CS 480

Introduction to Artificial Intelligence

February 1, 2022

Announcements / Reminders

- **Please follow the Week 03 TO DO List**
- **Quiz #01: due on Sunday (02/06) at 11:00 PM CST**
- **Written Assignment #1 will be posted within a week**
- **Programming Assignment #1 will be posted within 1.5 - 2 weeks**
- **Exam dates (consider fixed):**
  - **Midterm: February 24, 2022 during lecture time**
  - **Final: April 28, 2022 during lecture time**

Plan for Today

- **Problem Solving: Searching**
  - **Uninformed search: continued**
  - **Informed search**
    - **Hill Climbing algorithm**
    - **Greedy Best First algorithm**
    - **A* algorithm**

Designing the Searching Problem

Analyze and define the Problem / Task

Model and buid the State Space

Select searching algorithm

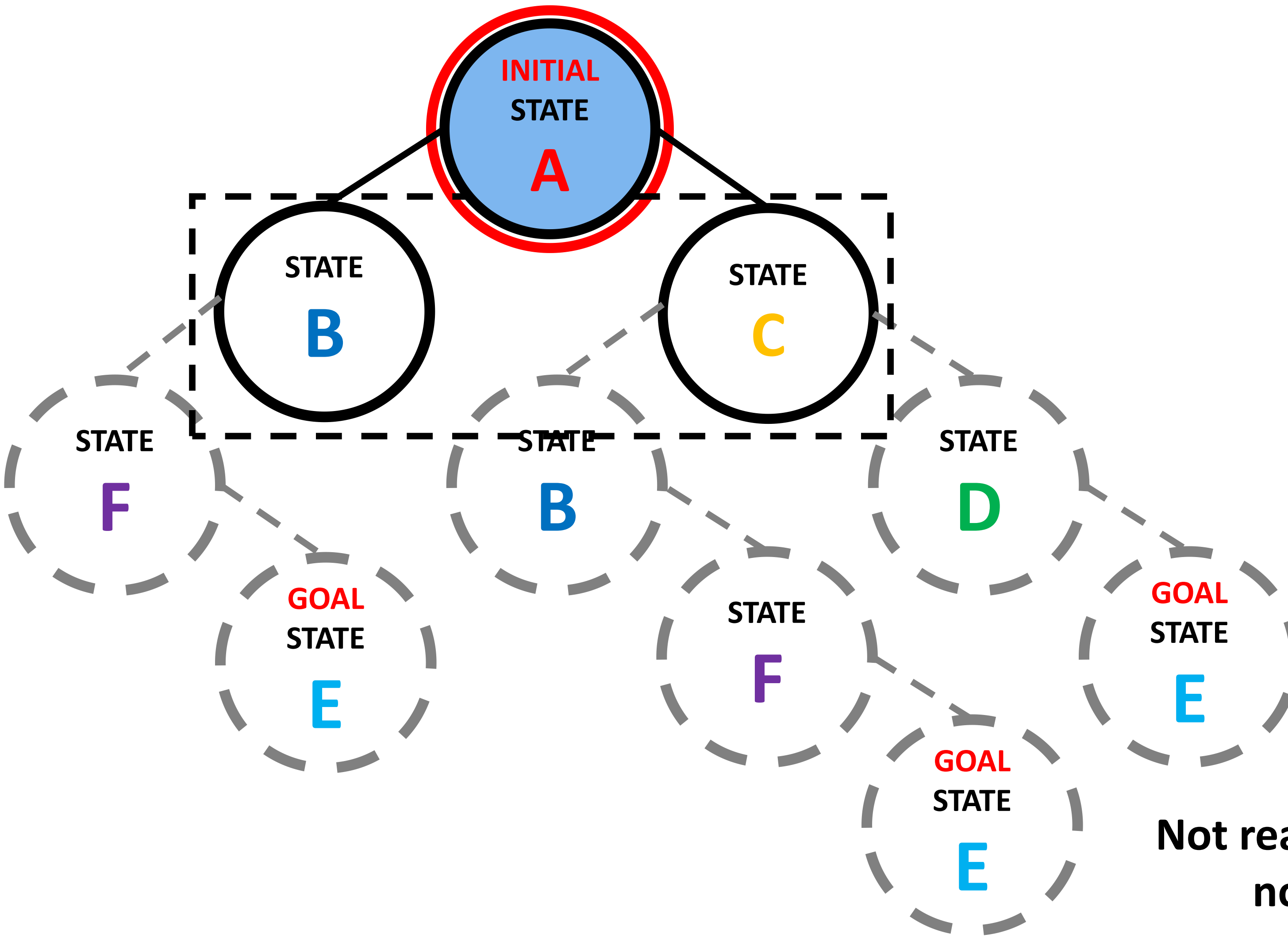
Search

Selected Searching Algorithms

- Searching Algorithms
  - **Uninformed** Search
    - Breadth First Search
    - Depth First Search
    - Brute Force Search
    - Uniform Cost Search
  - **Informed** Search
    - Best First Search
    - Branch and Bound
    - A* Algorithm
    - Hill Climbing Algorithm
    - Constraint Satisfaction Search
    - α - β Pruning
    - Min-Max Search

Uninformed search: an agent <u>has no estimate</u> how far it is from the goal
Informed search: an agent <u>can estimate</u> how far it is from the goal

Expansion: Which Node to Expand?



Not reached yet nodes

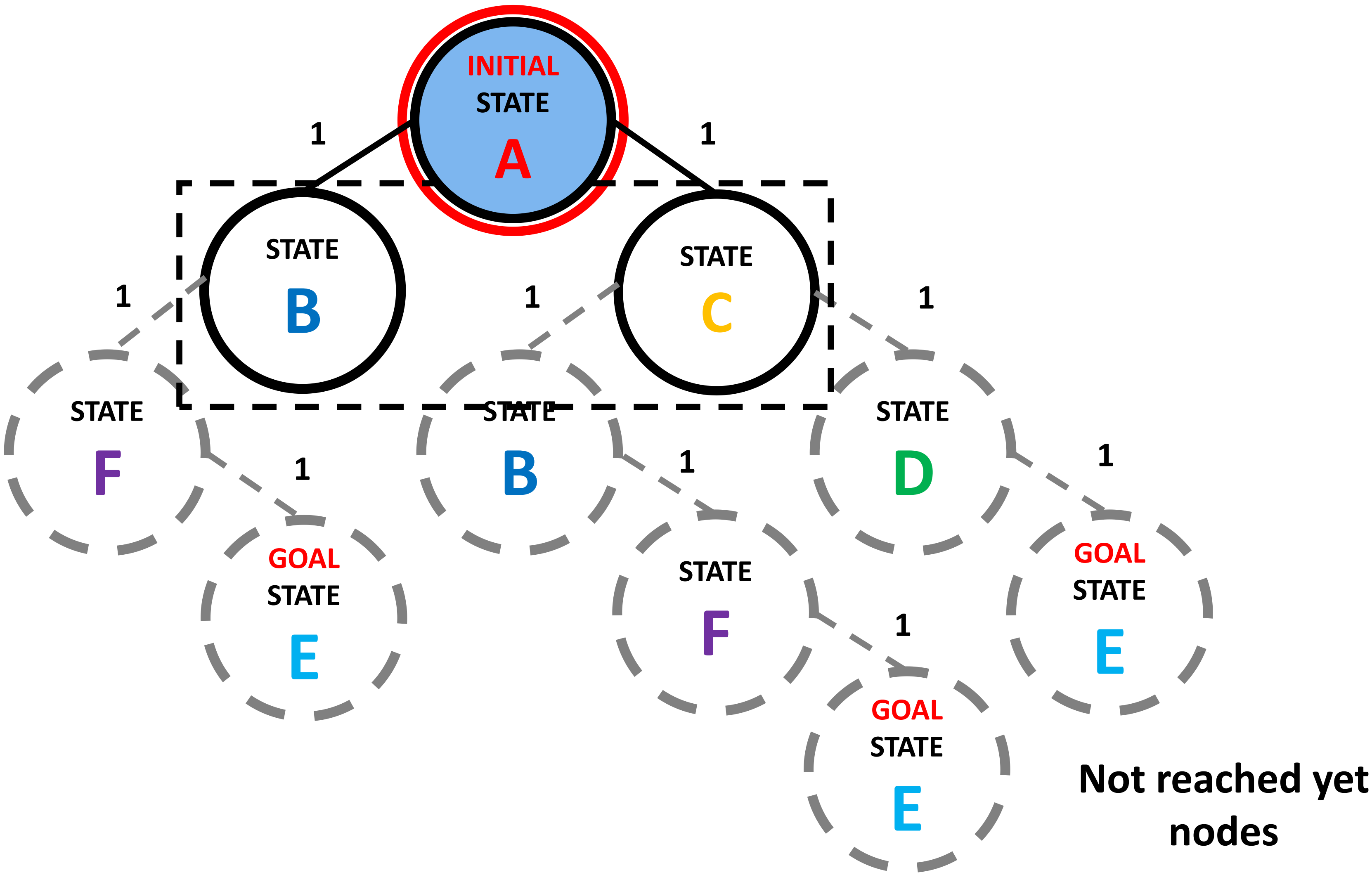
Evaluation function

Calculate / obtain:

f(n) = f(State n)
f(n) = f(relevant information about State n)

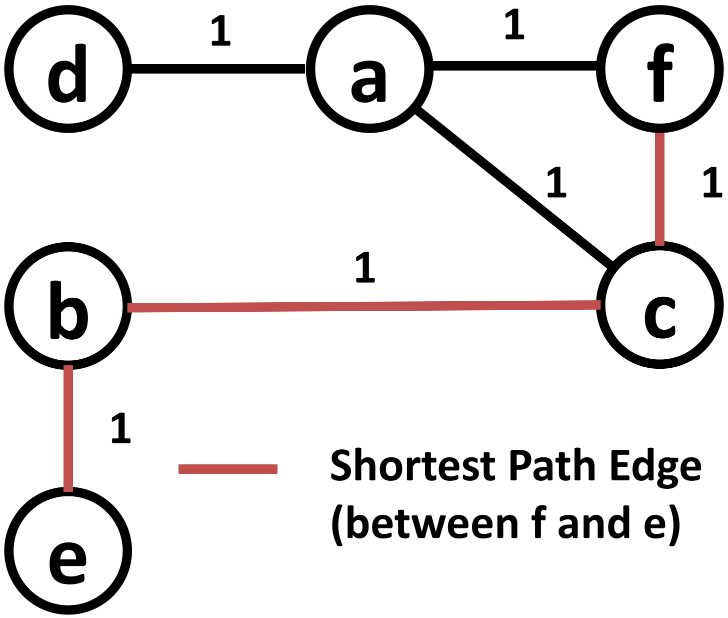
A state n with minimum f(n) should be chosen for expansion
What about ties?

Search Tree: Uniform Action Cost



Uniform Cost Search | Dijkstra's Algo

Weighted Graph G



Popular algorithms:

- **Dijkstra's algorithm**

Shortest Path Problem

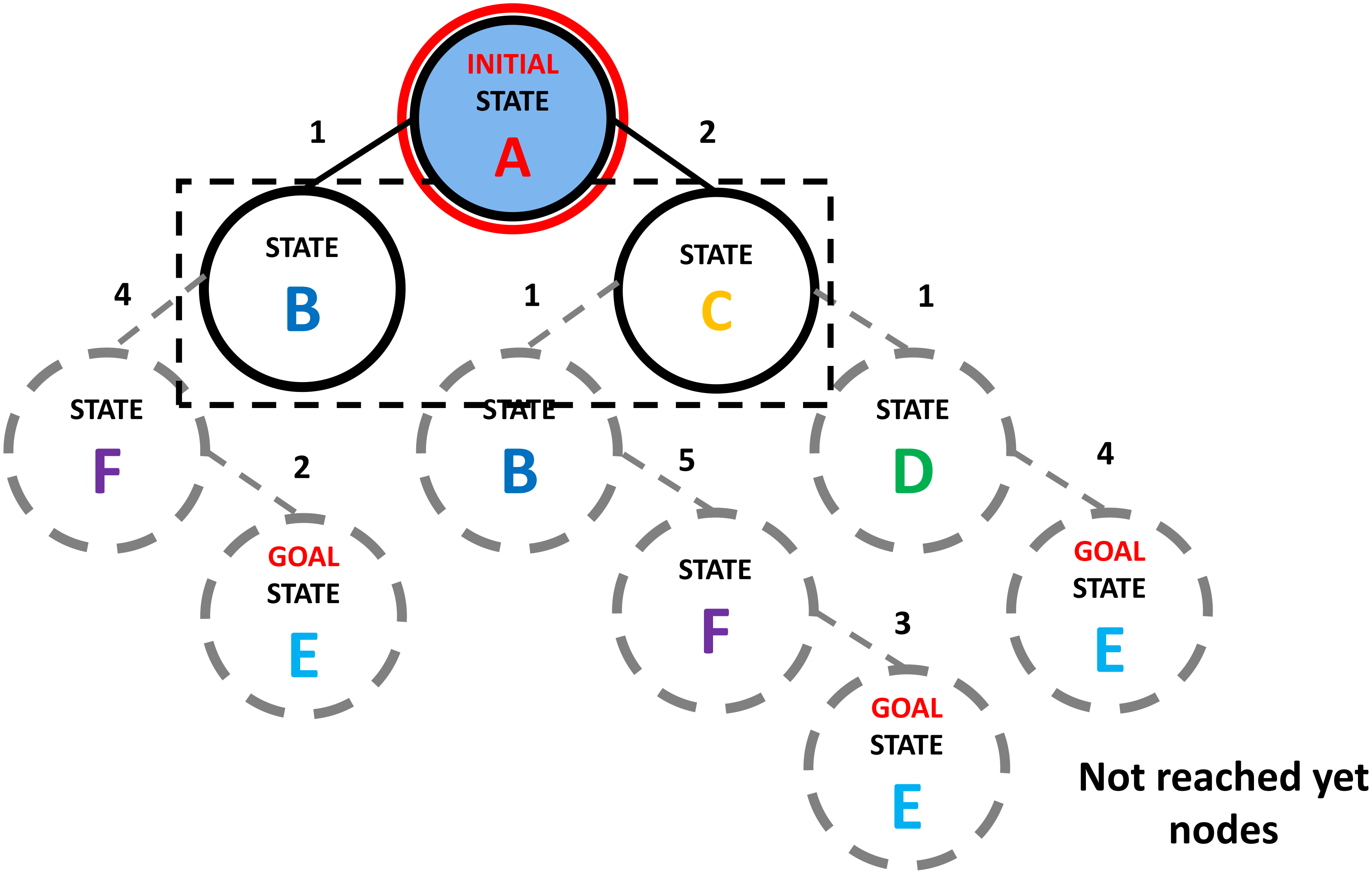
Shortest path problem:
Given a weighted graph $G(V, E, w)$ and two vertices a, b in V, find the shortest path between vertices a and b (**all edge weights are equal**).

BFS and UCS: Pseudocode

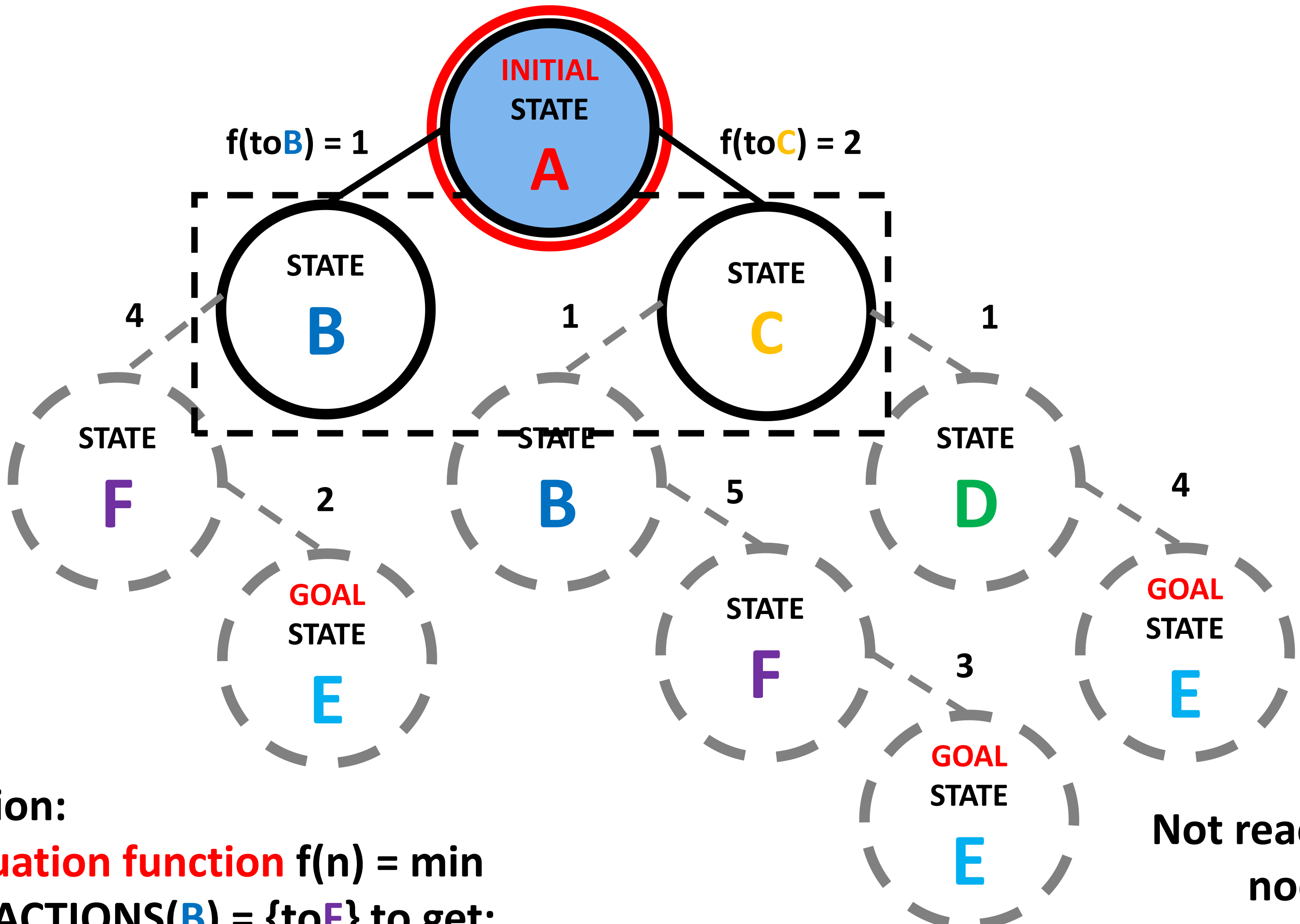
```
function BREADTH-FIRST-SEARCH(problem) returns a solution node or failure
  node ← NODE(problem.INITIAL)
  if problem.IS-GOAL(node.STATE) then return node
  frontier ← a FIFO queue, with node as an element
  reached ← {problem.INITIAL}
  while not IS-EMPTY(frontier) do
    node ← POP(frontier)
    for each child in EXPAND(problem, node) do
      s ← child.STATE
      if problem.IS-GOAL(s) then return child
      if s is not in reached then
        add s to reached
        add child to frontier
  return failure

function UNIFORM-COST-SEARCH(problem) returns a solution node, or failure
  return BEST-FIRST-SEARCH(problem, PATH-COST)
```

