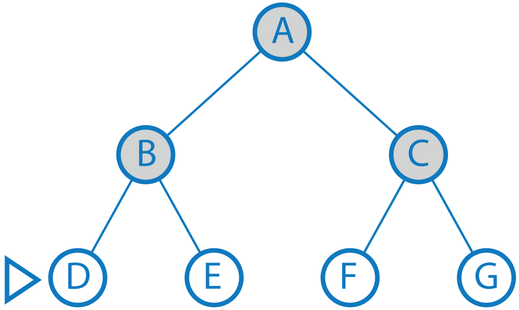
Breadth-First Search: Idea (3)

Special instance of the graph-search algorithm (slide 21): All nodes are expanded at a given depth in the search tree before any nodes at the next level are expanded:



Breadth-First Search: Idea (4)

Special instance of the graph-search algorithm (slide 21): All nodes are expanded at a given depth in the search tree before any nodes at the next level are expanded:



Breadth-First Search: Algorithm (UninformedSearch.ipynb)

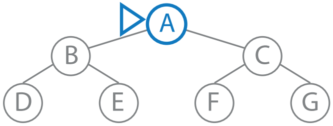
```
function Breadth-First-Search (problem) returns a solution or failure
node ← a node with State = problem.Initial-State, Path-Cost=0
if problem.Goal-Test(node.State) then return Solution(node)
frontier ← a FIFO queue with node as the only element
explored ← an empty set
loop do
    if Empty(frontier) then return failure
    node ← Pop(frontier) /* chooses the shallowest node in frontier*/
    add node.State to explored
    for each action in problem.Actions(node.State) do
        child ← Child-Node(problem, node, action)
        if child.State is neither in explored nor frontier then
            if problem.Goal-Test(child.State) then return Solution(child)
            frontier ← Insert(child,frontier)
```

Auxiliary Algorithm: Child-Node

```
function Child-Node (problem, parent, action) returns a node
return a node with
    State = $problem$.Result($parent$.State, $action$)
    Parent = $parent$
    Action = $action$
    Path-Cost = $parent$.Path-Cost
                    + $problem$.Step-Cost($parent$.State, $action$)
```

Breadth-First Search: Algorithm (Step 1a)

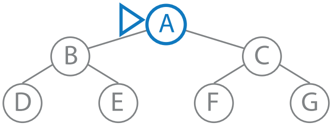
```
function Breadth-First-Search (problem) returns a solution or failure
node ← a node with State = problem.Initial-State, Path-Cost=0
if problem.Goal-Test(node.State) then return Solution(node)
frontier ← a FIFO queue with node as the only element
explored ← an empty set
loop do
    if Empty(frontier) then return failure
    node ← Pop(frontier) /* chooses the shallowest node in frontier*/
    add node.State to explored
    for each action in problem.Actions(node.State) do
        child ← Child-Node(problem, node, action)
        if child.State is neither in explored nor frontier then
            if problem.Goal-Test(child.State) then return Solution(child)
            frontier ← Insert(child,frontier)
```



goal: F
node: A
frontier: A
explored: ∅

Breadth-First Search: Algorithm (Step 1b)

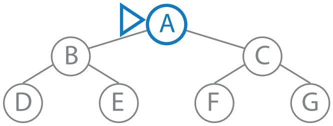
```
function Breadth-First-Search (problem) returns a solution or failure
node ← a node with State = problem.Initial-State, Path-Cost=0
if problem.Goal-Test(node.State) then return Solution(node)
frontier ← a FIFO queue with node as the only element
explored ← an empty set
loop do
    if Empty(frontier) then return failure
    node ← Pop(frontier) /* chooses the shallowest node in frontier*/
    add node.State to explored
    for each action in problem.Actions(node.State) do
        child ← Child-Node(problem, node, action)
        if child.State is neither in explored nor frontier then
            if problem.Goal-Test(child.State) then return Solution(child)
            frontier ← Insert(child,frontier)
```



goal: F
node: A
frontier: ∅
explored: ∅

Breadth-First Search: Algorithm (Step 1c)

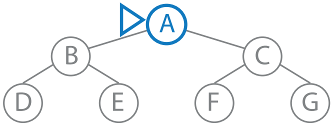
```
function Breadth-First-Search (problem) returns a solution or failure
node ← a node with State = problem.Initial-State, Path-Cost=0
if problem.Goal-Test(node.State) then return Solution(node)
frontier ← a FIFO queue with node as the only element
explored ← an empty set
loop do
    if Empty(frontier) then return failure
    node ← Pop(frontier) /* chooses the shallowest node in frontier*/
    add node.State to explored
    for each action in problem.Actions(node.State) do
        child ← Child-Node(problem, node, action)
        if child.State is neither in explored nor frontier then
            if problem.Goal-Test(child.State) then return Solution(child)
            frontier ← Insert(child,frontier)
```



goal: F
node: A
frontier: ∅
explored: A

Breadth-First Search: Algorithm (Step 1d)

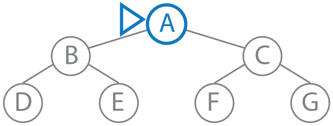
```
function Breadth-First-Search (problem) returns a solution or failure
node ← a node with State = problem.Initial-State, Path-Cost=0
if problem.Goal-Test(node.State) then return Solution(node)
frontier ← a FIFO queue with node as the only element
explored ← an empty set
loop do
    if Empty(frontier) then return failure
    node ← Pop(frontier) /* chooses the shallowest node in frontier*/
    add node.State to explored
    for each action in problem.Actions(node.State) do
        child ← Child-Node(problem, node, action)
        if child.State is neither in explored nor frontier then
            if problem.Goal-Test(child.State) then return Solution(child)
            frontier ← Insert(child,frontier)
```



goal: F
node: A
frontier: B
explored: A

Breadth-First Search: Algorithm (Step 1e)

```
function Breadth-First-Search (problem) returns a solution or failure
node ← a node with State = problem.Initial-State, Path-Cost=0
if problem.Goal-Test(node.State) then return Solution(node)
frontier ← a FIFO queue with node as the only element
explored ← an empty set
loop do
    if Empty(frontier) then return failure
    node ← Pop(frontier) /* chooses the shallowest node in frontier*/
    add node.State to explored
    for each action in problem.Actions(node.State) do
        child ← Child-Node(problem, node, action)
        if child.State is neither in explored nor frontier then
            if problem.Goal-Test(child.State) then return Solution(child)
            frontier ← Insert(child,frontier)
```



goal: F
node: A
frontier: B, C
explored: A

Breadth-First Search: Algorithm (Step 2a)

```
function Breadth-First-Search (problem) returns a solution or failure
node ← a node with State = problem.Initial-State, Path-Cost=0
if problem.Goal-Test(node.State) then return Solution(node)
frontier ← a FIFO queue with node as the only element
explored ← an empty set
loop do
    if Empty(frontier) then return failure
    node ← Pop(frontier) /* chooses the shallowest node in frontier*/
    add node.State to explored
    for each action in problem.Actions(node.State) do
        child ← Child-Node(problem, node, action)
        if child.State is neither in explored nor frontier then
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            frontier ← Insert(child,frontier)
```
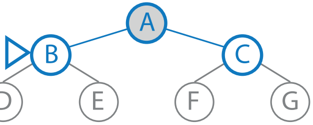
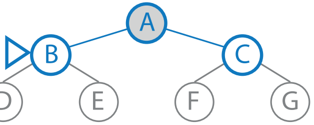



goal: F
node: B
frontier: C
explored: A

Breadth-First Search: Algorithm (Step 2b)

```
function Breadth-First-Search (problem) returns a solution or failure
node ← a node with State = problem.Initial-State, Path-Cost=0
if problem.Goal-Test(node.State) then return Solution(node)
frontier ← a FIFO queue with node as the only element
explored ← an empty set
loop do
    if Empty(frontier) then return failure
    node ← Pop(frontier) /* chooses the shallowest node in frontier*/
    add node.State to explored
    for each action in problem.Actions(node.State) do
        child ← Child-Node(problem, node, action)
        if child.State is neither in explored nor frontier then
            if problem.Goal-Test(child.State) then return Solution(child)
            frontier ← Insert(child,frontier)
```



goal: F
node: B
frontier: C
explored: A, B

Breadth-First Search: Algorithm (Step 2c)

```
function Breadth-First-Search (problem) returns a solution or failure
node ← a node with State = problem.Initial-State, Path-Cost=0
if problem.Goal-Test(node.State) then return Solution(node)
frontier ← a FIFO queue with node as the only element
explored ← an empty set
loop do
    if Empty(frontier) then return failure
    node ← Pop(frontier) /* chooses the shallowest node in frontier*/
    add node.State to explored
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            frontier ← Insert(child,frontier)
```

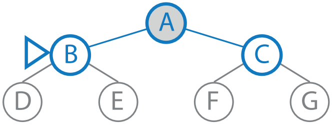

goal: F
node: B
frontier: C, D
explored: A, B

Breadth-First Search: Algorithm (Step 2d)

```
function Breadth-First-Search (problem) returns a solution or failure
node ← a node with State = problem.Initial-State, Path-Cost=0
if problem.Goal-Test(node.State) then return Solution(node)
frontier ← a FIFO queue with node as the only element
explored ← an empty set
loop do
    if Empty(frontier) then return failure
    node ← Pop(frontier) /* chooses the shallowest node in frontier*/
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            frontier ← Insert(child,frontier)
```
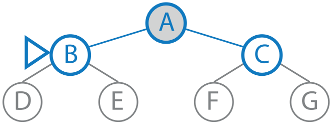
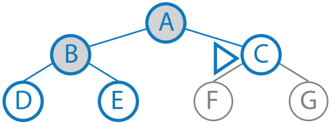



goal: F
node: B
frontier: C, D, E
explored: A, B

Breadth-First Search: Algorithm (Step 3a)