Search Tree: Variable Action Cost



Search Tree: Variable Action Cost

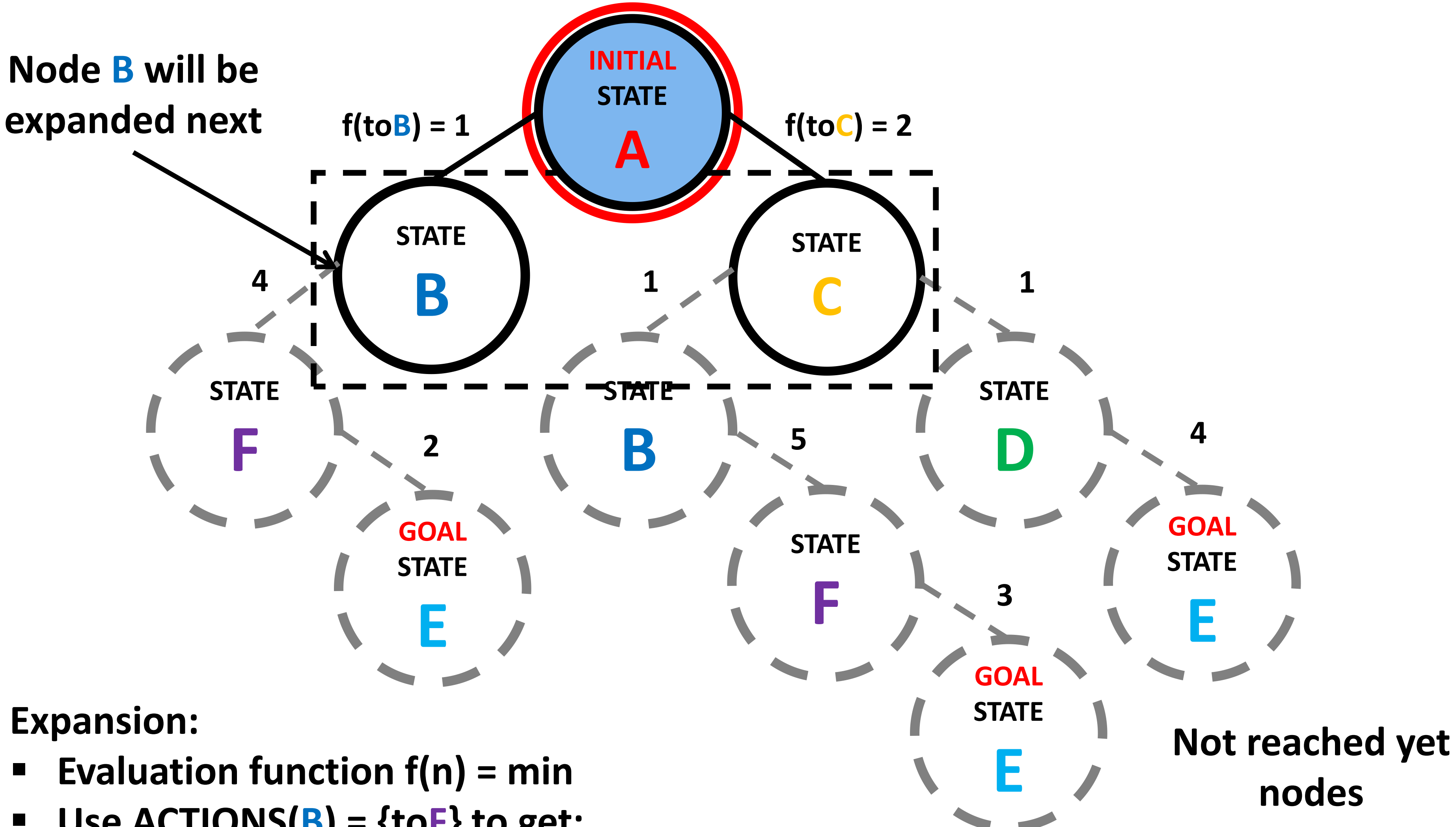


Expansion:

- Evaluation function f(n) = min
- Use ACTIONS(B) = {toF} to get:
- RESULT(B, toF) = F

Not reached yet nodes

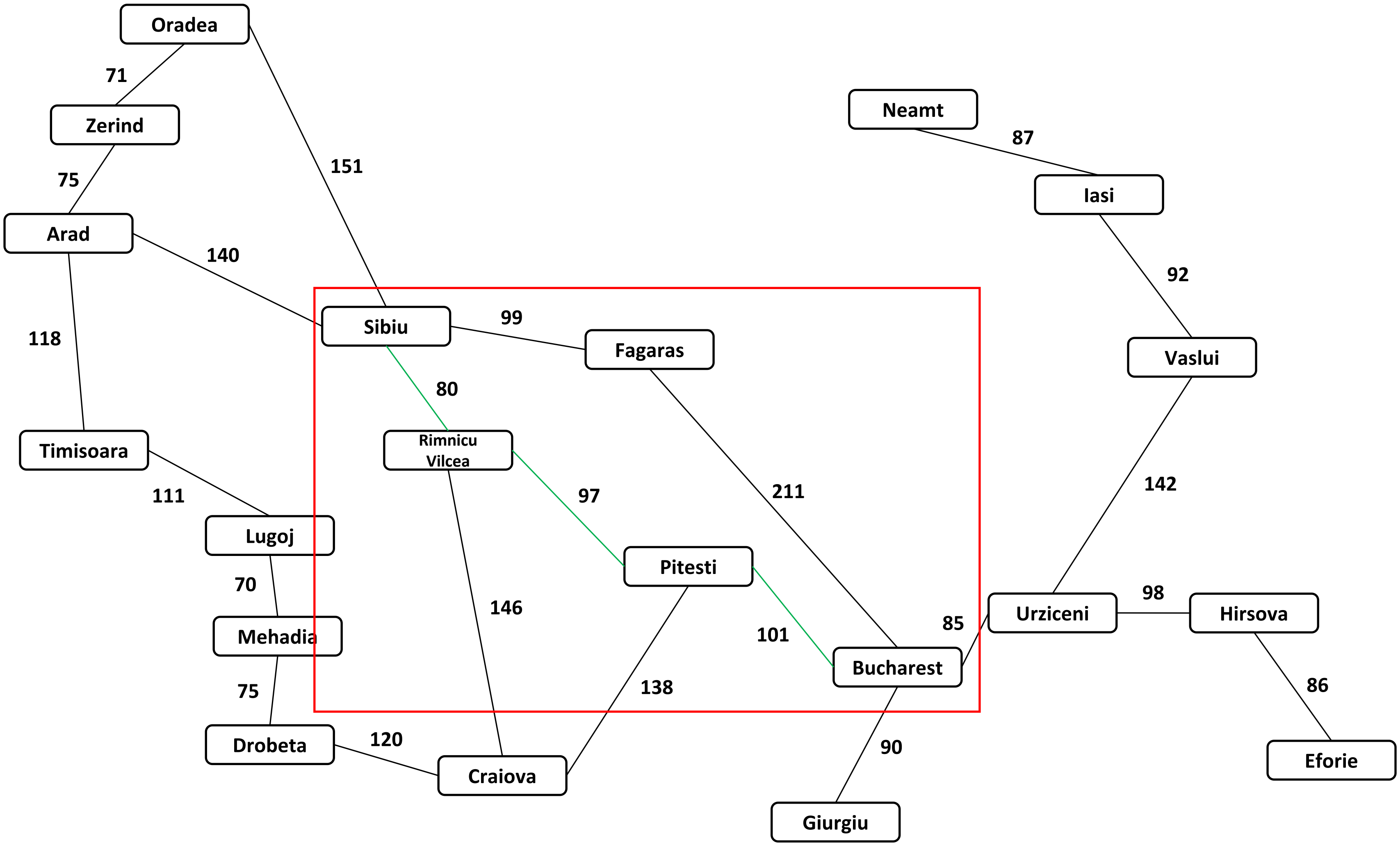
Search Tree: “Take Best First”



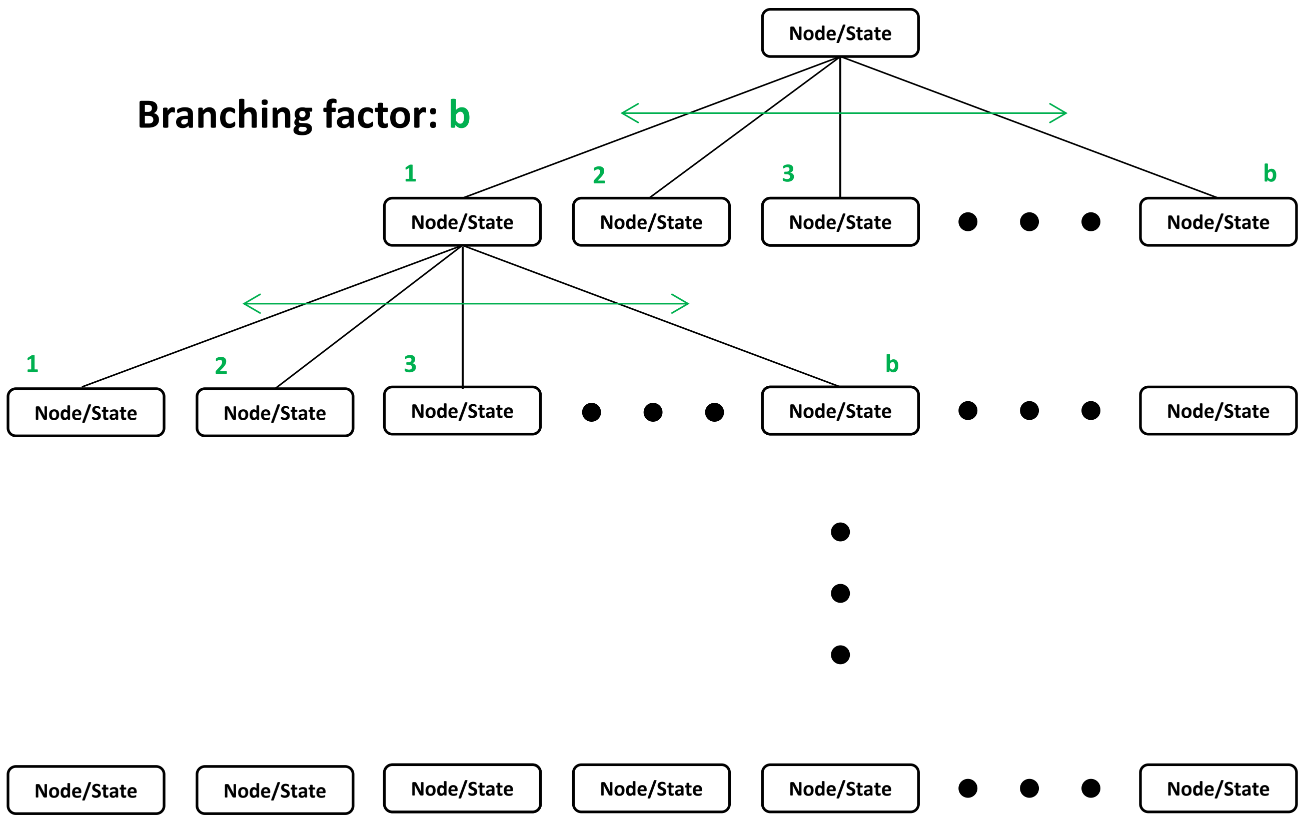
Expansion:

- Evaluation function f(n) = min
- Use ACTIONS(B) = {toF} to get:
- RESULT(B, toF) = F

“Take Best First” Search: Issue



Let’s Go Back to Depth First Search



Depth: 0 | $N_0 = 1$

Depth: 1 | $N_1 = b$

Depth: 2 | $N_2 = b^2$

•
•
•

Depth: d | $N_d = b^d$

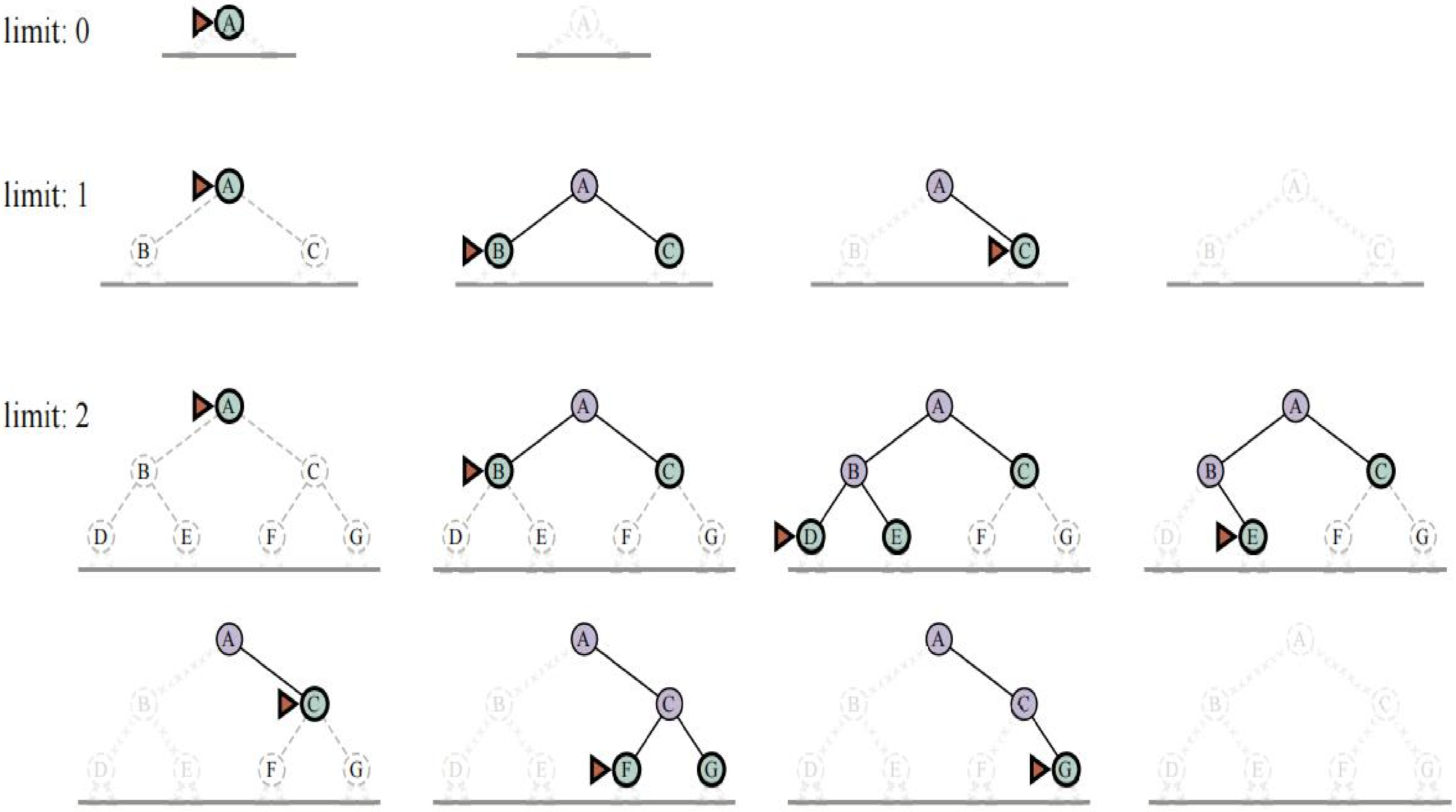
Tree depth is an issue!

“Controlled” DFS: Pseudocode

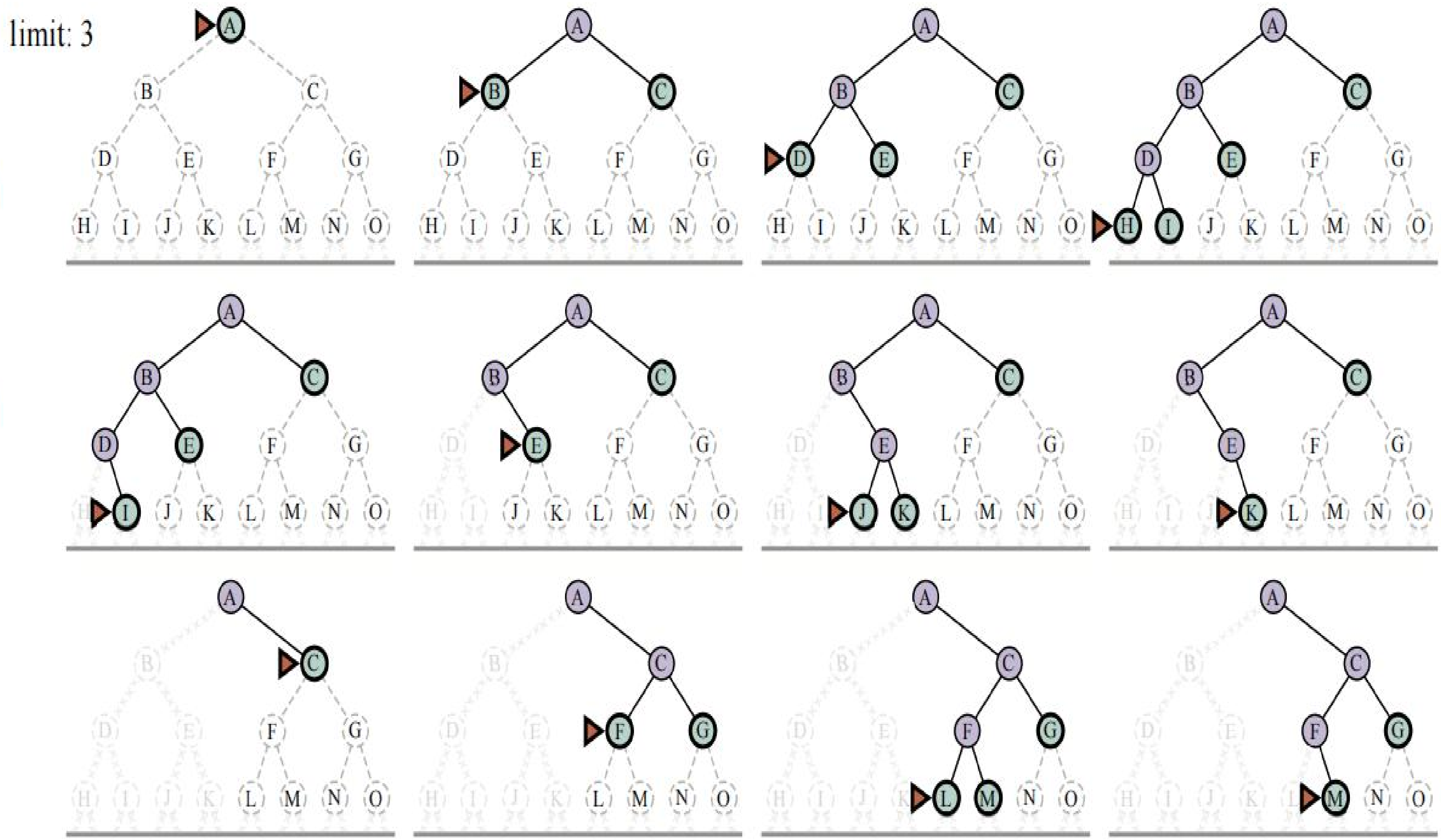
```
function ITERATIVE-DEEPENING-SEARCH(problem) returns a solution node or failure
  for depth = 0 to ∞ do
    result ← DEPTH-LIMITED-SEARCH(problem, depth)
    if result ≠ cutoff then return result

function DEPTH-LIMITED-SEARCH(problem, ℓ) returns a node or failure or cutoff
  frontier ← a LIFO queue (stack) with NODE(problem.INITIAL) as an element
  result ← failure
  while not IS-EMPTY(frontier) do
    node ← POP(frontier)
    if problem.IS-GOAL(node.STATE) then return node
    if DEPTH(node) > ℓ then
      result ← cutoff
    else if not IS-CYCLE(node) do
      for each child in EXPAND(problem, node) do
        add child to frontier
  return result
```

Iterative Deepening DFS: Illustration



Iterative Deepening DFS: Illustration



Uninformed Search

- **Traverse the search tree, possibly through all legal paths, to find a solution / reach goal state**
- **Search tree size can be large (or infinite)**
  - **Use node expansion / generation as you traverse**
- **Avoid repeated states (those cause "loops")**
  - **Keep track of already visited states**
- **Search tree depth can be a challenge**
  - **Use Iterative Deepening or Depth Limits**
- **Extra problem information? → informed search**