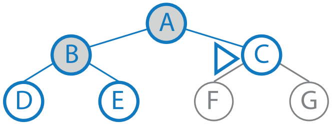
```
function Breadth-First-Search (problem) returns a solution or failure
node ← a node with State = problem.Initial-State, Path-Cost=0
if problem.Goal-Test(node.State) then return Solution(node)
frontier ← a FIFO queue with node as the only element
explored ← an empty set
loop do
    if Empty(frontier) then return failure
    node ← Pop(frontier) /* chooses the shallowest node in frontier*/
    add node.State to explored
    for each action in problem.Actions(node.State) do
        child ← Child-Node(problem, node, action)
        if child.State is neither in explored nor frontier then
            if problem.Goal-Test(child.State) then return Solution(child)
            frontier ← Insert(child,frontier)
```



goal: F
node: C
frontier: D, E
explored: A, B

Breadth-First Search: Algorithm (Step 3b)

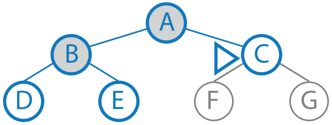
```
function Breadth-First-Search (problem) returns a solution or failure
node ← a node with State = problem.Initial-State, Path-Cost=0
if problem.Goal-Test(node.State) then return Solution(node)
frontier ← a FIFO queue with node as the only element
explored ← an empty set
loop do
    if Empty(frontier) then return failure
    node ← Pop(frontier) /* chooses the shallowest node in frontier*/
    add node.State to explored
    for each action in problem.Actions(node.State) do
        child ← Child-Node(problem, node, action)
        if child.State is neither in explored nor frontier then
            if problem.Goal-Test(child.State) then return Solution(child)
            frontier ← Insert(child,frontier)
```



goal: F
node: C
frontier: D, E
explored: A, B, C

Breadth-First Search: Algorithm (Step 3c)

```
function Breadth-First-Search (problem) returns a solution or failure
node ← a node with State = problem.Initial-State, Path-Cost=0
if problem.Goal-Test(node.State) then return Solution(node)
frontier ← a FIFO queue with node as the only element
explored ← an empty set
loop do
    if Empty(frontier) then return failure
    node ← Pop(frontier) /* chooses the shallowest node in frontier*/
    add node.State to explored
    for each action in problem.Actions(node.State) do
        child ← Child-Node(problem, node, action)
        if child.State is neither in explored nor frontier then
            if problem.Goal-Test(child.State) then return Solution(child)
            frontier ← Insert(child,frontier)
```



goal state F found!
node: C
frontier: D, E
explored: A, B, C

Breadth-First Search: Performance

We introduce

- the branching factor b (maximum number of successors of any node),
- the depth d (depth of the shallowest goal node),
- the maximum length m of any path in the state space,

and use the previously introduced criteria:

- **Completeness**: Yes, if depth d and branching factor b are finite.
- **Optimality**: Yes, if cost is equal per step; not optimal in general.
- **Time complexity**: The worst case is that each node has b successors. The number of explored nodes sums up to

$$b + b^2 + b^3 + \cdots + b^d = \mathcal{O}(b^d)$$

- **Space complexity**: All explored nodes are $\mathcal{O}(b^{d-1})$ and all nodes in the frontier are $\mathcal{O}(b^d)$

Landau Notation aka Big O Notation (for students from other disciplines)

Describes the limiting behavior of a function when the argument tends towards a particular value or infinity. Shall $f(x)$ be the actual function for parameter x, then there exist positive constants M, x_0, such that

$$|f(x)| \leq M|g(x)| \text{ for all } x > x_0.$$

Here, $f(b) = b + b^2 + b^3 + \cdots + b^d$ and $g(b) = b^d$. Possible combinations of M, b_0 for $d = 5$ are:

- $M = 2,\ b_0 = 2,$
- $M = 1.5,\ b_0 = 3,$
- $M = 1.35,\ b_0 = 4.$

Since M, b_0 only have to exist and their concrete values do not matter, we just write $\mathcal{O}(b^d)$.

Tweedback Question

Assume: branching factor is $b = 10$

Up to what depth is a breadth-first-search problem solvable on your laptop?

A $d = 8$

B $d = 16$

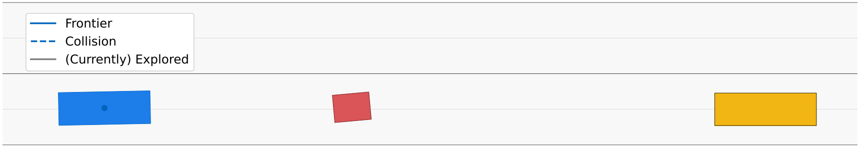
C $d = 32$

Breadth-First Search: Complexity Issue

An exponential complexity, such as $\mathcal{O}(b^d)$, is a big problem. The following table lists example time and memory requirements for a branching factor of $b = 10$ on a modern computer:

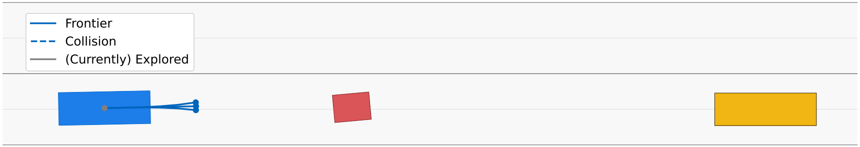
Depth	**Nodes**	**Time**	**Memory**
2	110	0.11 ms	107 kilobytes
4	$11,110$	11 ms	10.6 megabytes
6	10^6	1.1 s	1 gigabyte
8	10^8	2 min	103 gigabytes
10	10^{10}	3 h	10 terabytes
12	10^{12}	13 days	1 petabyte
14	10^{14}	3.5 years	99 petabytes
16	10^{16}	350 years	10 exabytes

Breadth-First Search: CommonRoad Example



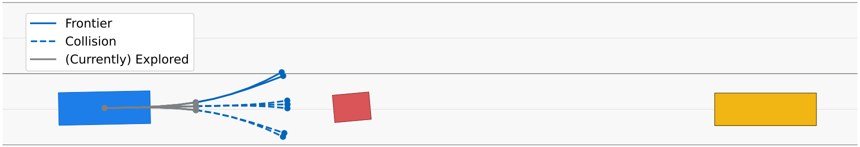
- Concatenation of motion primitives.
- Note: Colliding states are not further considered (collision with obstacle or out of road boundary).
- Link to tutorial: cr_uninformed_search_tutorial.ipynb.

Breadth-First Search: CommonRoad Example



- Concatenation of motion primitives.
- Note: Colliding states are not further considered (collision with obstacle or out of road boundary).
- Link to tutorial: cr_uninformed_search_tutorial.ipynb.

Breadth-First Search: CommonRoad Example



- Concatenation of motion primitives.
- Note: Colliding states are not further considered (collision with obstacle or out of road boundary).
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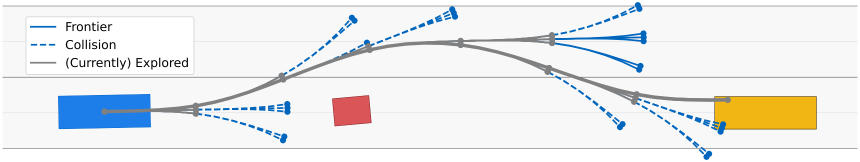
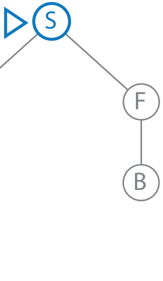
Breadth-First Search: CommonRoad Example

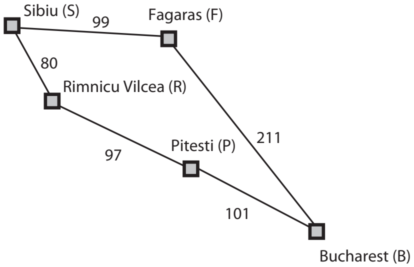


- Concatenation of motion primitives.
- Note: Colliding states are not further considered (collision with obstacle or out of road boundary).
- Link to tutorial: cr_uninformed_search_tutorial.ipynb.

Uniform-Cost Search (aka Dijkstra's algorithm): Idea (1)

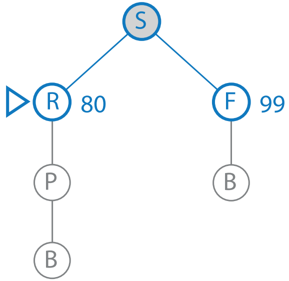
- When all step costs are equal, breadth-first is optimal because it always expands the shallowest nodes.
- Uniform-cost search is optimal for any step costs, as it expands the node with the lowest path cost $g(n)$.
- This is realized by storing the frontier as a priority queue ordered by g.

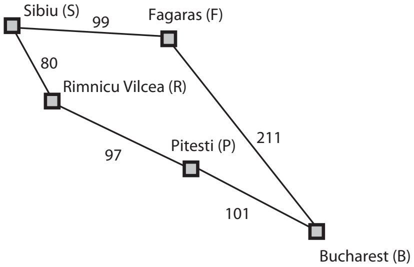




Uniform-Cost Search (aka Dijkstra's algorithm): Idea (2)

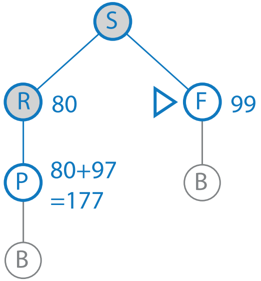
- When all step costs are equal, breadth-first is optimal because it always expands the shallowest nodes.
- Uniform-cost search is optimal for any step costs, as it expands the node with the lowest path cost $g(n)$.
- This is realized by storing the frontier as a priority queue ordered by g

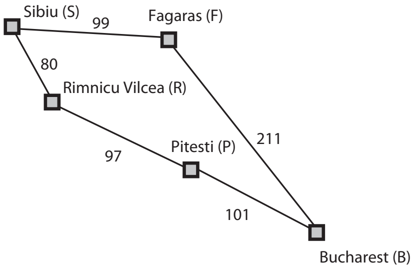




Uniform-Cost Search (aka Dijkstra's algorithm): Idea (3)

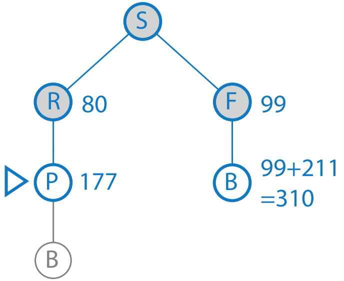
- When all step costs are equal, breadth-first is optimal because it always expands the shallowest nodes.
- Uniform-cost search is optimal for any step costs, as it expands the node with the lowest path cost $g(n)$.
- This is realized by storing the frontier as a priority queue ordered by g

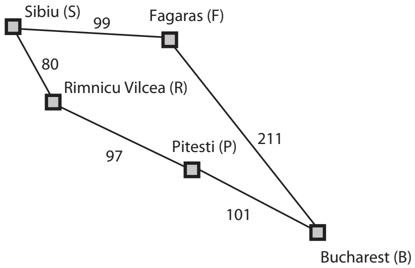




Uniform-Cost Search (aka Dijkstra's algorithm): Idea (4)

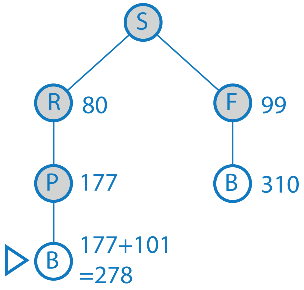
- When all step costs are equal, breadth-first is optimal because it always expands the shallowest nodes.
- Uniform-cost search is optimal for any step costs, as it expands the node with the lowest path cost $g(n)$.
- This is realized by storing the frontier as a priority queue ordered by g

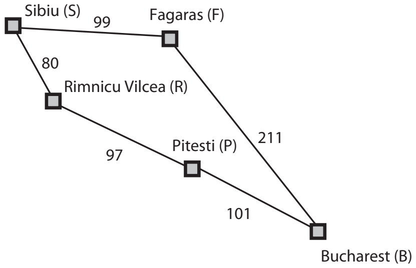




Uniform-Cost Search (aka Dijkstra's algorithm): Idea (5)

- When all step costs are equal, breadth-first is optimal because it always expands the shallowest nodes.
- Uniform-cost search is optimal for any step costs, as it expands the node with the lowest path cost $g(n)$.
- This is realized by storing the frontier as a priority queue ordered by g





Uniform-Cost Search: Changes to Breadth-First Algorithm

- Ordering of the queue according to path costs.
- Goal test is applied to a node when it is selected for expansion rather than when it is first generated. This is because the first generated goal node might be on a suboptimal path.
- A test is added in case a better path to a frontier node is found.

Uniform-Cost Search: Algorithm (UninformedSearch.ipynb)

```
function Uniform-Cost-Search (problem) returns a solution or failure
node ← a node with State = problem.Initial-State, Path-Cost=0
frontier ← a priority queue by Path-Cost with node as the only element
explored ← an empty set
loop do
    if Empty(frontier) then return failure
    node ← Pop(frontier) /* chooses the lowest-cost node in frontier*/
    if problem.Goal-Test(node.State) then return Solution(node)
    add node.State to explored
    for each action in problem.Actions(node.State) do
        child ← Child-Node(problem, node, action)
        if child.State is neither in explored nor frontier then
            frontier ← Insert(child,frontier)
        else if child.State is in frontier with higher Path-Cost then
            replace that frontier node with child
```

Uniform-Cost Search: Algorithm (Step 1a)

```
function Uniform-Cost-Search (problem) returns a solution or failure
node ← a node with State = problem.Initial-State, Path-Cost=0
frontier ← a priority queue by Path-Cost with node as the only element
explored ← an empty set
loop do
    if Empty(frontier) then return failure
    node ← Pop(frontier) /* chooses the lowest-cost node in frontier*/
    if problem.Goal-Test(node.State) then return Solution(node)
    add node.State to explored
    for each action in problem.Actions(node.State) do
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        if child.State is neither in explored nor frontier then
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        else if child.State is in frontier with higher Path-Cost then
            replace that frontier node with child
```
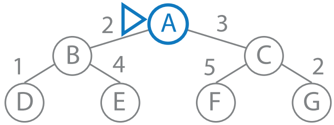
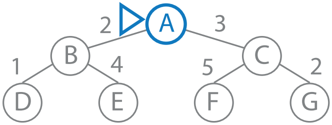



goal: G
node: A
frontier: A
explored: ∅

Uniform-Cost Search: Algorithm (Step 1b)

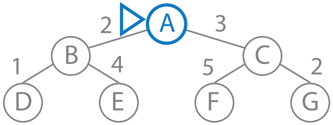
```
function Uniform-Cost-Search (problem) returns a solution or failure
node ← a node with State = problem.Initial-State, Path-Cost=0
frontier ← a priority queue by Path-Cost with node as the only element
explored ← an empty set
loop do
    if Empty(frontier) then return failure
    node ← Pop(frontier) /* chooses the lowest-cost node in frontier*/
    if problem.Goal-Test(node.State) then return Solution(node)
    add node.State to explored
    for each action in problem.Actions(node.State) do
        child ← Child-Node(problem, node, action)
        if child.State is neither in explored nor frontier then
            frontier ← Insert(child,frontier)
        else if child.State is in frontier with higher Path-Cost then
            replace that frontier node with child
```



goal: G
node: A
frontier: ∅
explored: ∅

Uniform-Cost Search: Algorithm (Step 1c)

```
function Uniform-Cost-Search (problem) returns a solution or failure
node ← a node with State = problem.Initial-State, Path-Cost=0
frontier ← a priority queue by Path-Cost with node as the only element
explored ← an empty set
loop do
    if Empty(frontier) then return failure
    node ← Pop(frontier) /* chooses the lowest-cost node in frontier*/
    if problem.Goal-Test(node.State) then return Solution(node)
    add node.State to explored
    for each action in problem.Actions(node.State) do
        child ← Child-Node(problem, node, action)
        if child.State is neither in explored nor frontier then
            frontier ← Insert(child,frontier)
        else if child.State is in frontier with higher Path-Cost then
            replace that frontier node with child
```



goal: G
node: A
frontier: ∅
explored: A

Uniform-Cost Search: Algorithm (Step 1d)

```
function Uniform-Cost-Search (problem) returns a solution or failure
node ← a node with State = problem.Initial-State, Path-Cost=0
frontier ← a priority queue by Path-Cost with node as the only element
explored ← an empty set
loop do
    if Empty(frontier) then return failure
    node ← Pop(frontier) /* chooses the lowest-cost node in frontier*/
    if problem.Goal-Test(node.State) then return Solution(node)
    add node.State to explored
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        if child.State is neither in explored nor frontier then
            frontier ← Insert(child,frontier)
        else if child.State is in frontier with higher Path-Cost then
            replace that frontier node with child
```
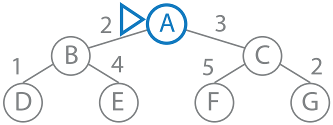
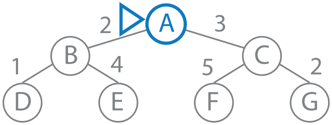



goal: G
node: A
frontier: B
explored: A

Uniform-Cost Search: Algorithm (Step 1e)

```
function Uniform-Cost-Search (problem) returns a solution or failure
node ← a node with State = problem.Initial-State, Path-Cost=0
frontier ← a priority queue by Path-Cost with node as the only element
explored ← an empty set
loop do
    if Empty(frontier) then return failure
    node ← Pop(frontier) /* chooses the lowest-cost node in frontier*/
    if problem.Goal-Test(node.State) then return Solution(node)
    add node.State to explored
    for each action in problem.Actions(node.State) do
        child ← Child-Node(problem, node, action)
        if child.State is neither in explored nor frontier then
            frontier ← Insert(child,frontier)
        else if child.State is in frontier with higher Path-Cost then
            replace that frontier node with child
```



goal: G
node: A
frontier: B, C
explored: A

Uniform-Cost Search: Algorithm (Step 2a)

```
function Uniform-Cost-Search (problem) returns a solution or failure
node ← a node with State = problem.Initial-State, Path-Cost=0
frontier ← a priority queue by Path-Cost with node as the only element
explored ← an empty set
loop do
    if Empty(frontier) then return failure
    node ← Pop(frontier) /* chooses the lowest-cost node in frontier*/
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```

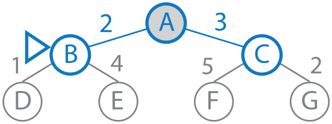

goal: G
node: B
frontier: C
explored: A

Uniform-Cost Search: Algorithm (Step 2b)