Uninformed Search Algorithms

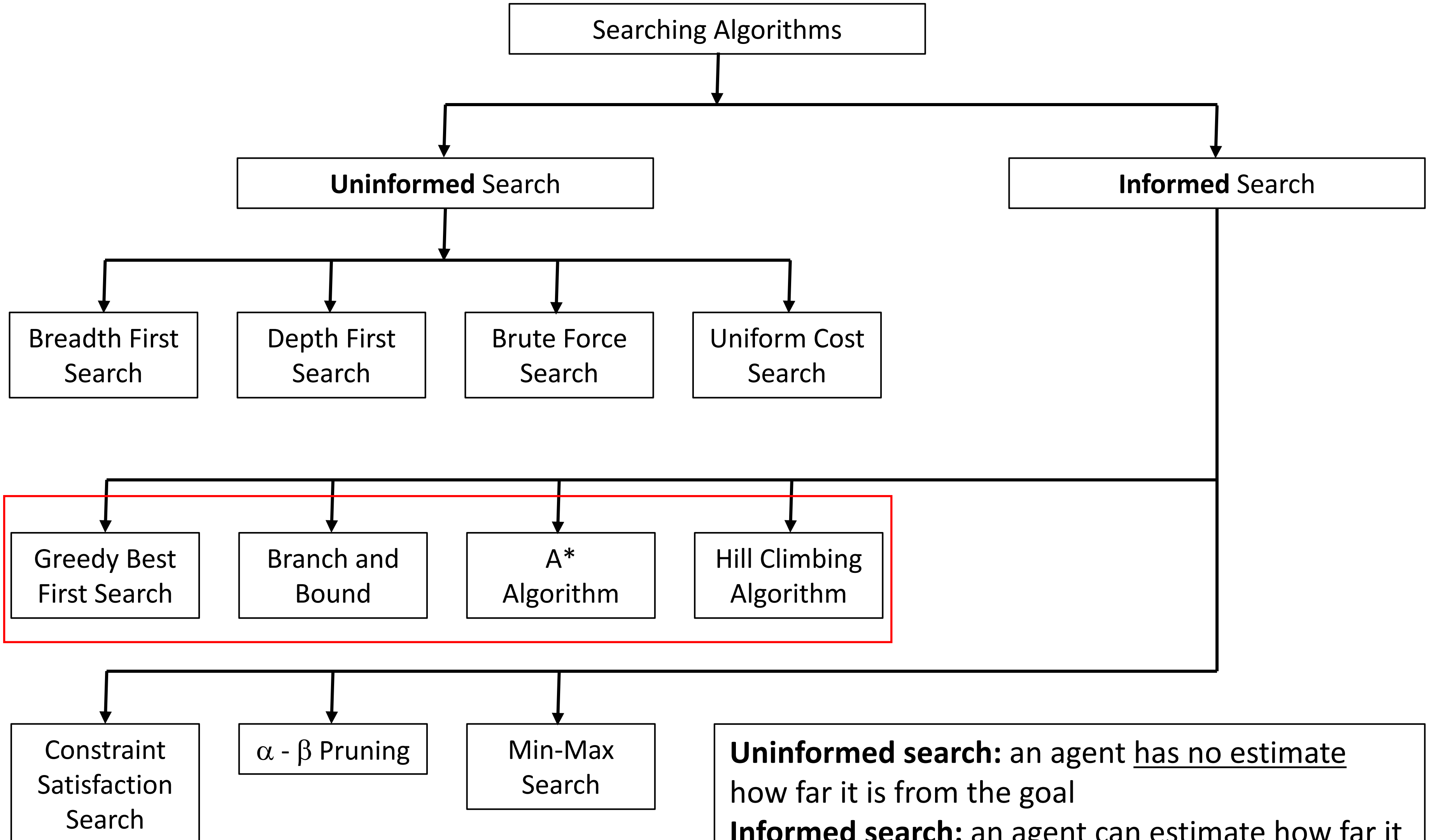
Criterion	Breadth-First	Uniform-Cost	Depth-First	Depth-Limited	Iterative Deepening	Bidirectional (if applicable)
Complete?	Yes[1]	Yes[1,2]	No	No	Yes[1]	Yes[1,4]
Optimal cost?	Yes[3]	Yes	No	No	Yes[3]	Yes[3,4]
Time	$O(b^d)$	$O(b^{1+\lfloor C^*/\epsilon \rfloor})$	$O(b^m)$	$O(b^\ell)$	$O(b^d)$	$O(b^{d/2})$
Space	$O(b^d)$	$O(b^{1+\lfloor C^*/\epsilon \rfloor})$	$O(bm)$	$O(b\ell)$	$O(bd)$	$O(b^{d/2})$

Figure 3.15 Evaluation of search algorithms. b is the branching factor; m is the maximum depth of the search tree; d is the depth of the shallowest solution, or is m when there is no solution; ℓ is the depth limit. Superscript caveats are as follows: [1] complete if b is finite, and the state space either has a solution or is finite. [2] complete if all action costs are $\geq \epsilon > 0$; [3] cost-optimal if action costs are all identical; [4] if both directions are breadth-first or uniform-cost.

DFS vs. BFS: When to Use? Tips

- **Breadth First Search**
  - **branching factor b is not excessive**
  - **solution is expected to exist at a reasonable level (depth d is reasonable)**
  - **some search paths can be very deep**
- **Depth First Search**
  - **branching factor b is relatively large**
  - **solution is expected to exist at a relatively shallow level (depth d is low)**
  - **search paths are not excessively deep**

Selected Searching Algorithms



Uninformed search: an agent has no estimate how far it is from the goal
Informed search: an agent can estimate how far it is from the goal

Informed Search: the Idea

When traversing the search tree use domain knowledge / heuristics to avoid search paths that are likely to be fruitless

Informed Search and Heuristics

Informed search relies on domain-specific knowledge / hints that help locate the goal state.

$$h(n) = h(\text{State } n)$$

$$h(n) = n(\text{relevant information about State } n)$$

h(n) : heuristic function - estimated cost of the cheapest path from State n to the goal state

Evaluation function

Calculate / obtain:

f(n) = f(State n)
f(n) = f(relevant information about State n)

A state n with minimum (or maximum) f(n) should be chosen for expansion
What about ties?

Best-First Search

```
function BEST-FIRST-SEARCH(problem, f) returns a solution node or failure
  node ← NODE(STATE=problem.INITIAL)
  frontier ← a priority queue ordered by f, with node as an element
  reached ← a lookup table, with one entry with key problem.INITIAL and value node
  while not IS-EMPTY(frontier) do
    node ← POP(frontier)
    if problem.IS-GOAL(node.STATE) then return node
    for each child in EXPAND(problem, node) do
      s ← child.STATE
      if s is not in reached or child.PATH-COST < reached[s].PATH-COST then
        reached[s] ← child
        add child to frontier
  return failure
```

Best-First Search is really a class of search algorithms that:

- **Use the evaluation function f(n) to pick next action**
- **Keep track of visited states**
- **Keep track of frontier states**
- **Evaluation function f(n) choice controls their behavior**

Informed Search and Heuristics

Informed search relies on domain-specific knowledge / hints that help locate the goal state.

$$h(n) = h(\text{State } n)$$

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h(n) : heuristic function - estimated cost of the cheapest path from State n to the goal state

Hill Climbing Search

- **The most primitive informed search approach**
  - **a naive greedy algorithm**
  - **evaluation function: the cost of next move**
  - **does not care about the "bigger picture" (for example: total search path cost)**
- **Practicalities:**
  - **usually does not keep track of search history:**
    - **not tracking visited nodes → loops!**
    - **not tracking frontier nodes → does not look at alternatives**

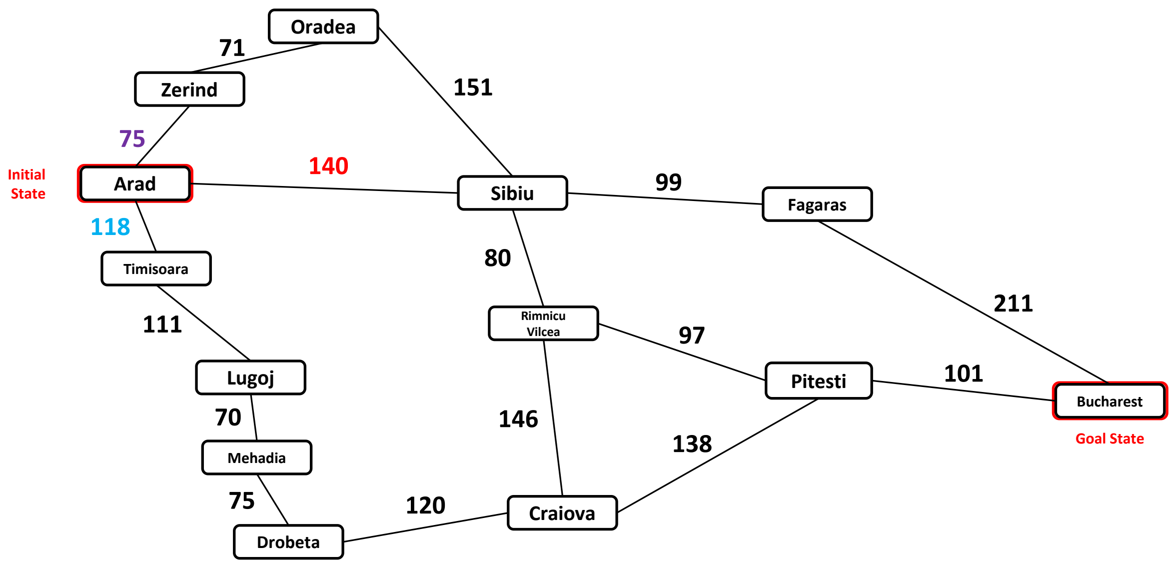
Hill Climbing: Evaluation function

Calculate / obtain:

f(n) = **ACTION-COST(State$_a$, toState$_n$, State$_n$)**

A state n with minimum (or maximum) f(n) should be chosen for expansion

Dracula's Roadtrip: Hill Climbing



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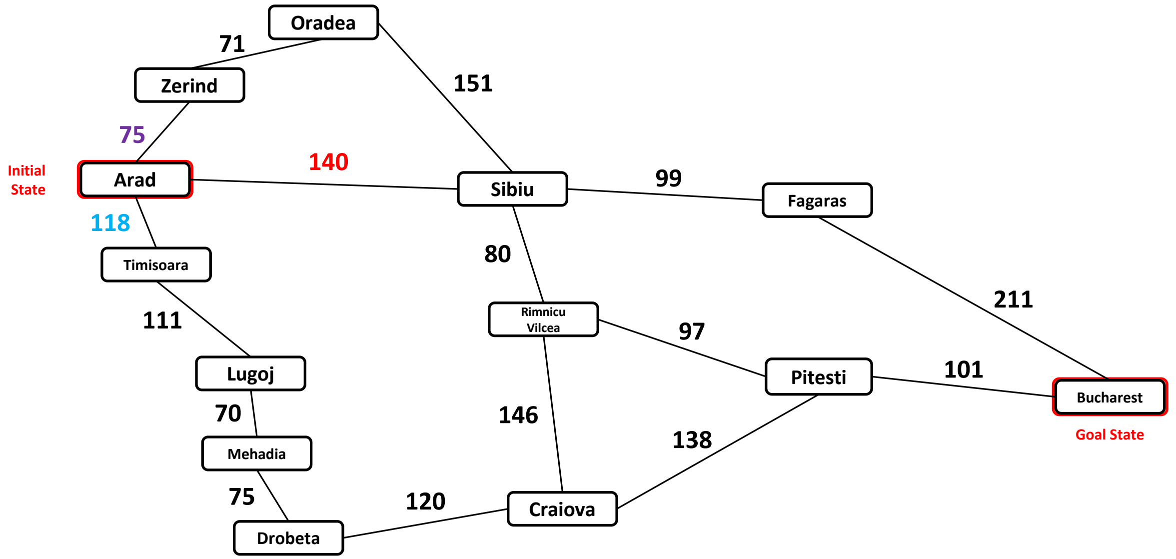

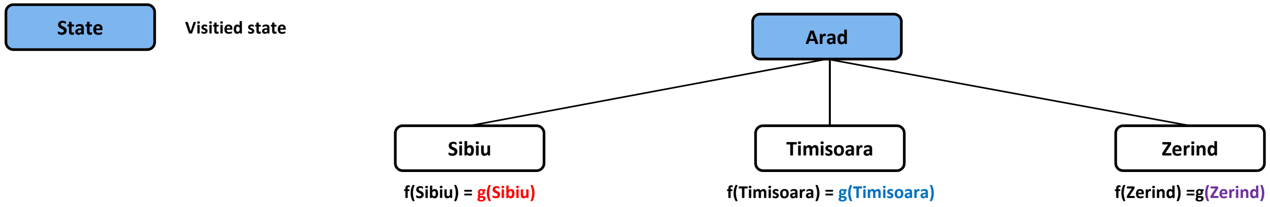

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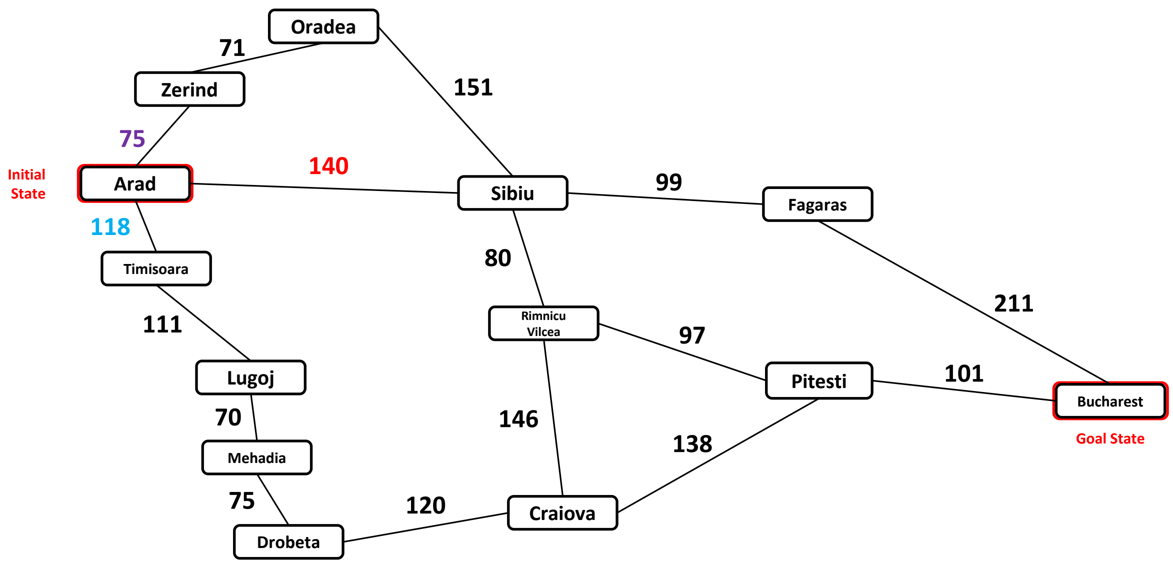

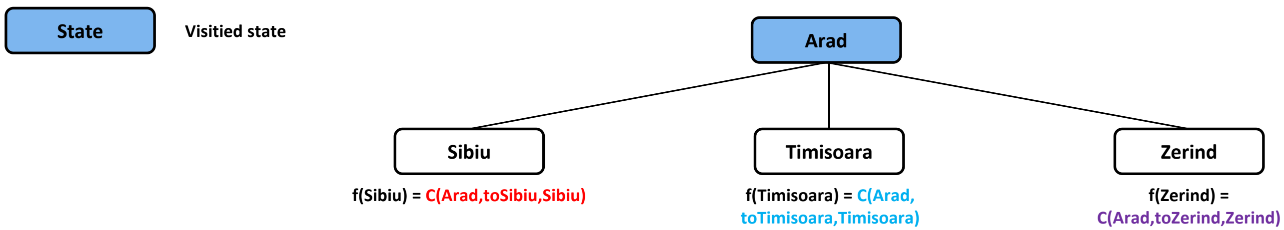

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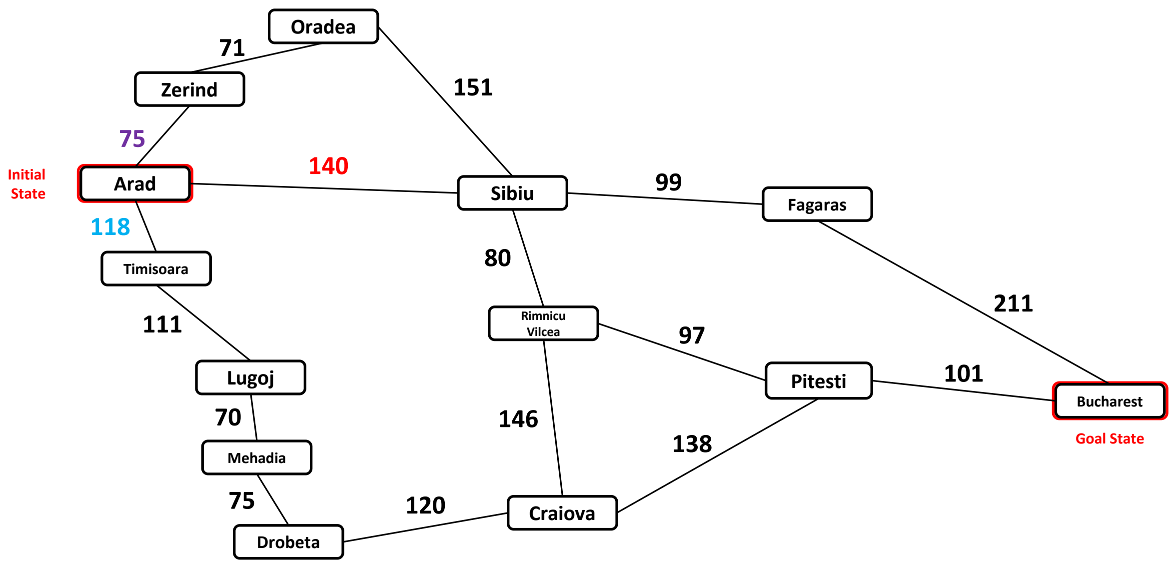