```
function Uniform-Cost-Search (problem) returns a solution or failure
node ← a node with State = problem.Initial-State, Path-Cost=0
frontier ← a priority queue by Path-Cost with node as the only element
explored ← an empty set
loop do
    if Empty(frontier) then return failure
    node ← Pop(frontier) /* chooses the lowest-cost node in frontier*/
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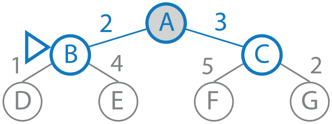

goal: G
node: B
frontier: C
explored: A, B

Uniform-Cost Search: Algorithm (Step 2c)

```
function Uniform-Cost-Search (problem) returns a solution or failure
node ← a node with State = problem.Initial-State, Path-Cost=0
frontier ← a priority queue by Path-Cost with node as the only element
explored ← an empty set
loop do
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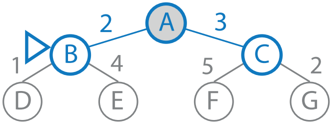

goal: G
node: B
frontier: C, D
explored: A, B

Uniform-Cost Search: Algorithm (Step 2d)

```
function Uniform-Cost-Search (problem) returns a solution or failure
node ← a node with State = problem.Initial-State, Path-Cost=0
frontier ← a priority queue by Path-Cost with node as the only element
explored ← an empty set
loop do
    if Empty(frontier) then return failure
    node ← Pop(frontier) /* chooses the lowest-cost node in frontier*/
    if problem.Goal-Test(node.State) then return Solution(node)
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```

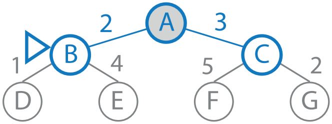

goal: G
node: B
frontier: C, D, E
explored: A, B

Uniform-Cost Search: Algorithm (Step 3a)

```
function Uniform-Cost-Search (problem) returns a solution or failure
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frontier ← a priority queue by Path-Cost with node as the only element
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```
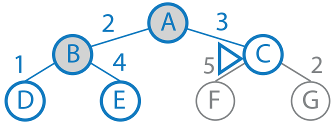
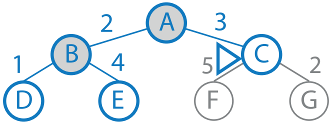



goal: G
node: C
frontier: D, E
explored: A, B

Uniform-Cost Search: Algorithm (Step 3b)

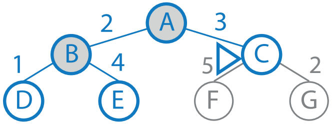
```
function Uniform-Cost-Search (problem) returns a solution or failure
node ← a node with State = problem.Initial-State, Path-Cost=0
frontier ← a priority queue by Path-Cost with node as the only element
explored ← an empty set
loop do
    if Empty(frontier) then return failure
    node ← Pop(frontier) /* chooses the lowest-cost node in frontier*/
    if problem.Goal-Test(node.State) then return Solution(node)
    add node.State to explored
    for each action in problem.Actions(node.State) do
        child ← Child-Node(problem, node, action)
        if child.State is neither in explored nor frontier then
            frontier ← Insert(child,frontier)
        else if child.State is in frontier with higher Path-Cost then
            replace that frontier node with child
```



goal: G
node: C
frontier: D, E
explored: A, B, C

Uniform-Cost Search: Algorithm (Step 3c)

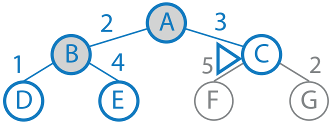
```
function Uniform-Cost-Search (problem) returns a solution or failure
node ← a node with State = problem.Initial-State, Path-Cost=0
frontier ← a priority queue by Path-Cost with node as the only element
explored ← an empty set
loop do
    if Empty(frontier) then return failure
    node ← Pop(frontier) /* chooses the lowest-cost node in frontier*/
    if problem.Goal-Test(node.State) then return Solution(node)
    add node.State to explored
    for each action in problem.Actions(node.State) do
        child ← Child-Node(problem, node, action)
        if child.State is neither in explored nor frontier then
            frontier ← Insert(child,frontier)
        else if child.State is in frontier with higher Path-Cost then
            replace that frontier node with child
```



goal: G
node: C
frontier: D, E, F
explored: A, B, C

Uniform-Cost Search: Algorithm (Step 3d)

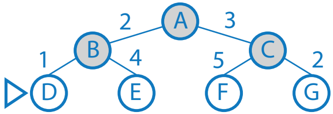
```
function Uniform-Cost-Search (problem) returns a solution or failure
node ← a node with State = problem.Initial-State, Path-Cost=0
frontier ← a priority queue by Path-Cost with node as the only element
explored ← an empty set
loop do
    if Empty(frontier) then return failure
    node ← Pop(frontier) /* chooses the lowest-cost node in frontier*/
    if problem.Goal-Test(node.State) then return Solution(node)
    add node.State to explored
    for each action in problem.Actions(node.State) do
        child ← Child-Node(problem, node, action)
        if child.State is neither in explored nor frontier then
            frontier ← Insert(child,frontier)
        else if child.State is in frontier with higher Path-Cost then
            replace that frontier node with child
```



goal: G
node: C
frontier: D, E, F, G
explored: A, B, C

Uniform-Cost Search: Algorithm (Step 4a)

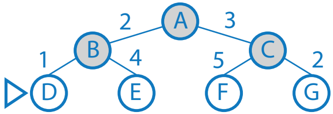
```
function Uniform-Cost-Search (problem) returns a solution or failure
node ← a node with State = problem.Initial-State, Path-Cost=0
frontier ← a priority queue by Path-Cost with node as the only element
explored ← an empty set
loop do
    if Empty(frontier) then return failure
    node ← Pop(frontier) /* chooses the lowest-cost node in frontier*/
    if problem.Goal-Test(node.State) then return Solution(node)
    add node.State to explored
    for each action in problem.Actions(node.State) do
        child ← Child-Node(problem, node, action)
        if child.State is neither in explored nor frontier then
            frontier ← Insert(child,frontier)
        else if child.State is in frontier with higher Path-Cost then
            replace that frontier node with child
```



goal: G
node: D
frontier: G, E, F
explored: A, B, C

Uniform-Cost Search: Algorithm (Step 4b)

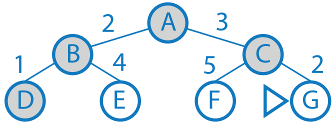
```
function Uniform-Cost-Search (problem) returns a solution or failure
node ← a node with State = problem.Initial-State, Path-Cost=0
frontier ← a priority queue by Path-Cost with node as the only element
explored ← an empty set
loop do
    if Empty(frontier) then return failure
    node ← Pop(frontier) /* chooses the lowest-cost node in frontier*/
    if problem.Goal-Test(node.State) then return Solution(node)
    add node.State to explored
    for each action in problem.Actions(node.State) do
        child ← Child-Node(problem, node, action)
        if child.State is neither in explored nor frontier then
            frontier ← Insert(child,frontier)
        else if child.State is in frontier with higher Path-Cost then
            replace that frontier node with child
```



goal: G
node: D
frontier: G, E, F
explored: A, B, C, D

Uniform-Cost Search: Algorithm (Step 5a)

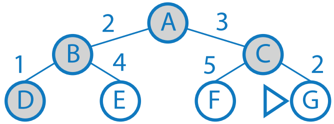
```
function Uniform-Cost-Search (problem) returns a solution or failure
node ← a node with State = problem.Initial-State, Path-Cost=0
frontier ← a priority queue by Path-Cost with node as the only element
explored ← an empty set
loop do
    if Empty(frontier) then return failure
    node ← Pop(frontier) /* chooses the lowest-cost node in frontier*/
    if problem.Goal-Test(node.State) then return Solution(node)
    add node.State to explored
    for each action in problem.Actions(node.State) do
        child ← Child-Node(problem, node, action)
        if child.State is neither in explored nor frontier then
            frontier ← Insert(child,frontier)
        else if child.State is in frontier with higher Path-Cost then
            replace that frontier node with child
```



goal: G
node: G
frontier: E, F
explored: A, B, C, D

Uniform-Cost Search: Algorithm (Step 5b)