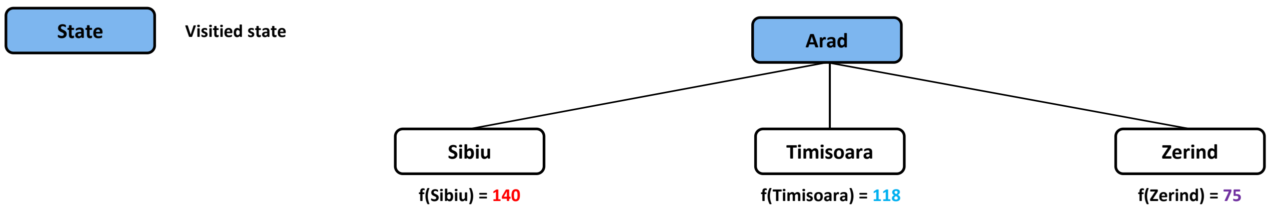

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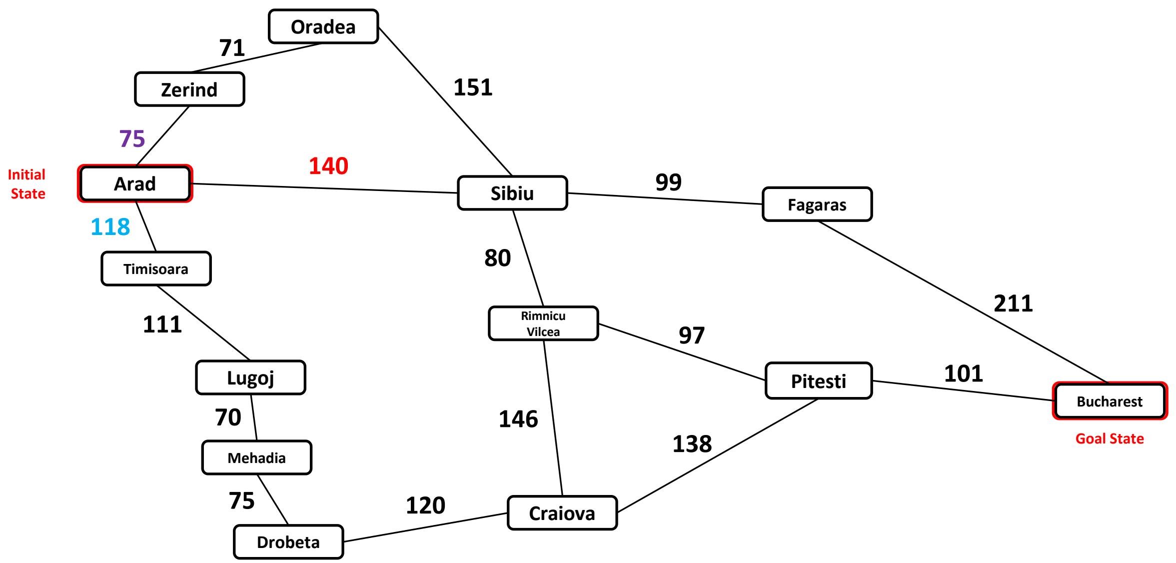

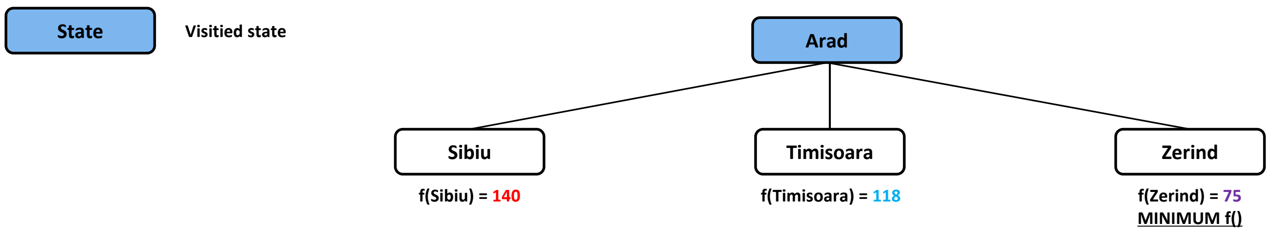

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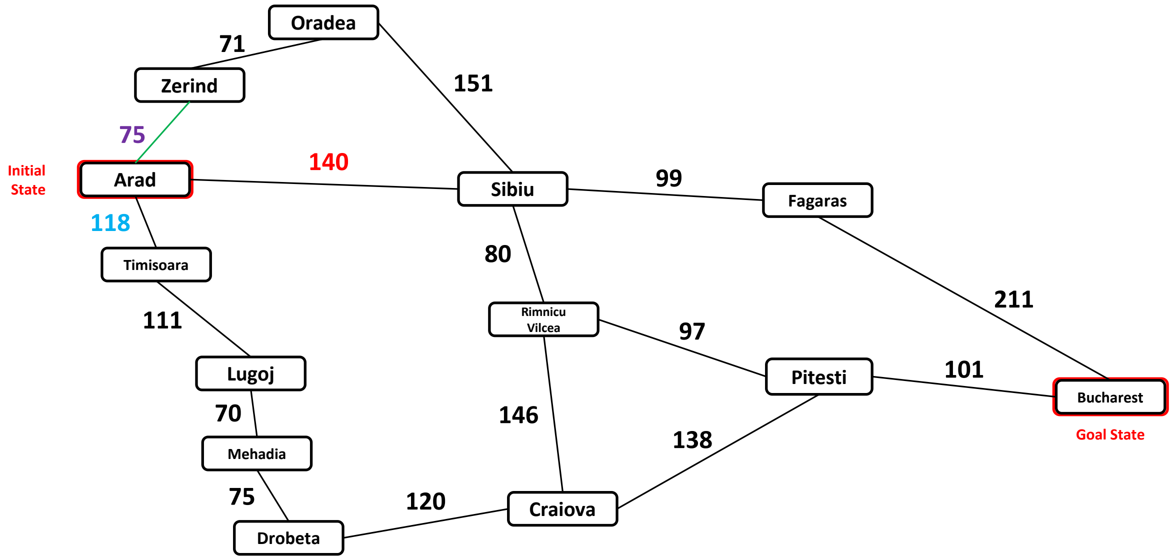

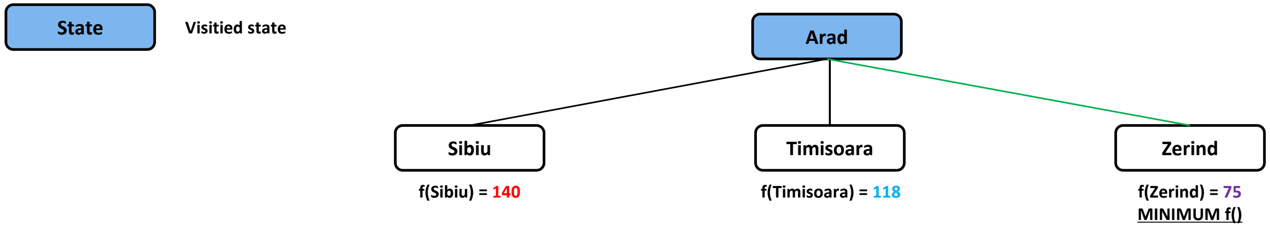

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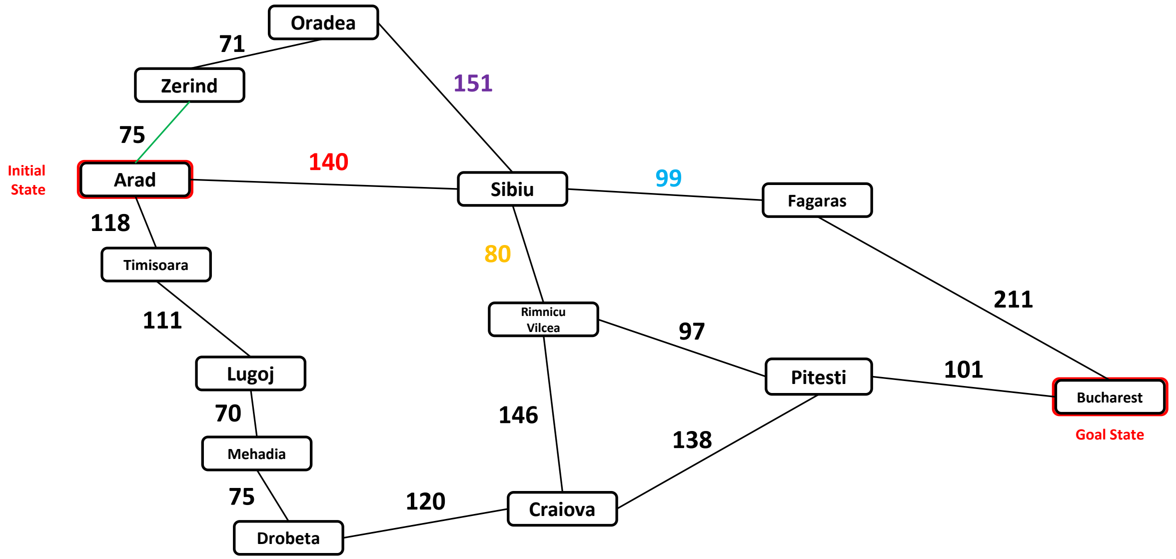

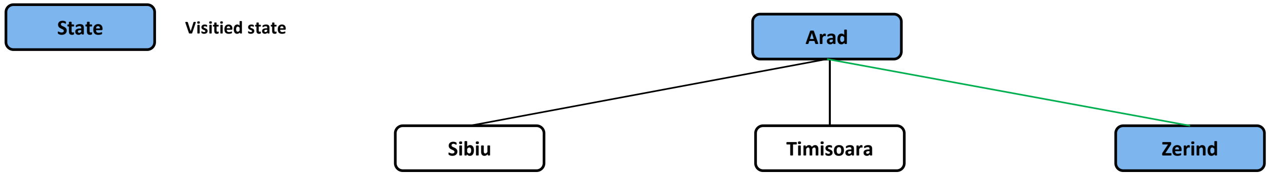

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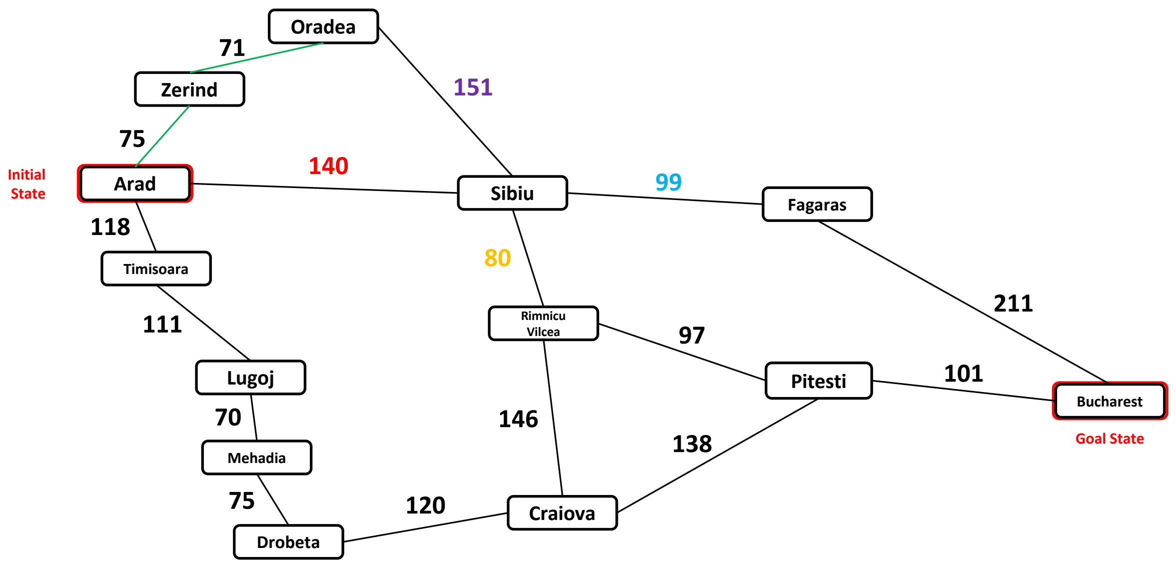

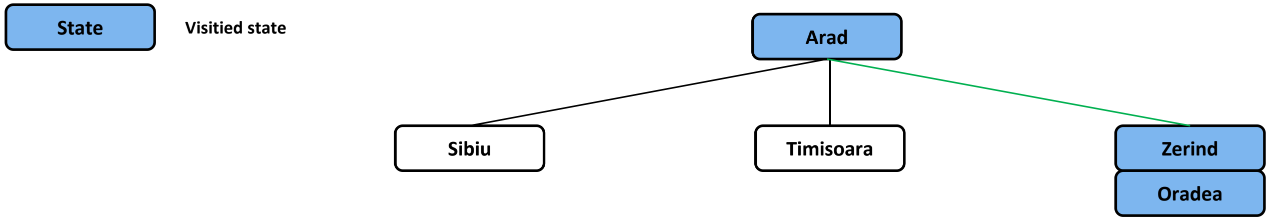

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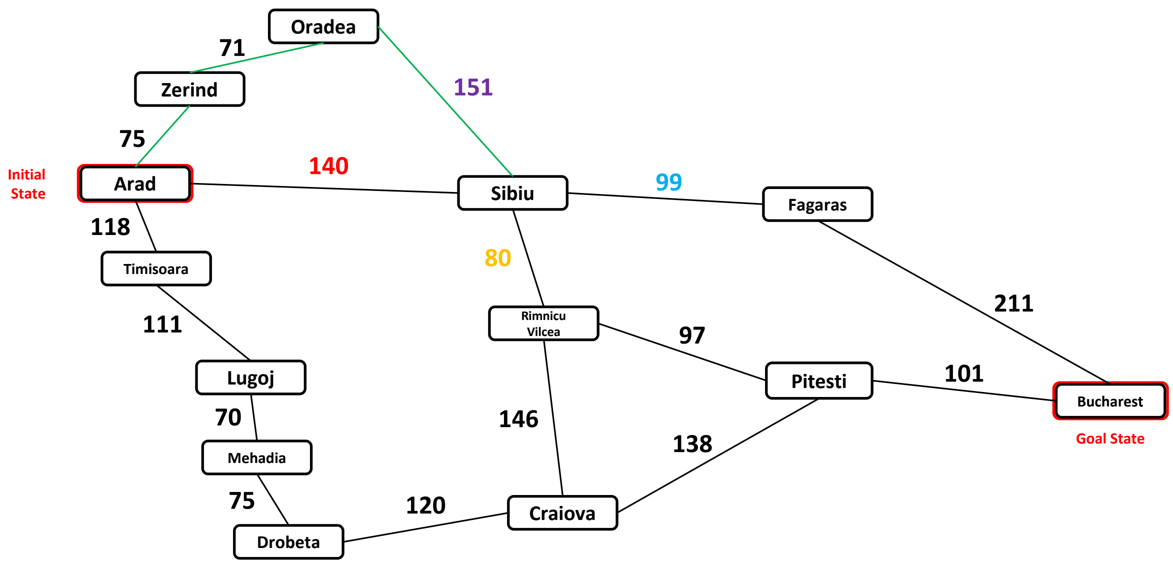

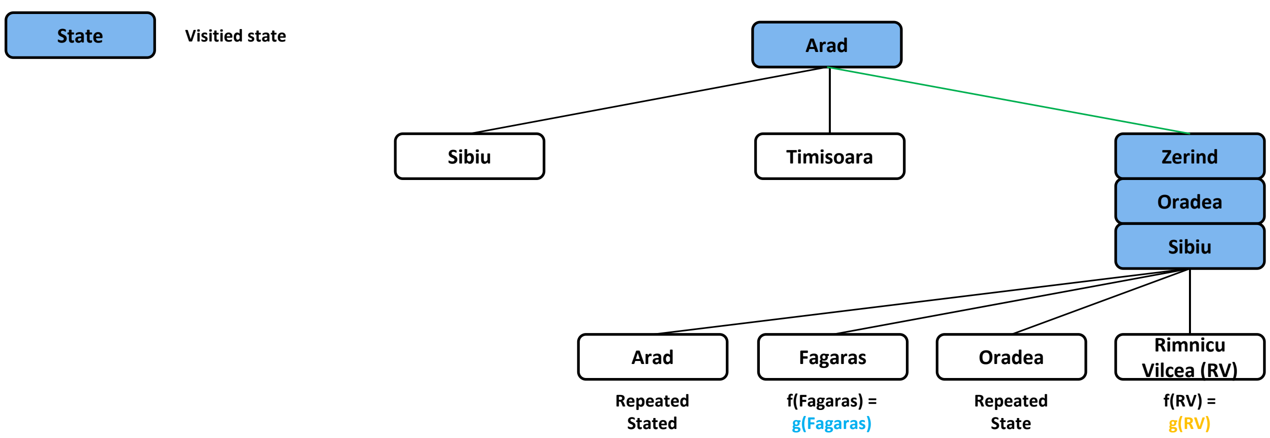

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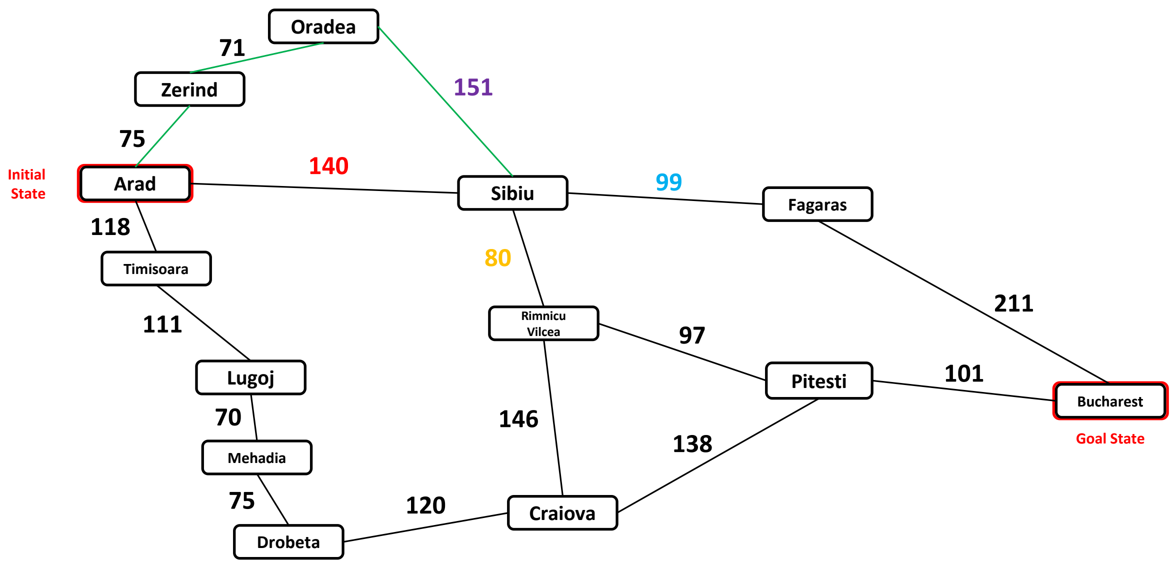

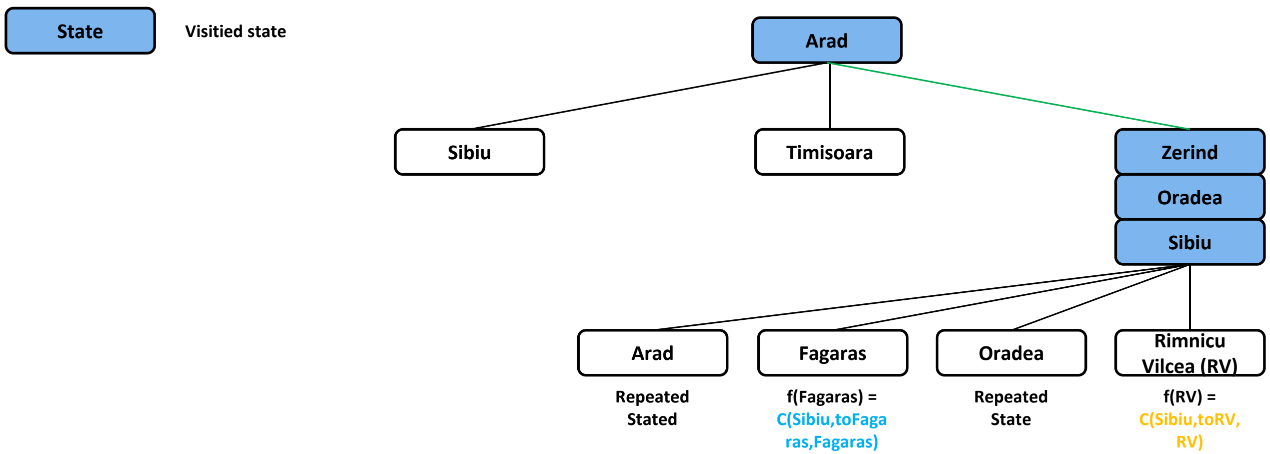

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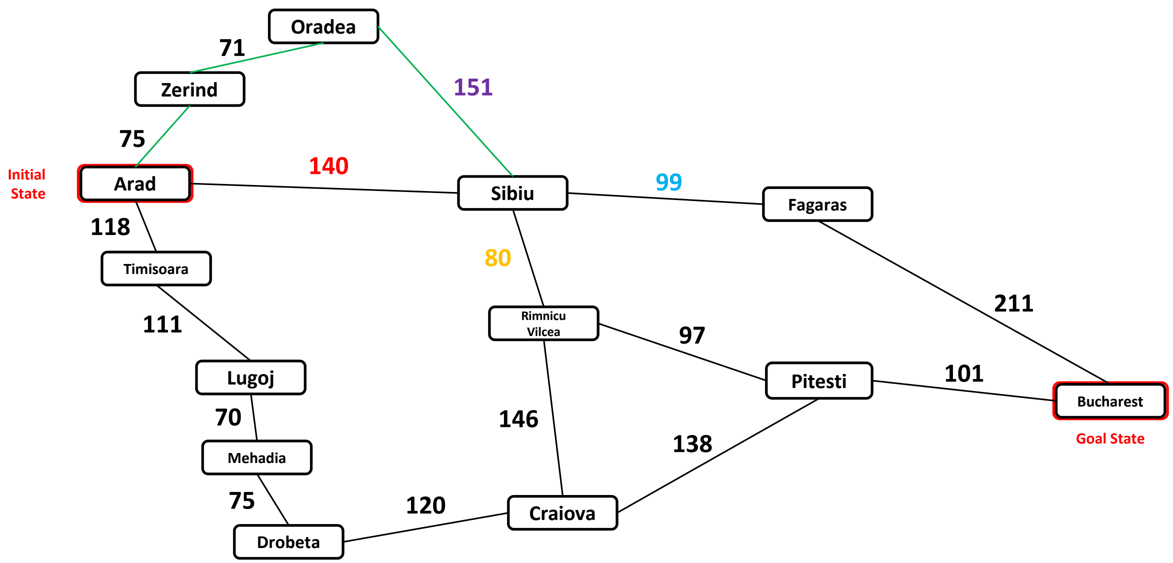