```
function Uniform-Cost-Search (problem) returns a solution or failure
node ← a node with State = problem.Initial-State, Path-Cost=0
frontier ← a priority queue by Path-Cost with node as the only element
explored ← an empty set
loop do
    if Empty(frontier) then return failure
    node ← Pop(frontier) /* chooses the lowest-cost node in frontier*/
    if problem.Goal-Test(node.State) then return Solution(node)
    add node.State to explored
    for each action in problem.Actions(node.State) do
        child ← Child-Node(problem, node, action)
        if child.State is neither in explored nor frontier then
            frontier ← Insert(child,frontier)
        else if child.State is in frontier with higher Path-Cost then
            replace that frontier node with child
```



goal state G found!
node: G
frontier: E, F
explored: A, B, C, D

Uniform-Cost Search: Performance

We introduce

- the cost C^* of the optimal solution,
- the minimum step-cost ϵ,

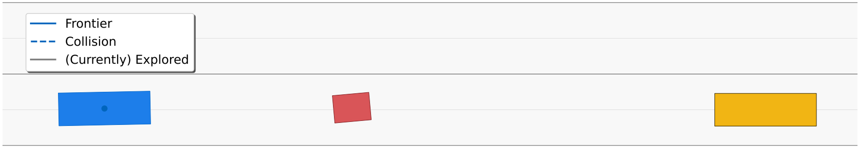
and use the previously introduced criteria:

- **Completeness**: Yes, if costs are greater than 0 (otherwise infinite optimal paths of zero cost exist).
- **Optimality**: Yes (if cost $\geq \epsilon$ for positive ϵ).
- **Time complexity**: The worst case is that the goal branches of a node with huge costs and all other step costs are ϵ. The number of explored nodes (for e.g. $d = 1$) sums up to

  $$(b-1) + (b-1)b + (b-1)b^2 + \cdots + (b-1)b^{\lfloor C^*/\epsilon \rfloor} = \mathcal{O}(b^{1+\lfloor C^*/\epsilon \rfloor}),$$

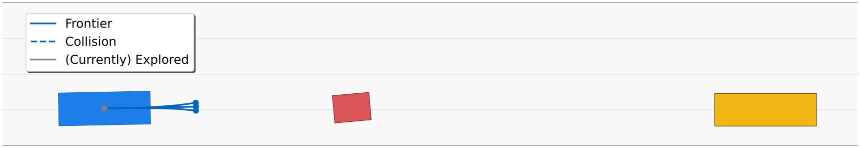
  where $\lfloor a \rfloor$ returns the next lower integer of a. We require '+1' since the goal test is performed after the expansion.
- **Space complexity**: Equals time complexity since all nodes are stored.

Uniform-Cost Search: CommonRoad Example



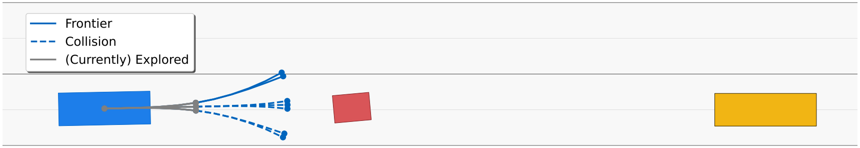
- Concatenation of motion primitives.
- Note: Colliding states are not further considered (collision with obstacle or out of road boundary).
- $g(n)$: Time to reach current state.
- Link to tutorial: cr_uninformed_search_tutorial.ipynb.

Uniform-Cost Search: CommonRoad Example



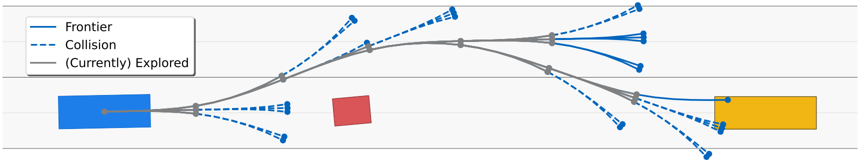
- Concatenation of motion primitives.
- Note: Colliding states are not further considered (collision with obstacle or out of road boundary).
- $g(n)$: Time to reach current state.
- Link to tutorial: cr_uninformed_search_tutorial.ipynb.

Uniform-Cost Search: CommonRoad Example



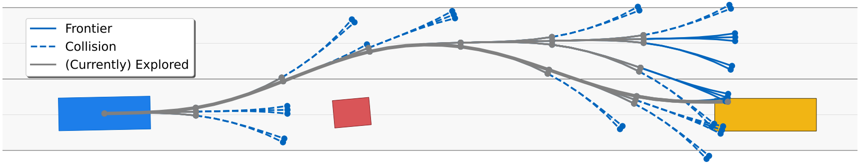
- Concatenation of motion primitives.
- Note: Colliding states are not further considered (collision with obstacle or out of road boundary).
- $g(n)$: Time to reach current state.
- Link to tutorial: cr_uninformed_search_tutorial.ipynb.

Uniform-Cost Search: CommonRoad Example



- Concatenation of motion primitives.
- Note: Colliding states are not further considered (collision with obstacle or out of road boundary).
- $g(n)$: Time to reach current state.
- Link to tutorial: cr_uninformed_search_tutorial.ipynb.

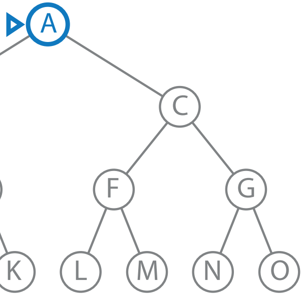
Uniform-Cost Search: CommonRoad Example



- Concatenation of motion primitives.
- Note: Colliding states are not further considered (collision with obstacle or out of road boundary).
- $g(n)$: Time to reach current state.
- Link to tutorial: cr_uninformed_search_tutorial.ipynb.

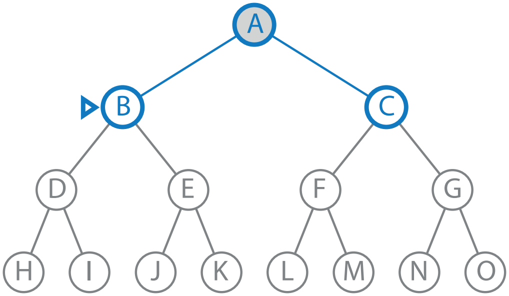
Depth-First Search: Idea (1) (UninformedSearch.ipynb)

The deepest node in the current frontier of the search tree is expanded:



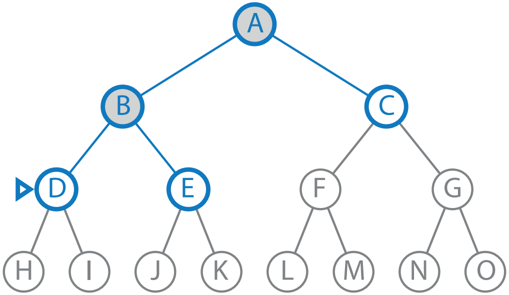
Depth-First Search: Idea (2)

The deepest node in the current frontier of the search tree is expanded:



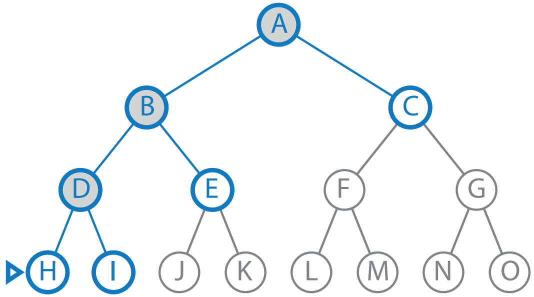
Depth-First Search: Idea (3)

The deepest node in the current frontier of the search tree is expanded:



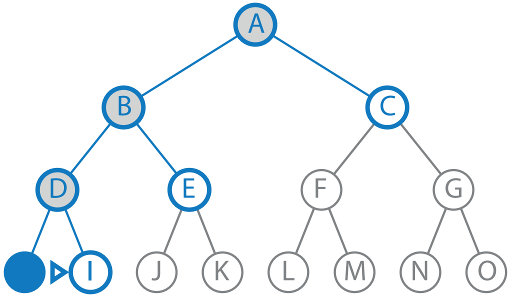
Depth-First Search: Idea (4)

The deepest node in the current frontier of the search tree is expanded:



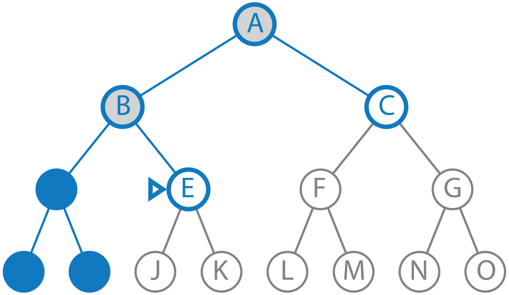
Depth-First Search: Idea (5)

The deepest node in the current frontier of the search tree is expanded:



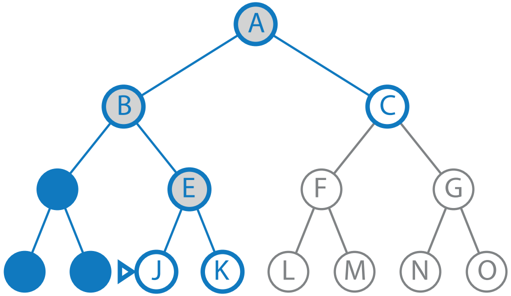
Depth-First Search: Idea (6)

The deepest node in the current frontier of the search tree is expanded:



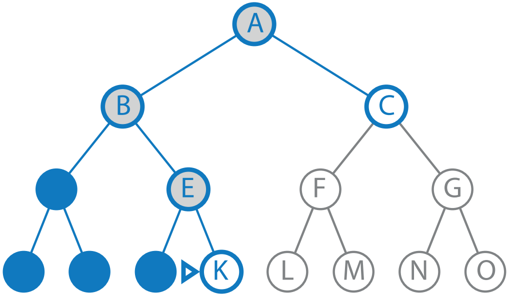
Depth-First Search: Idea (7)

The deepest node in the current frontier of the search tree is expanded:



Depth-First Search: Idea (8)

The deepest node in the current frontier of the search tree is expanded:

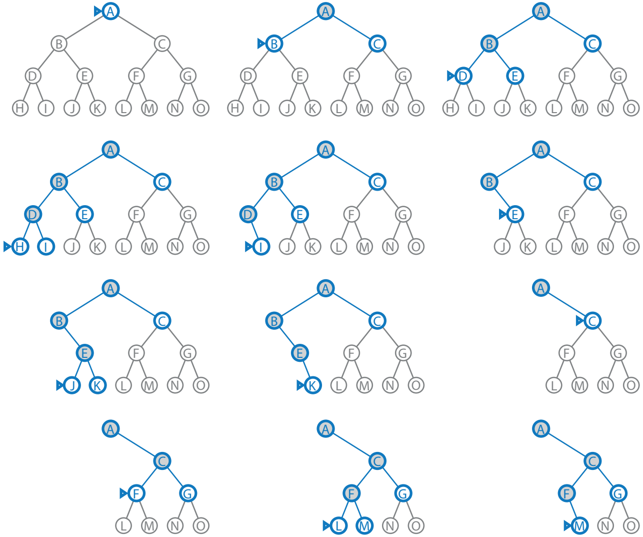


Depth-First Search: Performance

Reminder: Branching factor b, depth d, maximum length m of any path.

- **Completeness**: No, if recursively implemented (see later); Yes if repeated states are avoided and the state space is finite.
- **Optimality**: No. Why?
- **Time complexity**: The worst case is that the goal path is tested last, resulting in $\mathcal{O}(b^m)$.
  Reminder: Breadth-first has $\mathcal{O}(b^d)$ and $d \leq m$.
- **Space complexity**: The advantage of depth-first when recursively implemented is a good space complexity: One only needs to store a single path from the root to the leaf plus unexplored sibling nodes (see next slide). There are at most m nodes to a leaf and b nodes branching off from each node, resulting in $\mathcal{O}(bm)$ nodes.

Space Requirement for Depth-First Search



Example:
$b = 10$, $d = m = 16$:
breadth-first: 10 exabytes
depth-first: 156 kilobytes

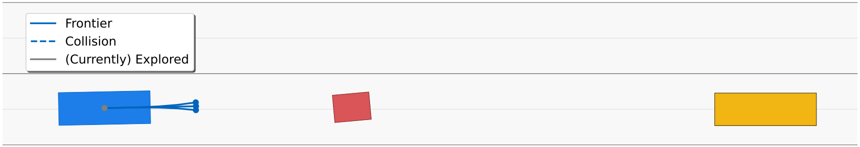
better by a factor of
$\approx 7 \cdot 10^{13}$

Depth-First Search: CommonRoad Example

Frontier
Collision
(Currently) Explored

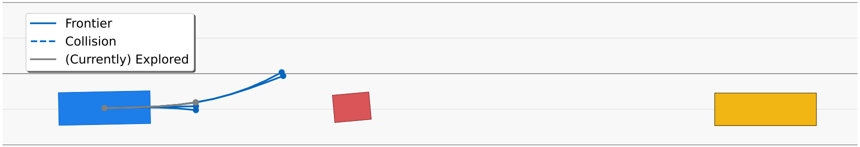
- Concatenation of motion primitives.
- Note: Colliding states are not further considered (collision with obstacle or out of road boundary).
- Link to tutorial: cr_uninformed_search_tutorial.ipynb.

Depth-First Search: CommonRoad Example



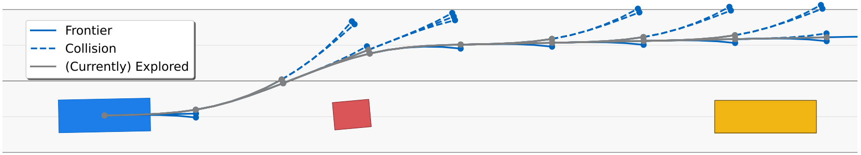
- Concatenation of motion primitives.
- Note: Colliding states are not further considered (collision with obstacle or out of road boundary).
- Link to tutorial: cr_uninformed_search_tutorial.ipynb.

Depth-First Search: CommonRoad Example



- Concatenation of motion primitives.
- Note: Colliding states are not further considered (collision with obstacle or out of road boundary).
- Link to tutorial: cr_uninformed_search_tutorial.ipynb.

Depth-First Search: CommonRoad Example



- Concatenation of motion primitives.
- Note: Colliding states are not further considered (collision with obstacle or out of road boundary).
- Link to tutorial: cr_uninformed_search_tutorial.ipynb.

Depth-Limited Search: Idea

Shortcoming in depth-first search:
Depth-first search does not terminate in infinite state spaces. Why?

Solution:
Introduce depth limit l.

New issue:
How to choose the depth-limit?

Comment:
The algorithm on the next slide can also be used for depth-first by removing the limit.

Depth-Limited Search: Algorithm (UninformedSearch.ipynb)

Several implementations exist; we use a recursive form.

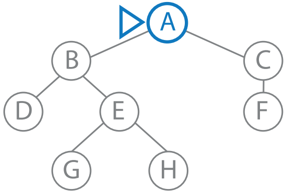
```
function Depth-Limited-S. (problem,limit) returns a solution or failure/cutoff
return Recursive-DLS(Make-Node(problem.Initial-State),problem, limit)
```