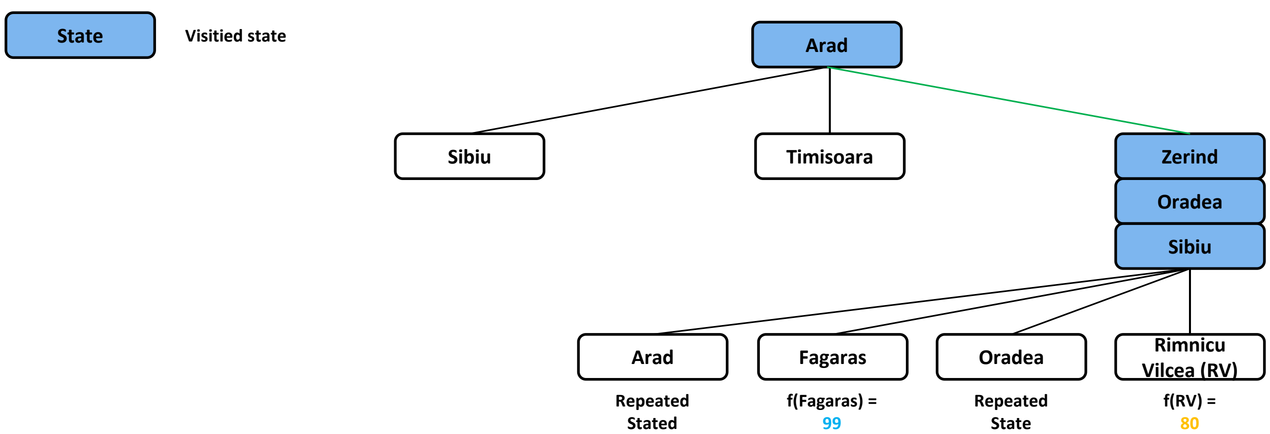

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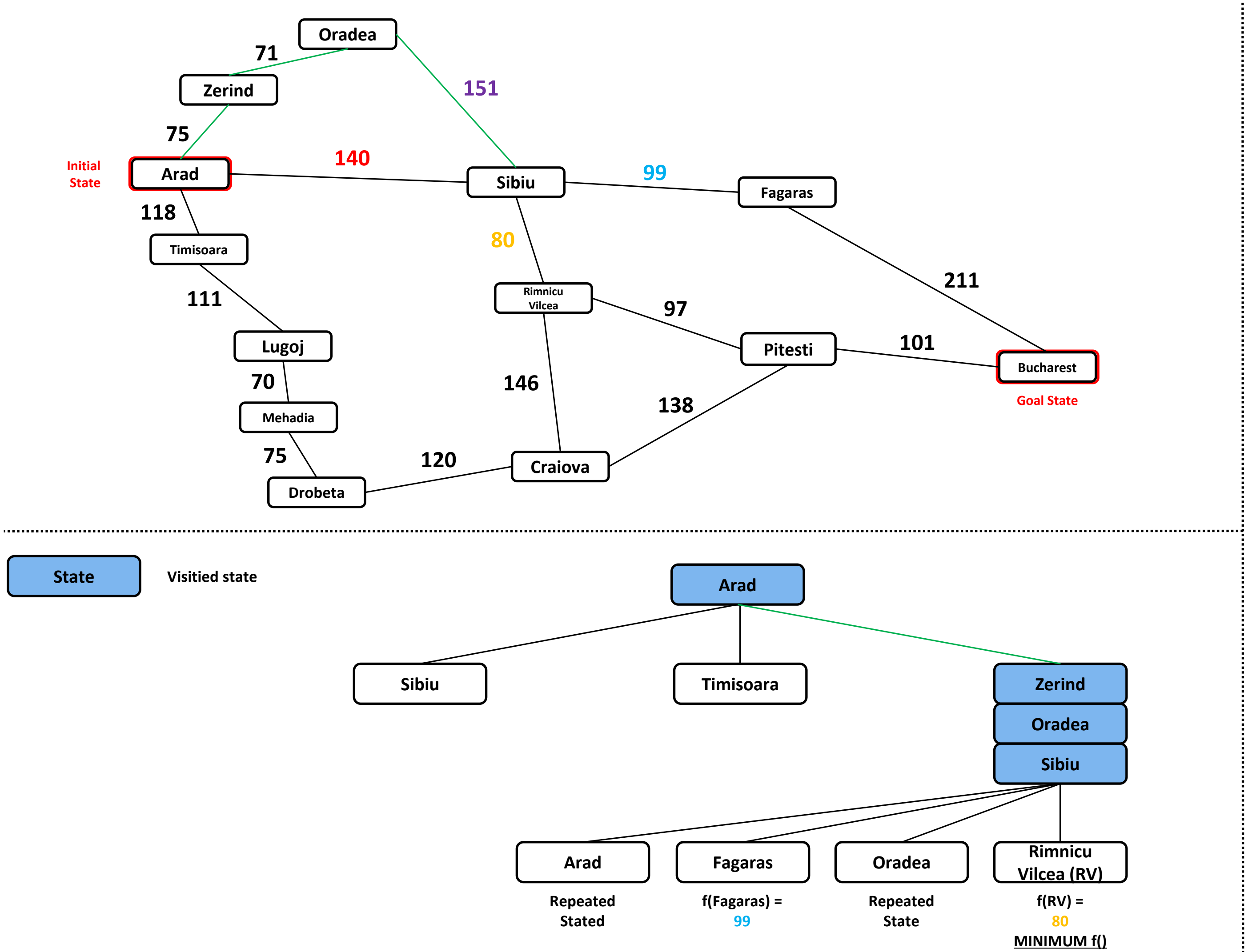

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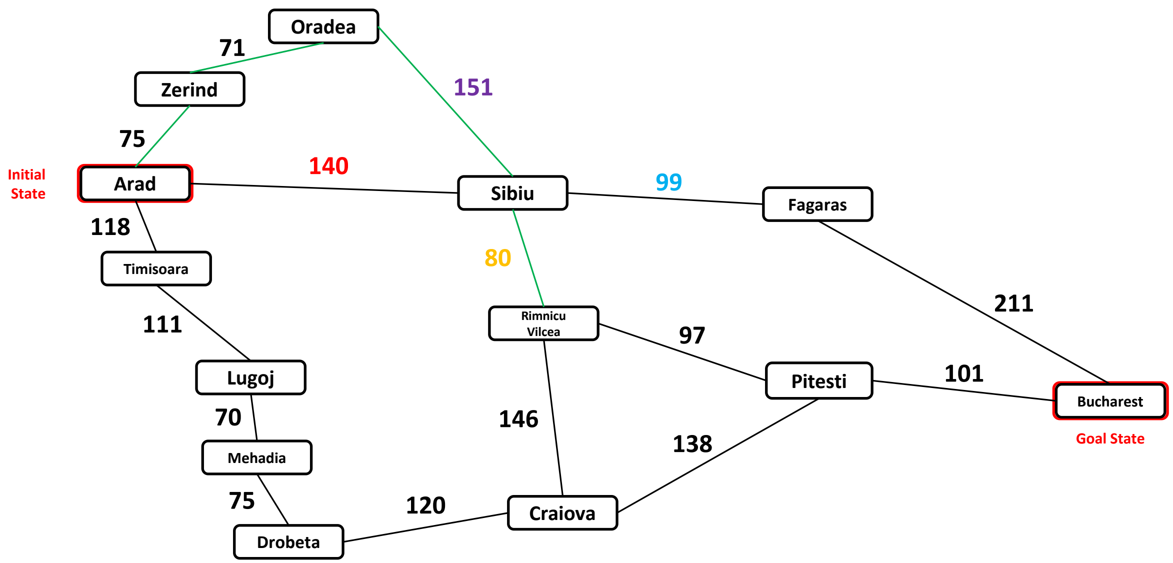

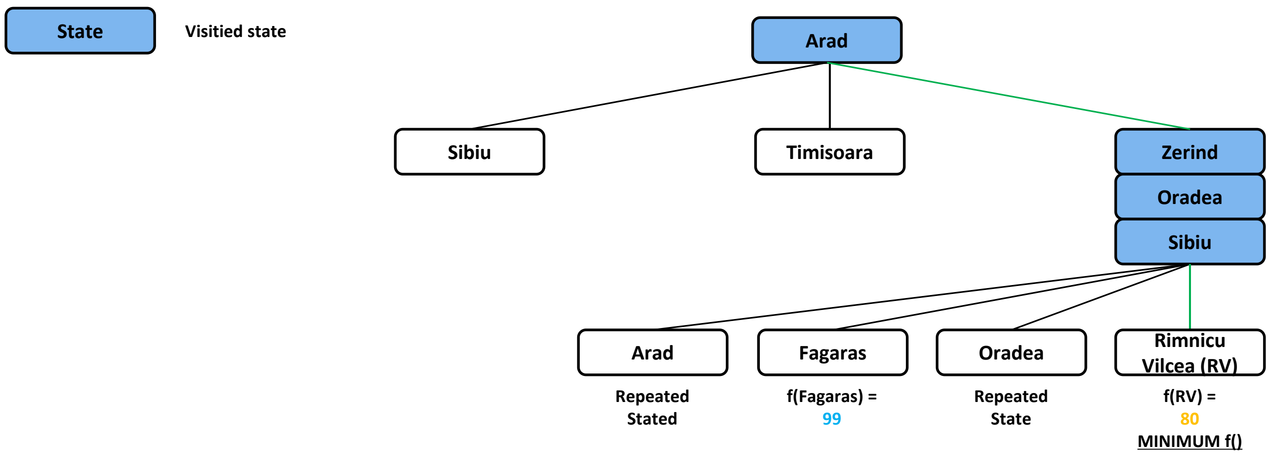

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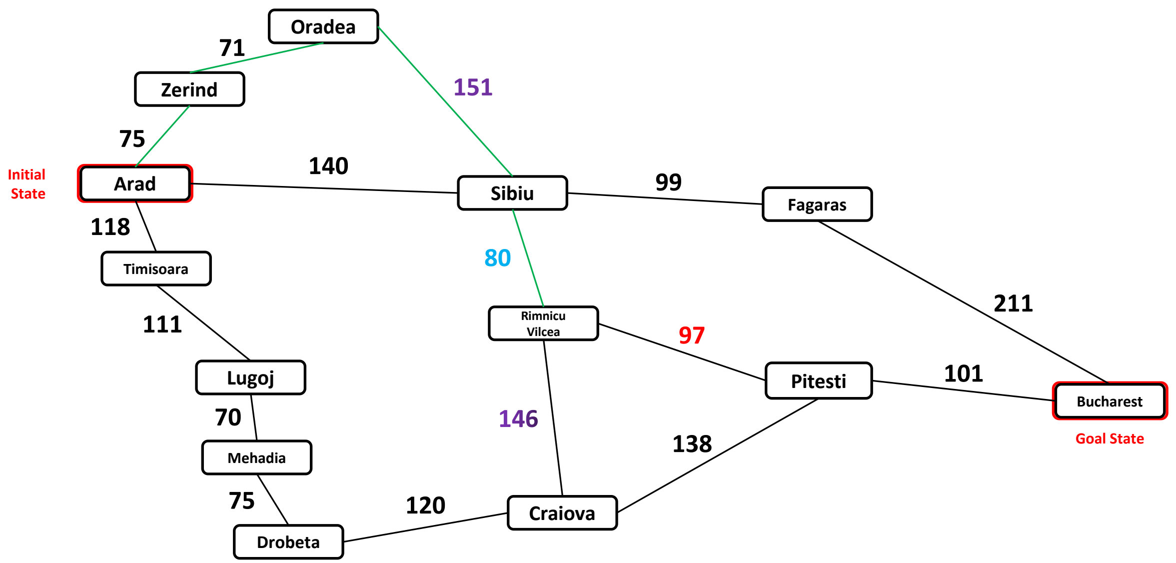

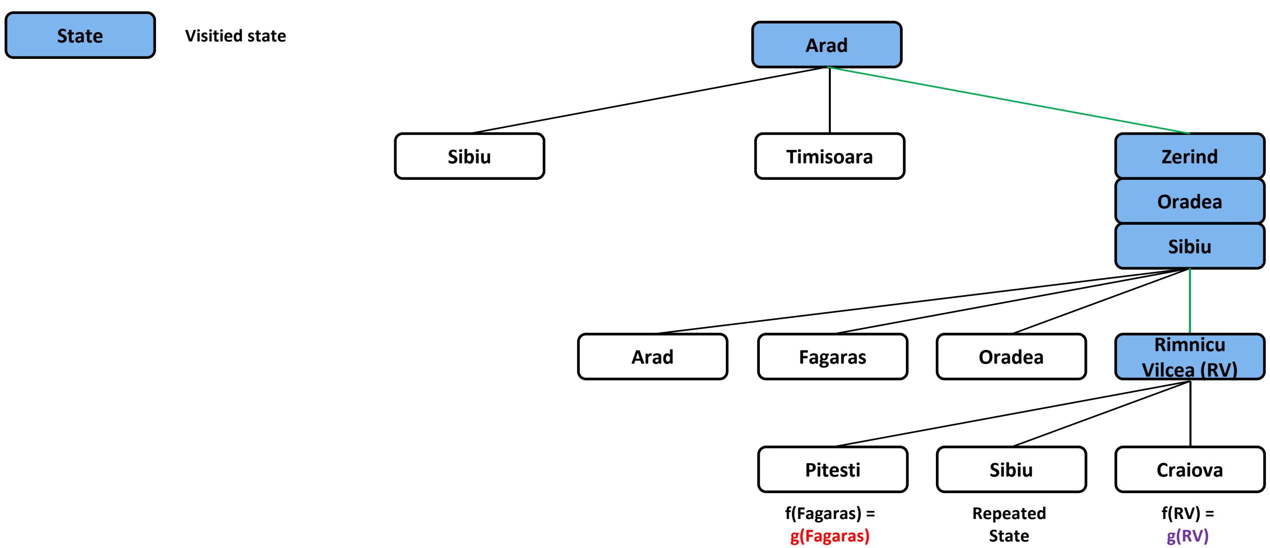

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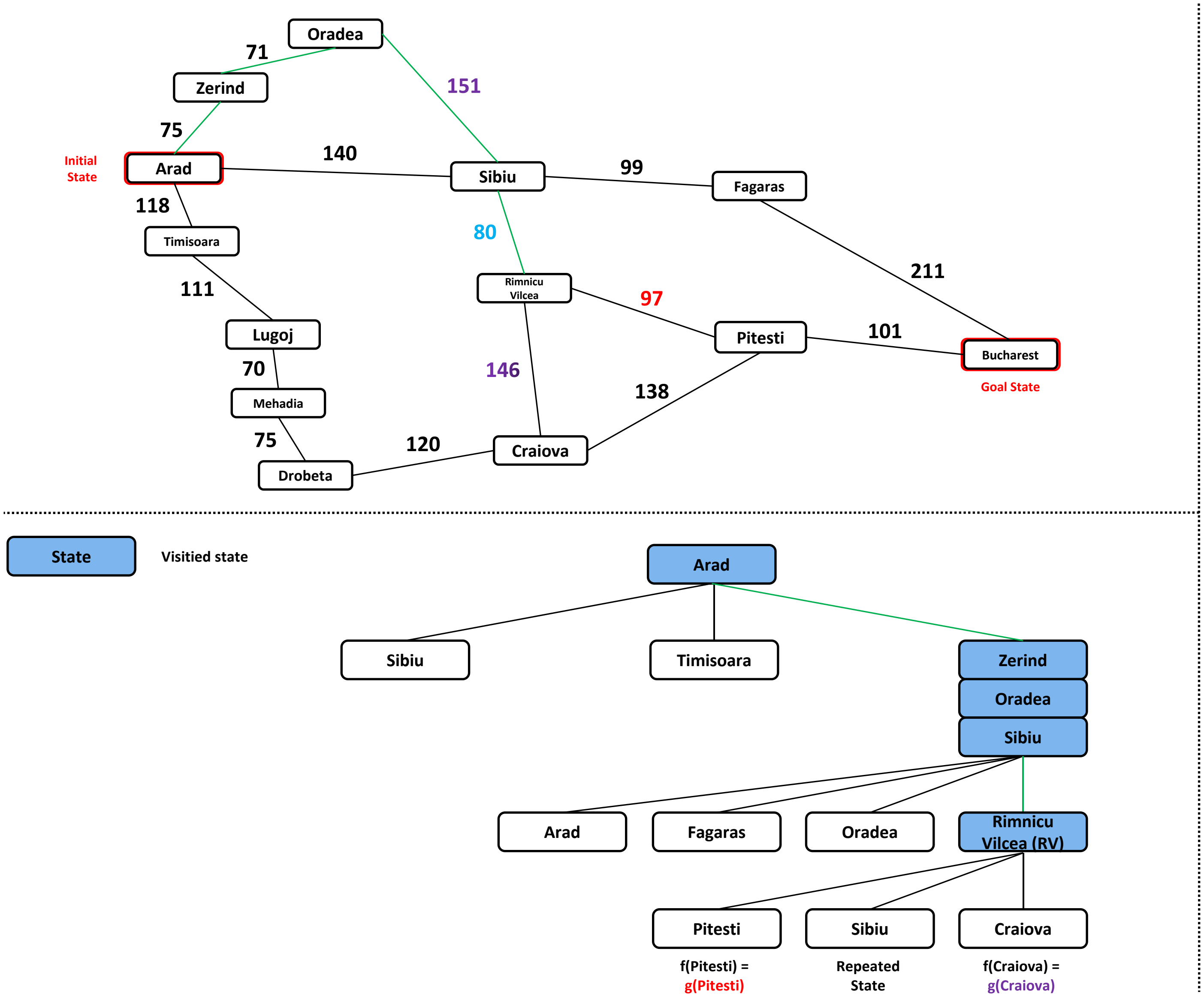

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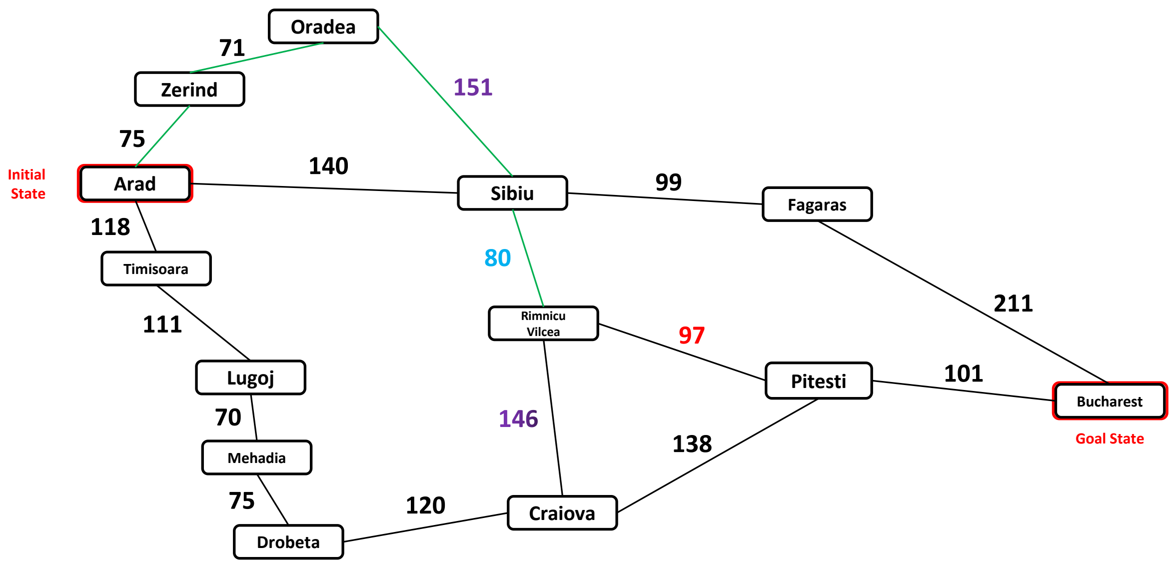

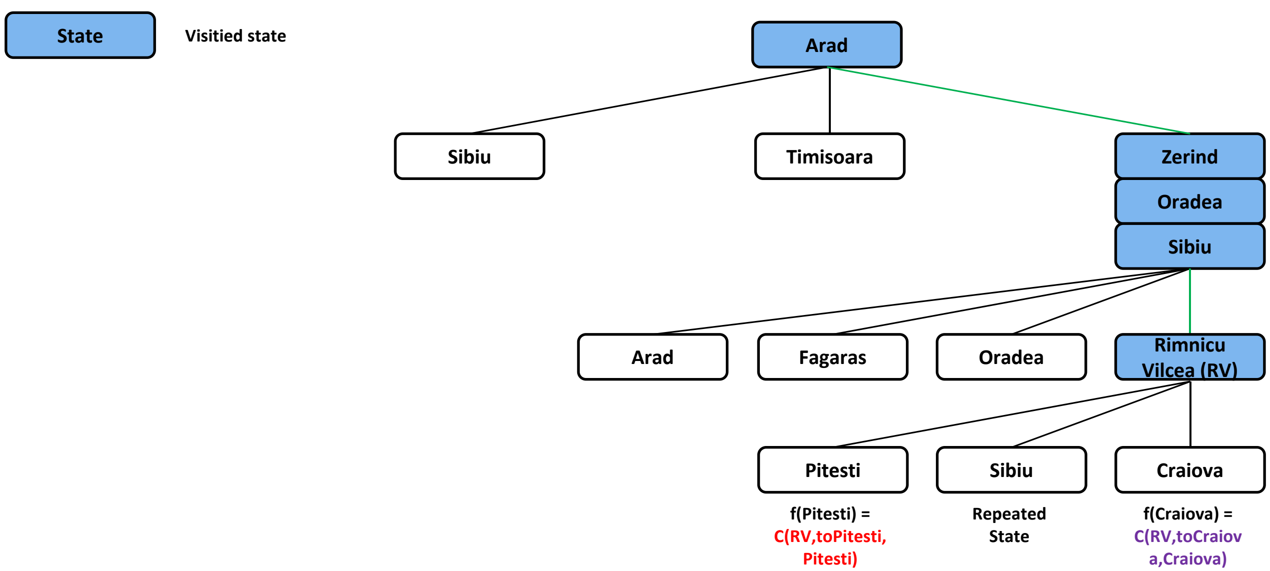

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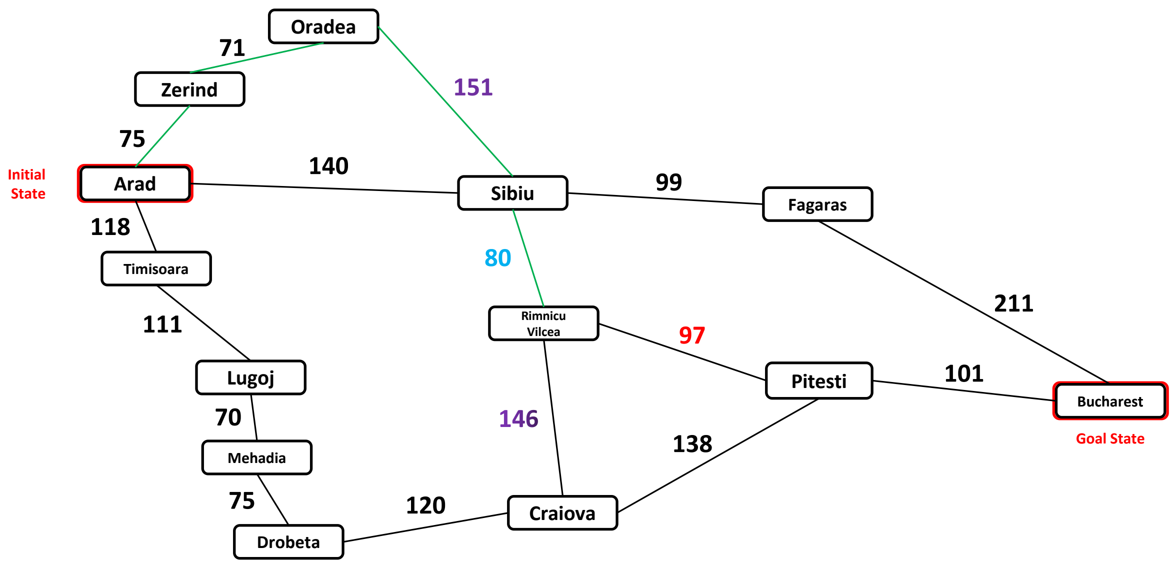

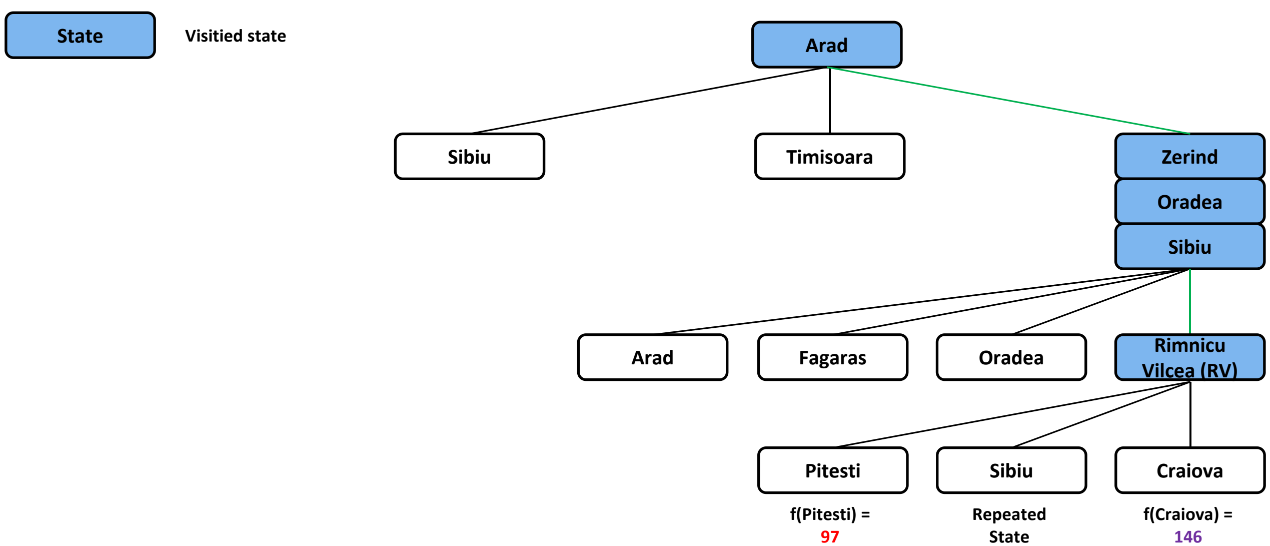

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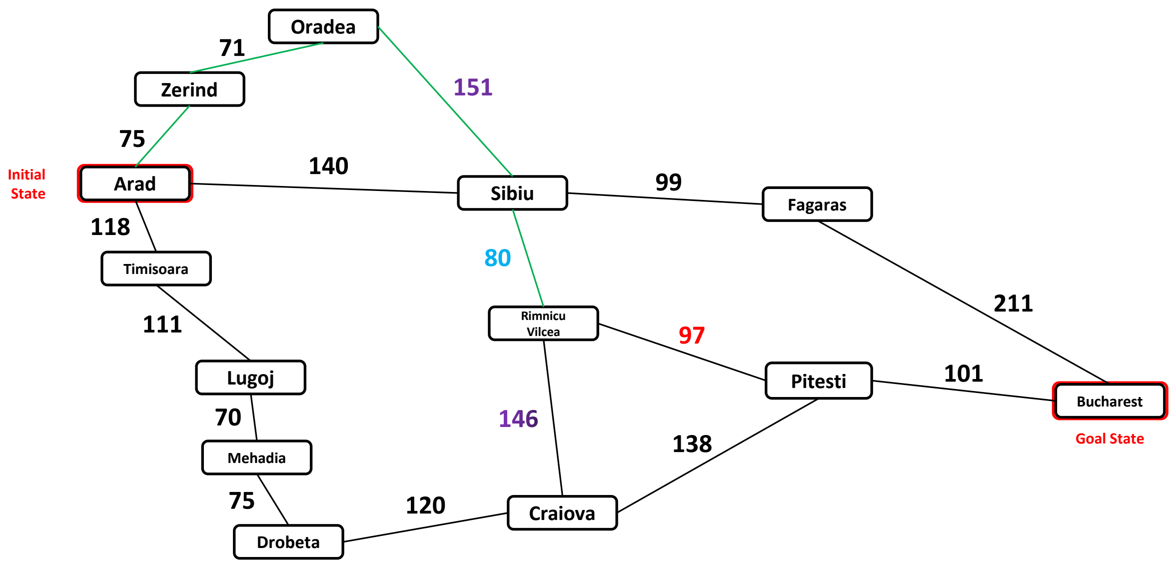

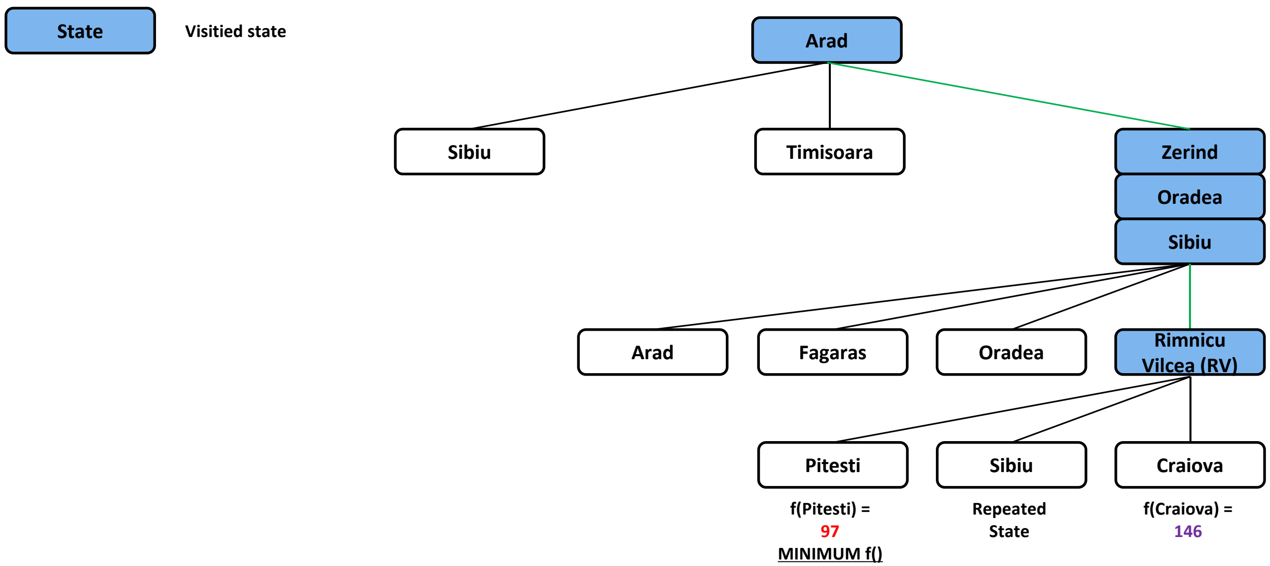

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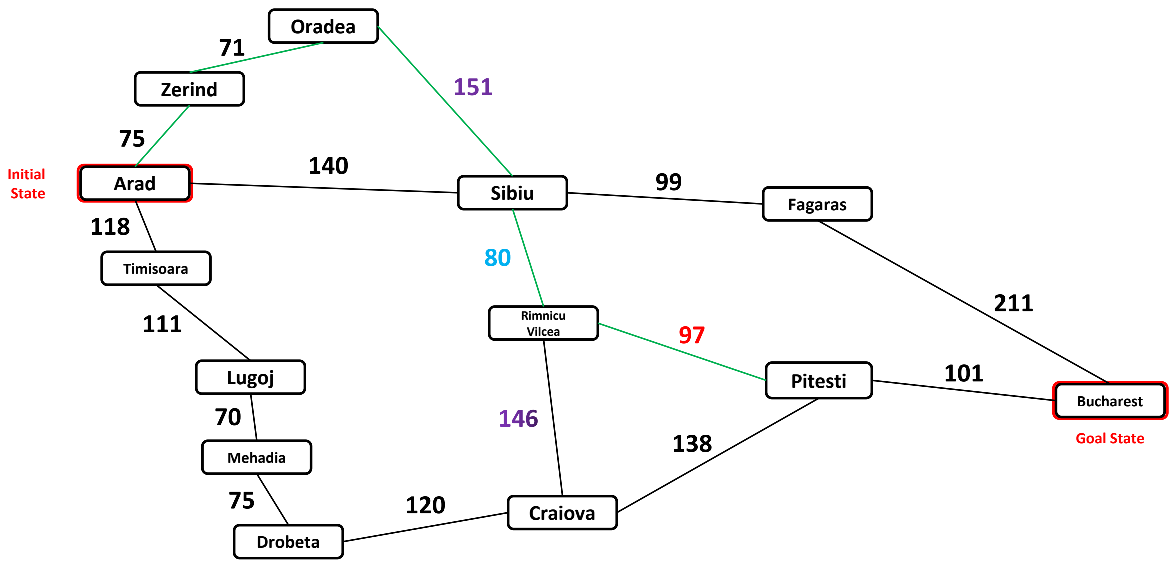

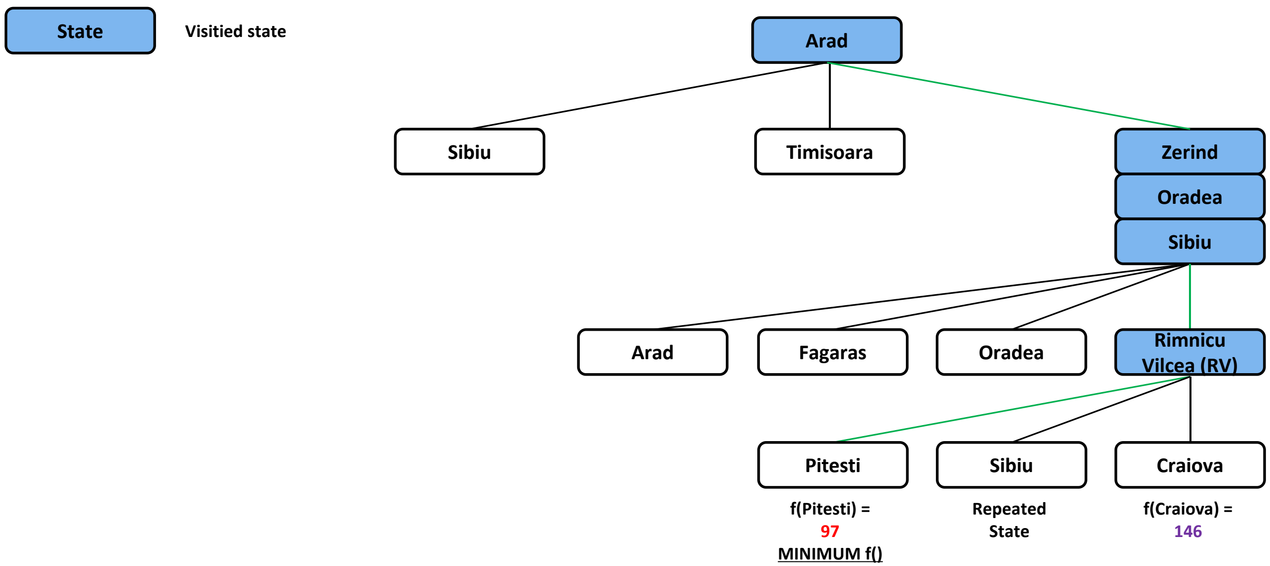

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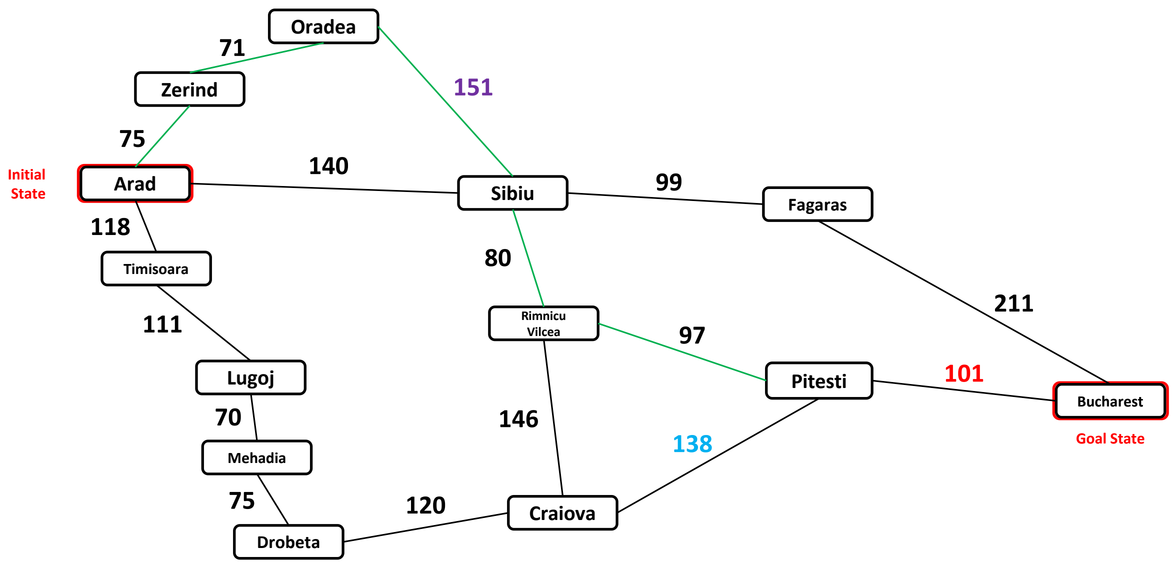