```
function Recursive-DLS (node,problem,limit) returns a solution or failure/cutoff
if problem.Goal-Test(node.State) then return Solution(node)
else if limit $= 0$ then return cutoff
else
    cutoff_occurred $\leftarrow$ false
    for each action in problem.Actions(node.State) do
        child $\leftarrow$ Child-Node(problem, node, action)
        result $\leftarrow$ Recursive-DLS(child, problem, limit - 1)
        if result $=$ cutoff then cutoff_occurred $\leftarrow$ true
        else if result $\neq$ failure then return result
    if cutoff_occurred then return cutoff else return failure
```

Depth-Limited Search: Algorithm (Step 1)

function Recursive-DLS (node,problem,limit) **returns** a solution or failure/cutoff

```
if problem.Goal-Test(node.State) then return Solution(node)
else if limit= 0 then return cutoff
else
    cutoff_occurred ← false
    for each action in problem.Actions(node.State) do
        child ← Child-Node(problem, node, action)
        result ← Recursive-DLS(child, problem, limit - 1)
        if result = cutoff then cutoff_occurred ← true
        else if result ≠ failure then return result
    if cutoff_occurred then return cutoff else return failure
```

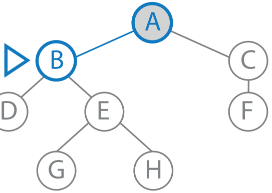


goal: F
limit: 2
current path: A
node: A
child: B
result: to be computed

Depth-Limited Search: Algorithm (Step 2)

function Recursive-DLS (node,problem,limit) **returns** a solution or failure/cutoff

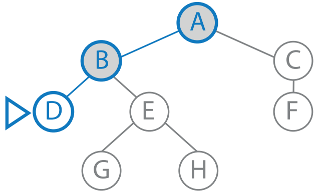
```
if problem.Goal-Test(node.State) then return Solution(node)
else if limit= 0 then return cutoff
else
    cutoff_occurred ← false
    for each action in problem.Actions(node.State) do
        child ← Child-Node(problem, node, action)
        result ← Recursive-DLS(child, problem, limit - 1)
        if result = cutoff then cutoff_occurred ← true
        else if result ≠ failure then return result
    if cutoff_occurred then return cutoff else return failure
```



goal: F
limit: 1
current path: A, B
node: B
child: D
result: to be computed

Depth-Limited Search: Algorithm (Step 3)

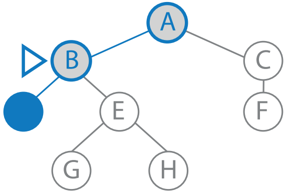
```
function Recursive-DLS (node,problem,limit) returns a solution or failure/cutoff
if problem.Goal-Test(node.State) then return Solution(node)
else if limit = 0 then return cutoff
else
    cutoff_occurred ← false
    for each action in problem.Actions(node.State) do
        child ← Child-Node(problem, node, action)
        result ← Recursive-DLS(child, problem, limit - 1)
        if result = cutoff then cutoff_occurred ← true
        else if result ≠ failure then return result
    if cutoff_occurred then return cutoff else return failure
```



goal: F
limit: 0
current path: A, B, D
node: D
child: -
return: cutoff

Depth-Limited Search: Algorithm (Step 4a)

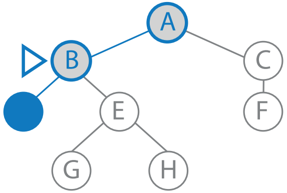
```
function Recursive-DLS (node,problem,limit) returns a solution or failure/cutoff
if problem.Goal-Test(node.State) then return Solution(node)
else if limit = 0 then return cutoff
else
    cutoff_occurred ← false
    for each action in problem.Actions(node.State) do
        child ← Child-Node(problem, node, action)
        result ← Recursive-DLS(child, problem, limit - 1)
        if result = cutoff then cutoff_occurred ← true
        else if result ≠ failure then return result
    if cutoff_occurred then return cutoff else return failure
```



goal: F
limit: 1
current path: A, B
node: B
child: D
result: cutoff

Depth-Limited Search: Algorithm (Step 4b)

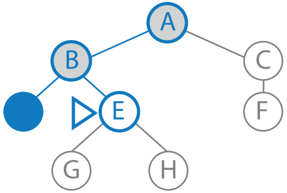
```
function Recursive-DLS (node,problem,limit) returns a solution or failure/cutoff
if problem.Goal-Test(node.State) then return Solution(node)
else if limit= 0 then return cutoff
else
    cutoff_occurred ← false
    for each action in problem.Actions(node.State) do
        child ← Child-Node(problem, node, action)
        result ← Recursive-DLS(child, problem, limit - 1)
        if result = cutoff then cutoff_occurred ← true
        else if result ≠ failure then return result
    if cutoff_occurred then return cutoff else return failure
```



goal: F
limit: 1
current path: A, B
node: B
child: E
result: to be computed

Depth-Limited Search: Algorithm (Step 5)

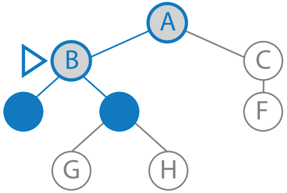
```
function Recursive-DLS (node,problem,limit) returns a solution or failure/cutoff
if problem.Goal-Test(node.State) then return Solution(node)
else if limit= 0 then return cutoff
else
    cutoff_occurred ← false
    for each action in problem.Actions(node.State) do
        child ← Child-Node(problem, node, action)
        result ← Recursive-DLS(child, problem, limit - 1)
        if result = cutoff then cutoff_occurred ← true
        else if result ≠ failure then return result
    if cutoff_occurred then return cutoff else return failure
```



goal: F
limit: 0
current path: A, B, E
node: E
child: -
return: cutoff

Depth-Limited Search: Algorithm (Step 6a)

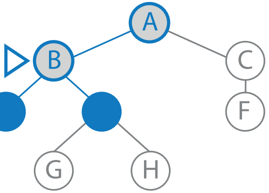
```
function Recursive-DLS (node,problem,limit) returns a solution or failure/cutoff
if problem.Goal-Test(node.State) then return Solution(node)
else if limit= 0 then return cutoff
else
    cutoff_occurred ← false
    for each action in problem.Actions(node.State) do
        child ← Child-Node(problem, node, action)
        result ← Recursive-DLS(child, problem, limit - 1)
        if result = cutoff then cutoff_occurred ← true
        else if result ≠ failure then return result
    if cutoff_occurred then return cutoff else return failure
```



goal: F
limit: 1
current path: A, B
node: B
child: E
result: cutoff

Depth-Limited Search: Algorithm (Step 6b)

```
function Recursive-DLS (node,problem,limit) returns a solution or failure/cutoff
if problem.Goal-Test(node.State) then return Solution(node)
else if limit= 0 then return cutoff
else
    cutoff_occurred ← false
    for each action in problem.Actions(node.State) do
        child ← Child-Node(problem, node, action)
        result ← Recursive-DLS(child, problem, limit - 1)
        if result = cutoff then cutoff_occurred ← true
        else if result ≠ failure then return result
    if cutoff_occurred then return cutoff else return failure
```

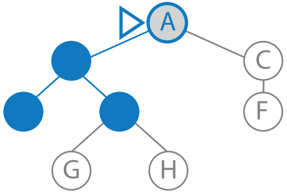


goal: F
limit: 1
current path: A, B
node: B
child: E
return: cutoff

Depth-Limited Search: Algorithm (Step 7)

function Recursive-DLS (node,problem,limit) **returns** a solution or failure/cutoff

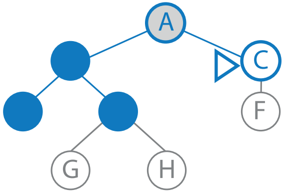
```
if problem.Goal-Test(node.State) then return Solution(node)
else if limit= 0 then return cutoff
else
    cutoff_occurred ← false
    for each action in problem.Actions(node.State) do
        child ← Child-Node(problem, node, action)
        result ← Recursive-DLS(child, problem, limit - 1)
        if result = cutoff then cutoff_occurred ← true
        else if result ≠ failure then return result
    if cutoff_occurred then return cutoff else return failure
```



goal: F
limit: 2
current path: A
node: A
child: C
return: to be computed

Depth-Limited Search: Algorithm (Step 8)

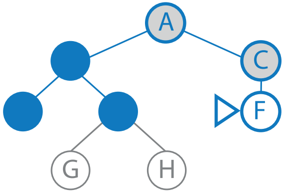
```
function Recursive-DLS (node,problem,limit) returns a solution or failure/cutoff
if problem.Goal-Test(node.State) then return Solution(node)
else if limit= 0 then return cutoff
else
    cutoff_occurred ← false
    for each action in problem.Actions(node.State) do
        child ← Child-Node(problem, node, action)
        result ← Recursive-DLS(child, problem, limit - 1)
        if result = cutoff then cutoff_occurred ← true
        else if result ≠ failure then return result
    if cutoff_occurred then return cutoff else return failure
```



goal: F
limit: 1
current path: A, C
node: C
child: F
return: to be computed

Depth-Limited Search: Algorithm (Step 9)

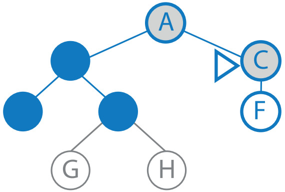
```
function Recursive-DLS (node,problem,limit) returns a solution or failure/cutoff
if problem.Goal-Test(node.State) then return Solution(node)
else if limit= 0 then return cutoff
else
    cutoff_occurred ← false
    for each action in problem.Actions(node.State) do
        child ← Child-Node(problem, node, action)
        result ← Recursive-DLS(child, problem, limit - 1)
        if result = cutoff then cutoff_occurred ← true
        else if result ≠ failure then return result
    if cutoff_occurred then return cutoff else return failure
```



goal: F
limit: 0
current path: A, C, F
node: F
child: -
return: F

Depth-Limited Search: Algorithm (Step 10)

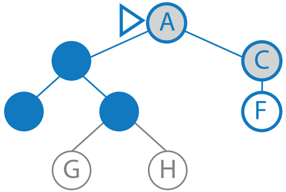
```
function Recursive-DLS (node,problem,limit) returns a solution or failure/cutoff
if problem.Goal-Test(node.State) then return Solution(node)
else if limit= 0 then return cutoff
else
    cutoff_occurred ← false
    for each action in problem.Actions(node.State) do
        child ← Child-Node(problem, node, action)
        result ← Recursive-DLS(child, problem, limit - 1)
        if result = cutoff then cutoff_occurred ← true
        else if result ≠ failure then return result
    if cutoff_occurred then return cutoff else return failure
```



goal: F
limit: 1
found path: A, C, F
node: C
child: F
return: F

Depth-Limited Search: Algorithm (Step 11)

```
function Recursive-DLS (node,problem,limit) returns a solution or failure/cutoff
if problem.Goal-Test(node.State) then return Solution(node)
else if limit = 0 then return cutoff
else
    cutoff_occurred ← false
    for each action in problem.Actions(node.State) do
        child ← Child-Node(problem, node, action)
        result ← Recursive-DLS(child, problem, limit - 1)
        if result = cutoff then cutoff_occurred ← true
        else if result ≠ failure then return result
    if cutoff_occurred then return cutoff else return failure
```

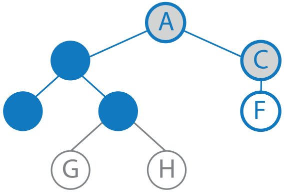


goal: F
limit: 2
found path: A, C, F
node: A
child: C
return: F

Depth-Limited Search: Algorithm (Step 12)

function Depth-Limited-S. (problem,limit) **returns** a solution or failure/cutoff