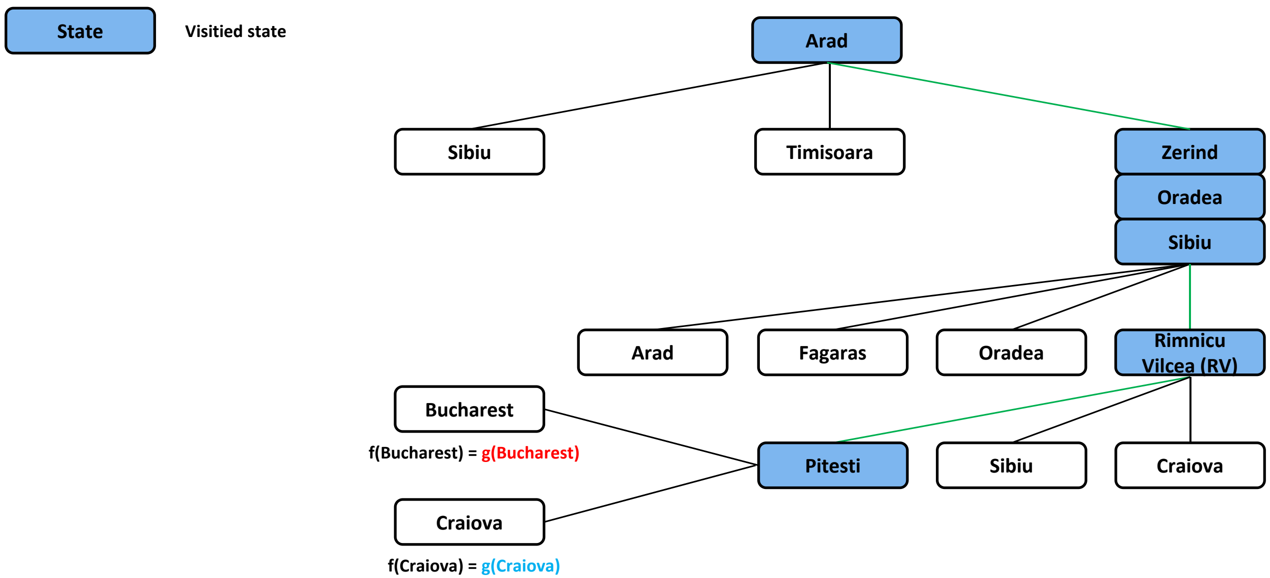

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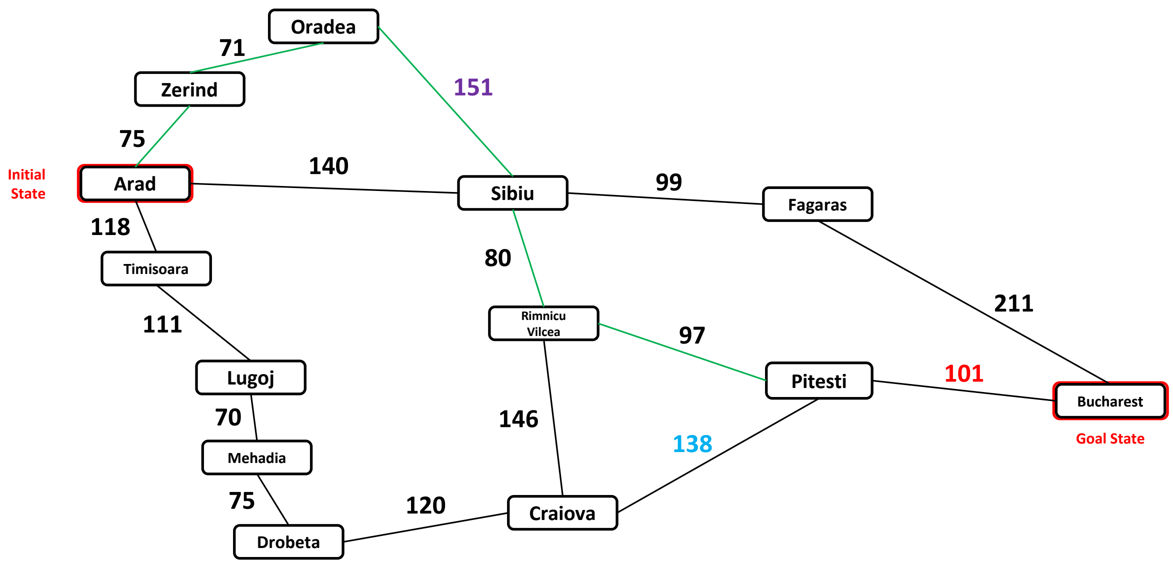
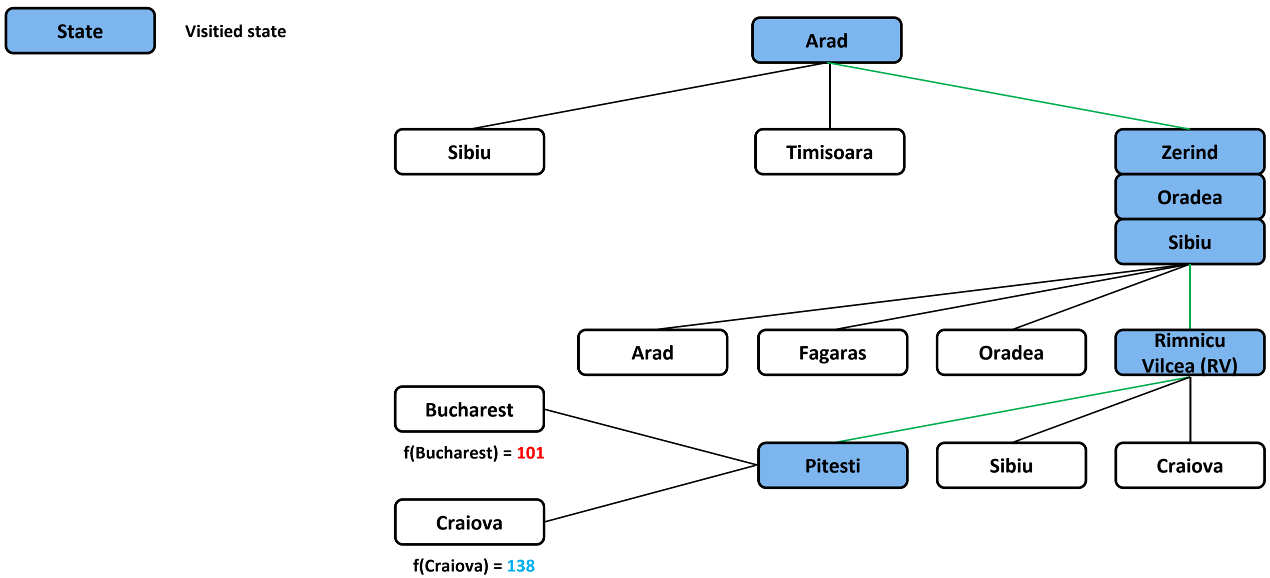
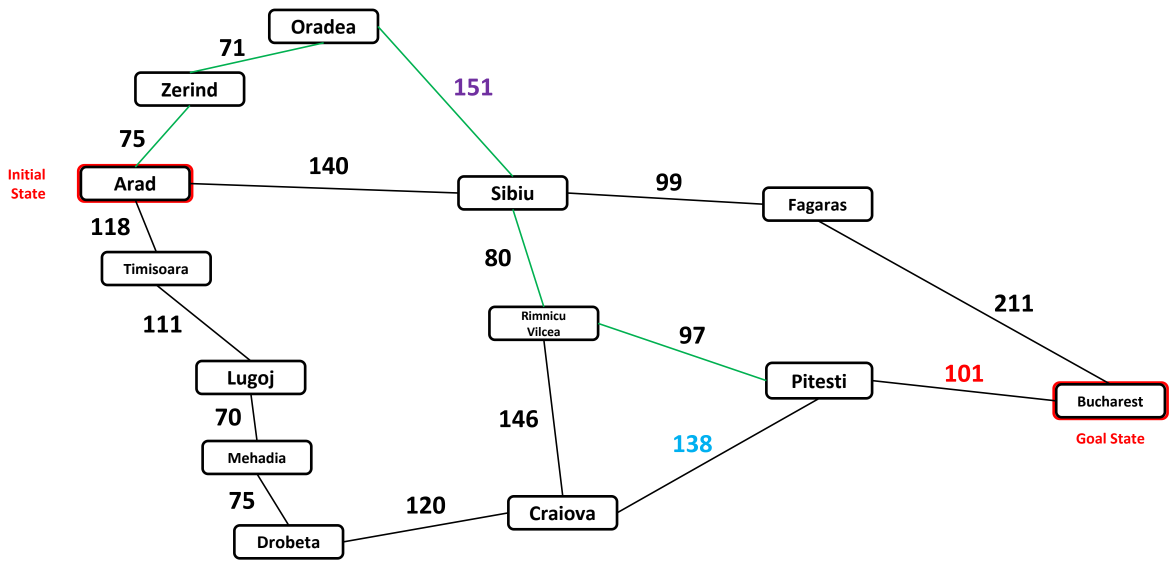
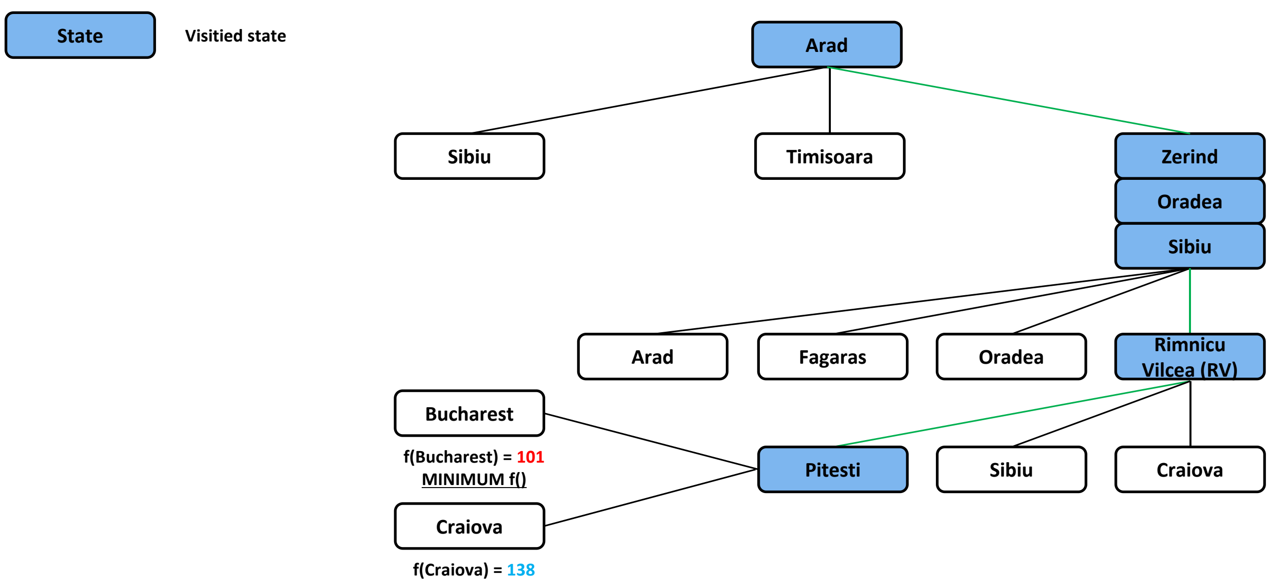




Dracula's Roadtrip: Hill Climbing





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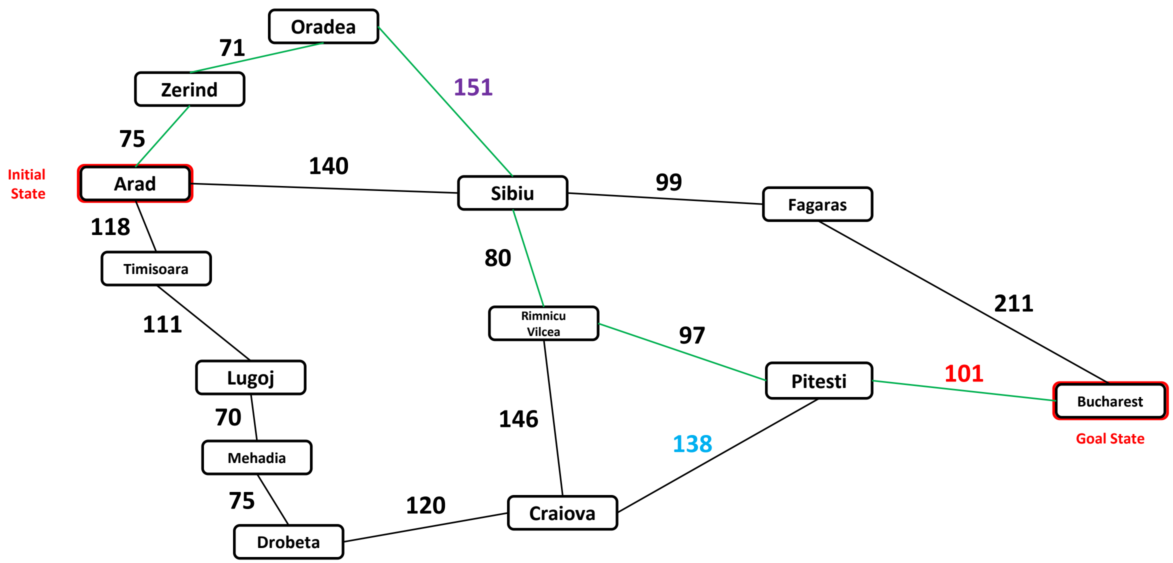
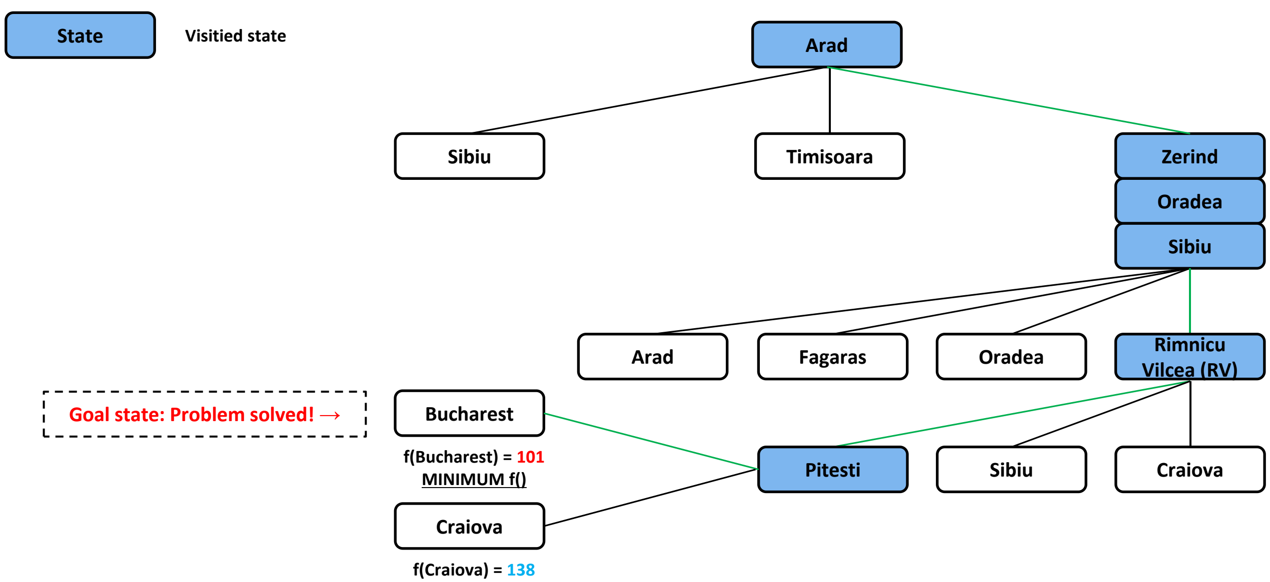
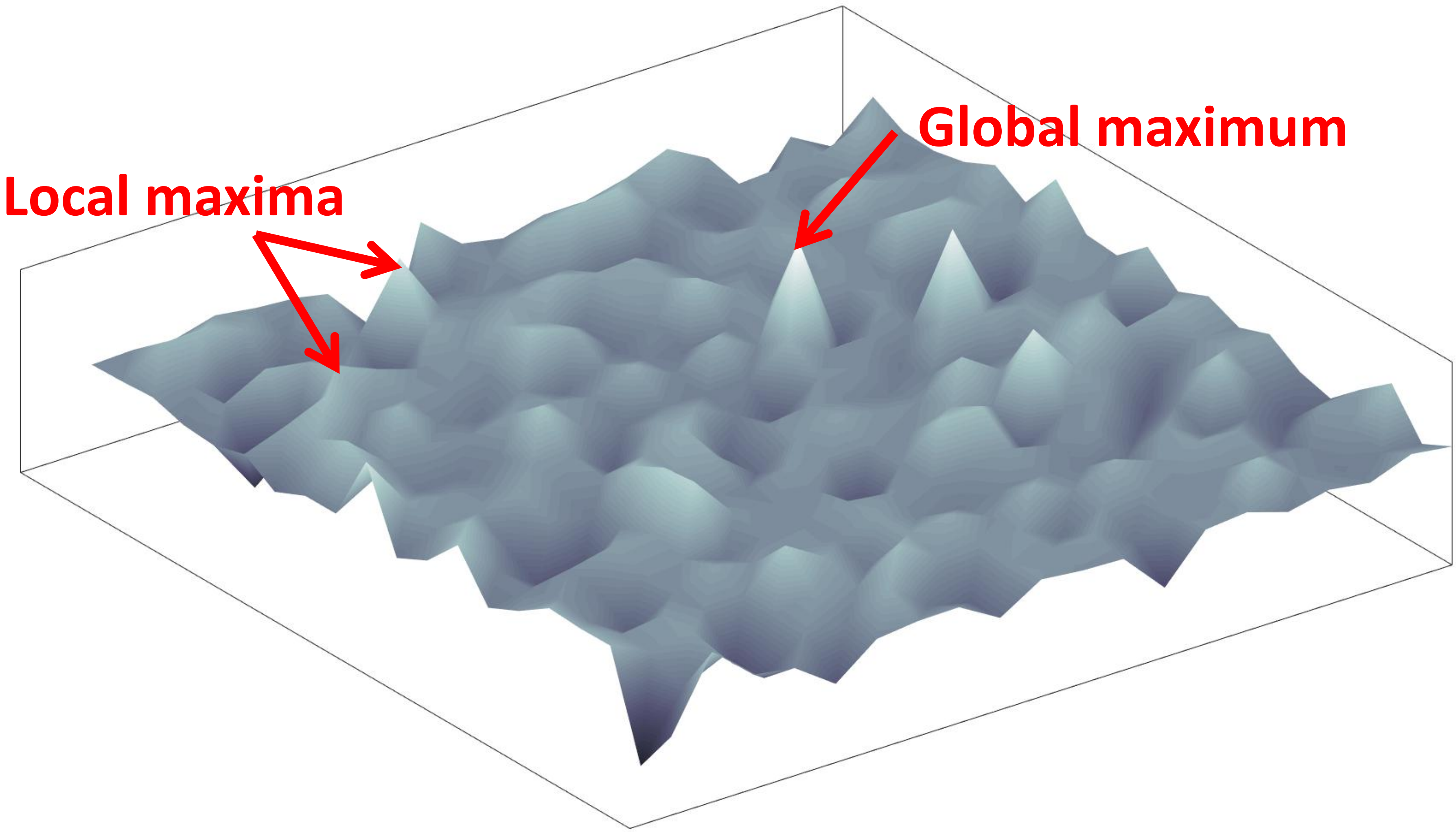