```
return Recursive-DLS(Make-Node(problem.Initial-State),problem, limit)
```



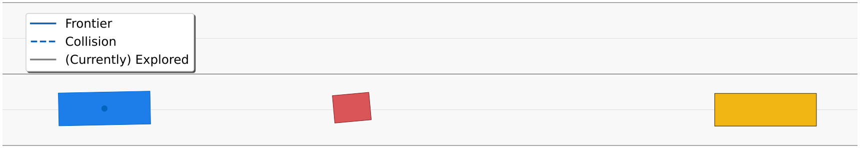
goal: F
limit: 2
return: F

Depth-Limited Search: Performance

Reminder: Branching factor b, depth d, maximum length m of any path, and depth limit l.

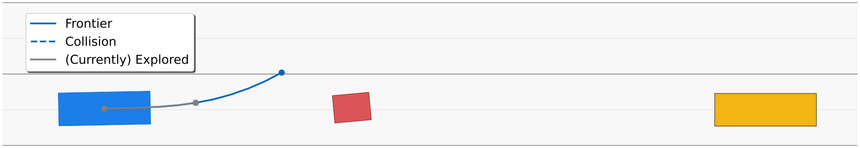
- **Completeness**: No, if $l < d$. Why?
- **Optimality**: No, if $l > d$. Why?
- **Time complexity**: Same as for depth-first search, but with l instead of m: $\mathcal{O}(b^l)$.
- **Space complexity**: Same as for depth-first search, but with l instead of m: $\mathcal{O}(bl)$.

Depth-Limited Search: CommonRoad Example



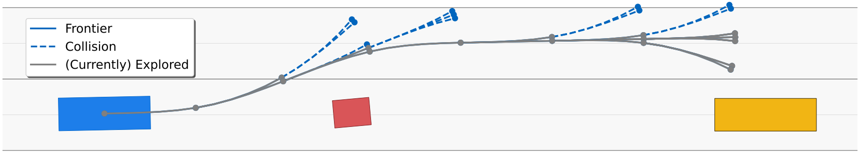
- Concatenation of motion primitives.
- Note: Colliding states are not further considered (collision with obstacle or out of road boundary).
- Depth limit: 7
- Link to tutorial: cr_uninformed_search_tutorial.ipynb.

Depth-Limited Search: CommonRoad Example



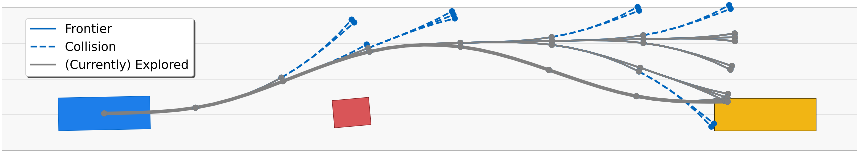
- Concatenation of motion primitives.
- Note: Colliding states are not further considered (collision with obstacle or out of road boundary).
- Depth limit: 7
- Link to tutorial: cr_uninformed_search_tutorial.ipynb.

Depth-Limited Search: CommonRoad Example



- Concatenation of motion primitives.
- Note: Colliding states are not further considered (collision with obstacle or out of road boundary).
- Depth limit: 7
- Link to tutorial: cr_uninformed_search_tutorial.ipynb.

Depth-Limited Search: CommonRoad Example



- Concatenation of motion primitives.
- Note: Colliding states are not further considered (collision with obstacle or out of road boundary).
- Depth limit: 7
- Link to tutorial: cr_uninformed_search_tutorial.ipynb.

Iterative Deepening Search: Idea and Algorithm

Shortcoming in depth-limited search:
One typically does not know the depth d of the goal state.

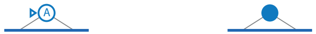
Solution:
Use depth-limited search and iteratively increase the depth limit l.

```
function Iterative-Deepening-Search (problem) returns a solution or failure
for depth= 0 to $\infty$ do
    result $\leftarrow$ Depth-Limited-Search(problem, depth)
    if result $\neq$ cutoff then return result
```

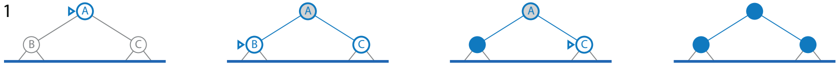
Iterative Deepening Search: Example (1)

(UninformedSearch.ipynb)

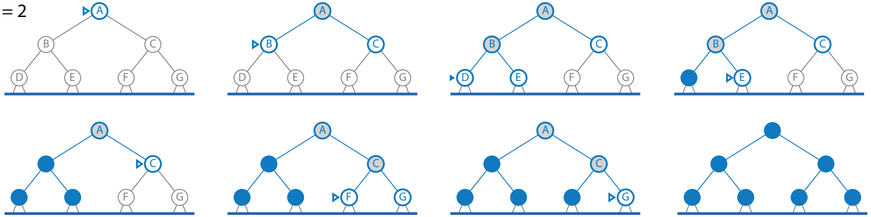
Limit = 0



Limit = 1

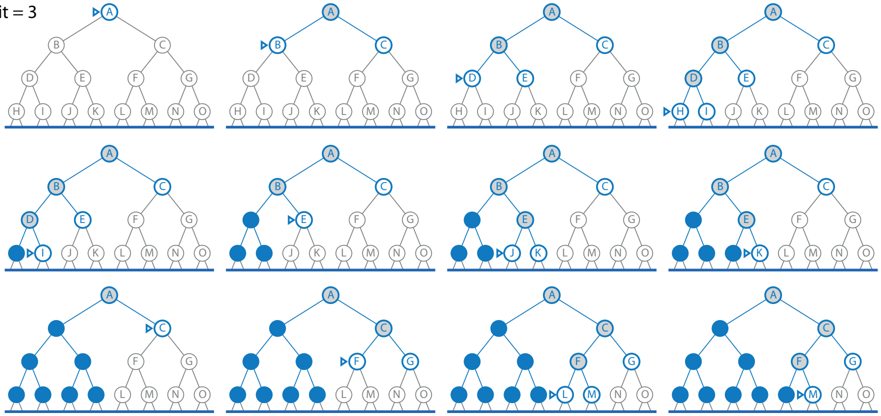


Limit = 2



Iterative Deepening Search: Example (2)

Limit = 3



Iterative Deepening Search: Performance

Reminder: Branching factor b, depth d, maximum length m of any path, and depth limit l.

- **Completeness**: Yes, if depth d of the goal state is finite.
- **Optimality**: Yes (if cost $= 1$ per step); not optimal in general.
- **Time complexity**: The nodes at the bottom level are generated once, those on the next-to-bottom level are generated twice, and so on, up to the children of the root, which are generated d times:

  $$(d)b + (d-1)b^2 + \ldots + (1)b^d = \mathcal{O}(b^d)$$

  which equals the one of breadth-first search.
- **Space complexity**: Same as for depth-first search, but with d instead of m: $\mathcal{O}(bd)$. Why?

Comparison of Computational Effort

The intuition that the iterative deepening search requires a lot of time is wrong. The search within the highest level is dominating.

Example:
$b = 10$, $d = 5$, solution at far right leaf:

- **Breadth-first search**:

$$\begin{aligned} & b + b^2 + b^3 + \cdots + b^d \\ =& 10 + 100 + 1000 + 10,000 + 100,000 = 111,110 \end{aligned}$$

- **Iterative deepening search**:

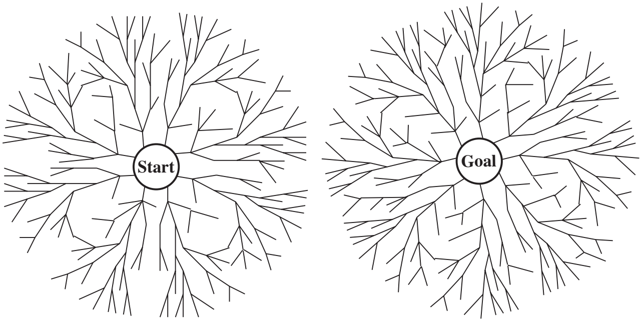
$$\begin{aligned} & (d)b + (d-1)b^2 + \ldots + (1)b^d \\ =& 5 \cdot 10 + 4 \cdot 100 + 3 \cdot 1000 + 2 \cdot 10,000 + 100,000 = 123,450 \end{aligned}$$

The difference is almost negligible and becomes relatively smaller, the larger the problem is.

Bidirectional Search: Idea

The main idea is to run two searches: One from the initial state and one backward from the goal, hoping that both searches meet in the middle.

Motivation:
$b^{\frac{d}{2}} + b^{\frac{d}{2}} < b^d$. This is also visualized in the figure, where the area from both search trees together is smaller than from one tree reaching the goal:



Tweedback Question

Is it always possible to use bidirectional search?

Bidirectional Search: Comments

Bidirectional search requires one to “search backwards”.

- **Easy:** When all actions are reversible and there is only one goal, e.g., 8-puzzle, or finding a route in Romania
- **Difficult:** When the goal is an abstract description and there exist many goal states,
  e.g., 8-queens: “No queen attacks another queen”. What are the goal states? This would already be the solution...

Comparing Uninformed Search Strategies

Criterion	**Breadth-First**	**Uniform-Cost**	**Depth-First**	**Depth-Limited**	**Iterative Deepening**
Complete?	Yes[a]	Yes[a,b]	No	Yes, if $l \geq d$	Yes[a]
Optimal?	Yes[c]	Yes	No	No	Yes[c]
Time	$\mathcal{O}(b^d)$	$\mathcal{O}(b^{1+\lfloor C^*/\epsilon \rfloor})$	$\mathcal{O}(b^m)$	$\mathcal{O}(b^l)$	$\mathcal{O}(b^d)$
Space	$\mathcal{O}(b^d)$	$\mathcal{O}(b^{1+\lfloor C^*/\epsilon \rfloor})$	$\mathcal{O}(bm)$	$\mathcal{O}(bl)$	$\mathcal{O}(bd)$

a: complete if b is finite

b: complete if step costs $\geq \epsilon$ for positive ϵ

c: optimal if all step costs are identical

Summary

- A well-defined search problem consists of: the **initial state**, **actions**, a **transition model**, a **goal test** function, and a **path cost** function.
- Search algorithms are typically judged by **completeness**, **optimality**, **time complexity**, and **space complexity**.
- **Breadth-first search**: expands the shallowest nodes first; it is complete, optimal for unit step costs, but has exponential space complexity.
- **Uniform-cost search**: expands the node with the lowest path cost and is optimal for general step costs.
- **Depth-first search** and **Depth-limited search**: expands the deepest unexpended node first. It is neither complete nor optimal, but has linear space complexity.
- **Iterative deepening search**: calls depth-first search with increasing depth limits. It is complete, optimal for unit step costs, has time complexity like breadth-first search and linear space complexity.
- **Bidirectional search**: can enormously reduce time complexity, but is not always applicable.