Hill Climbing Problems: Local Maxima



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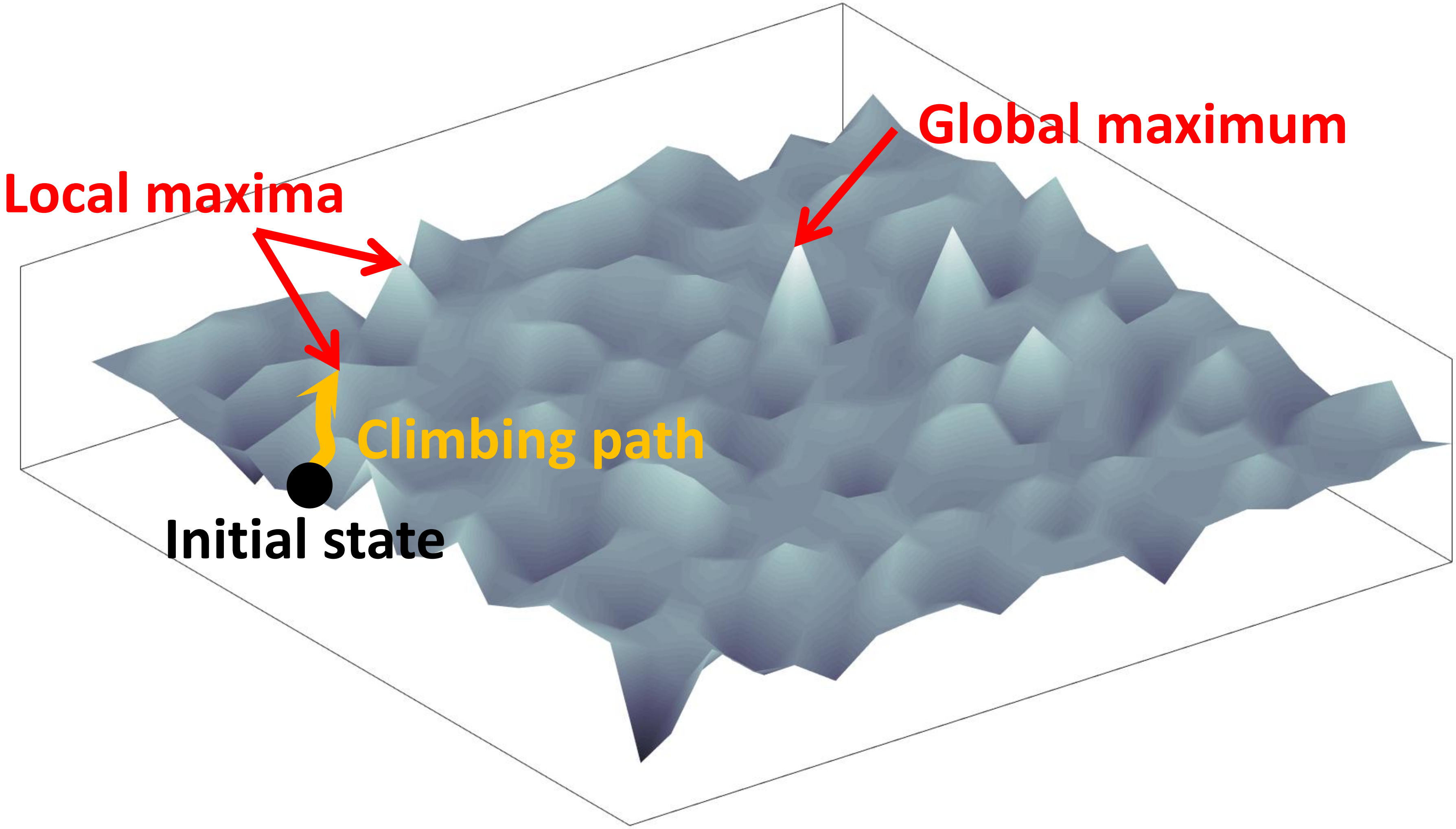

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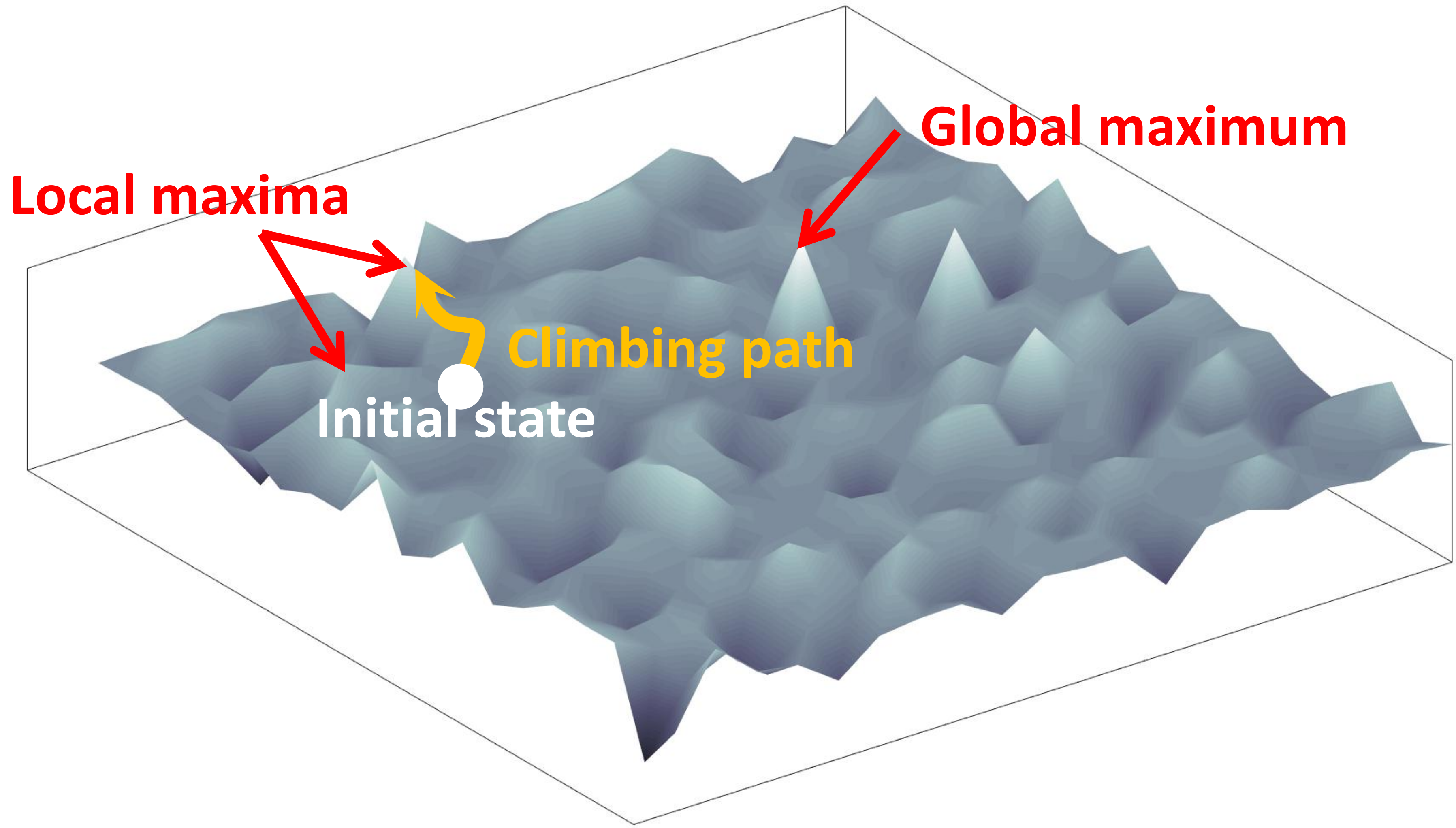
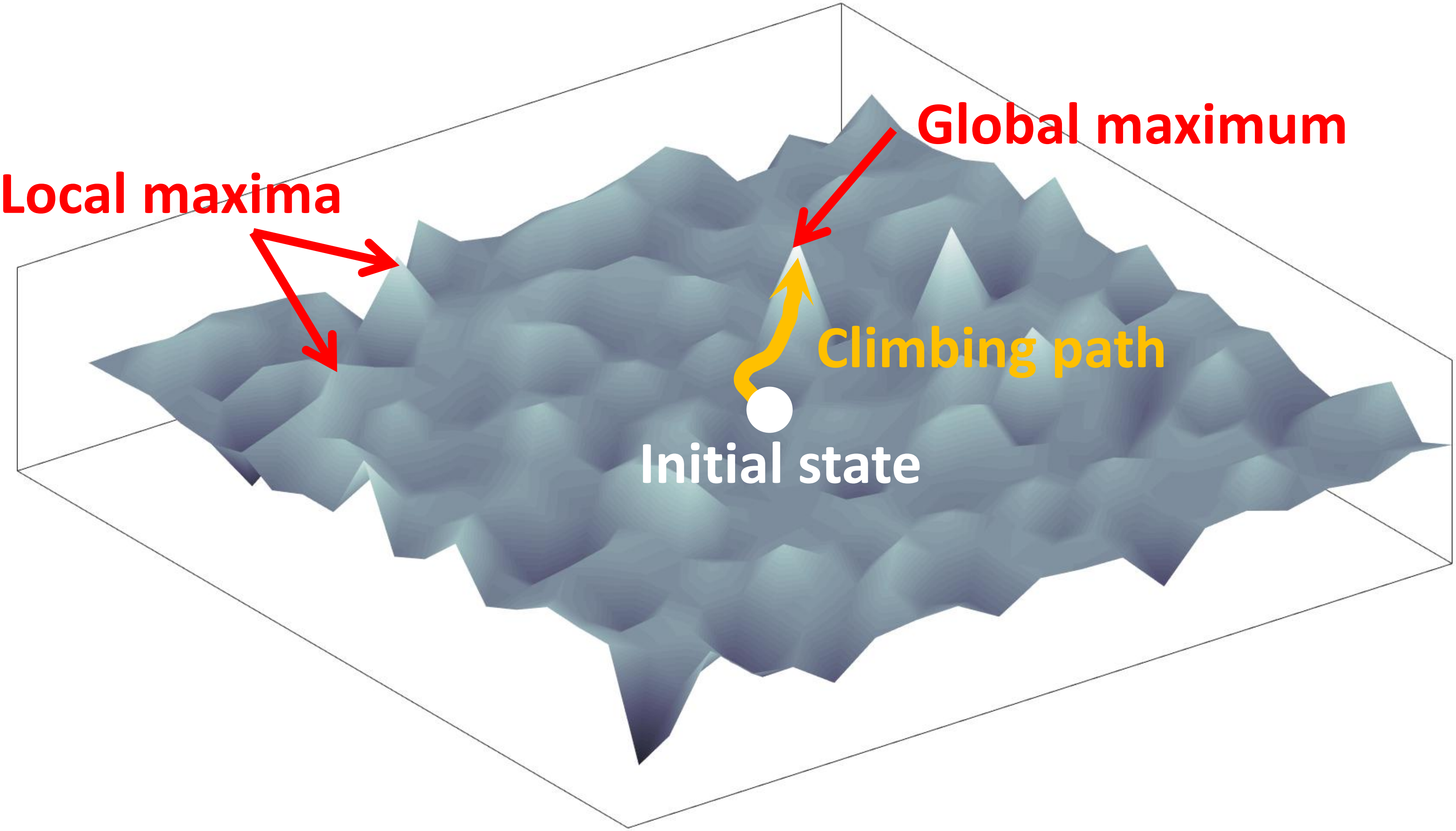
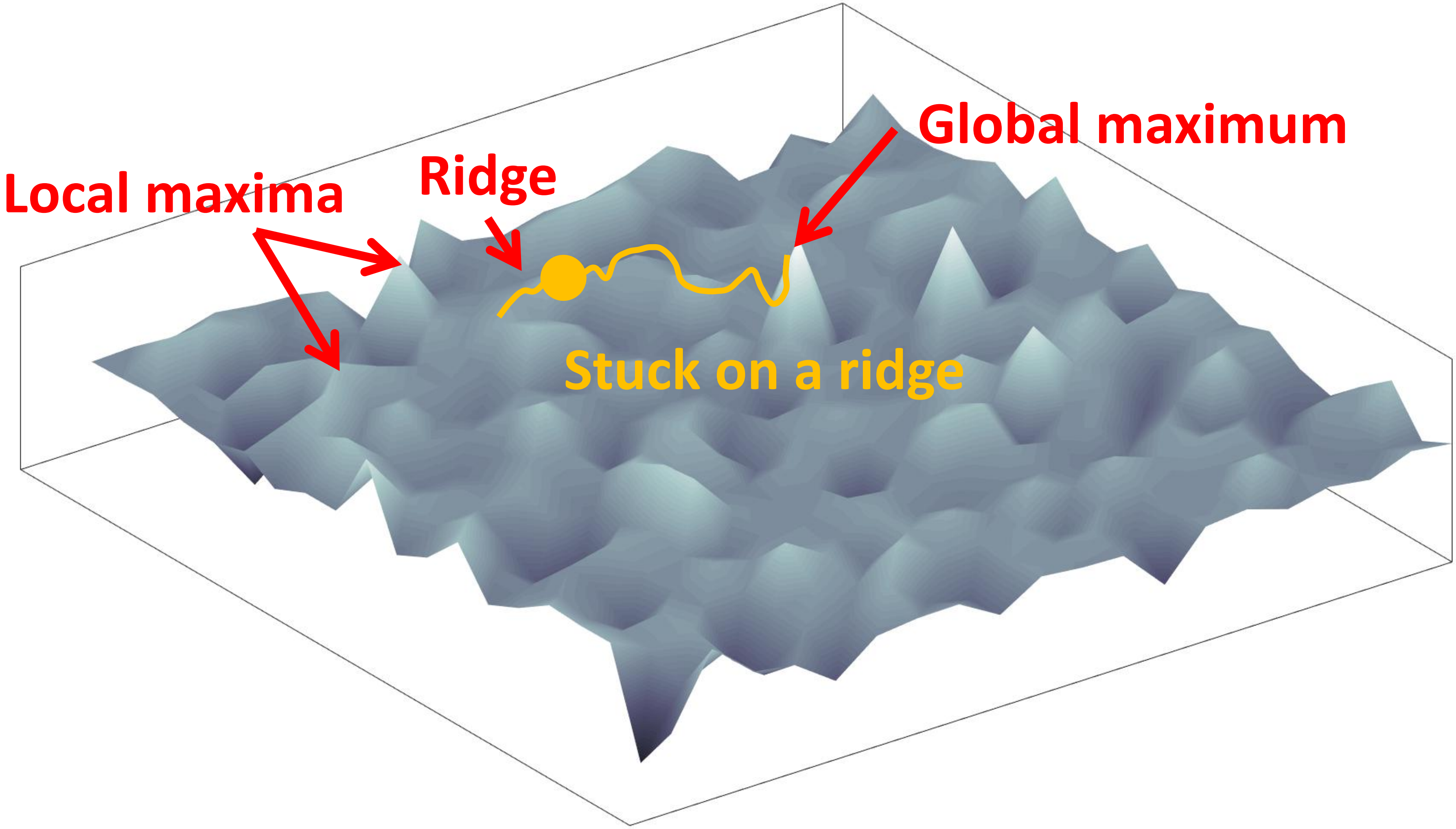


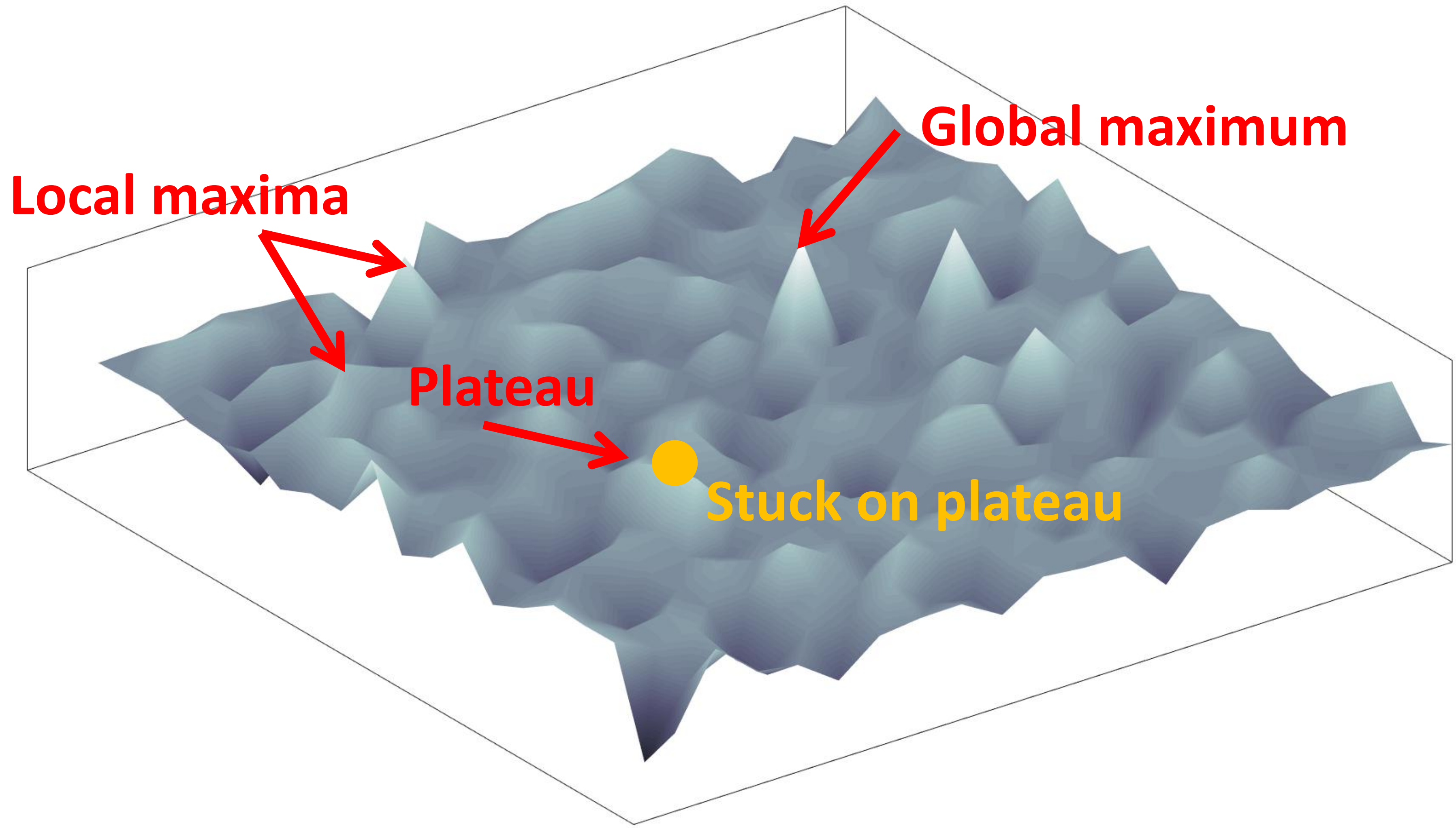
Hill Climbing Problems: Local Maxima



Hill Climbing Problems: Ridges



Hill Climbing Problems: Plateaus



Greedy Best First Search

- **Also a rather primitive informed search approach**
  - **a naive greedy algorithm**
  - **evaluation function: heuristics h(n)**
  - **tries to not "move farther away" from the goal**
  - **does not care about the total path cost**
- **Practicalities:**
  - **it keep track of search history:**
    - **tracks visited states / nodes**
    - **tracks frontier states / nodes**

Greedy Best First: Evaluation Function

Calculate / obtain:

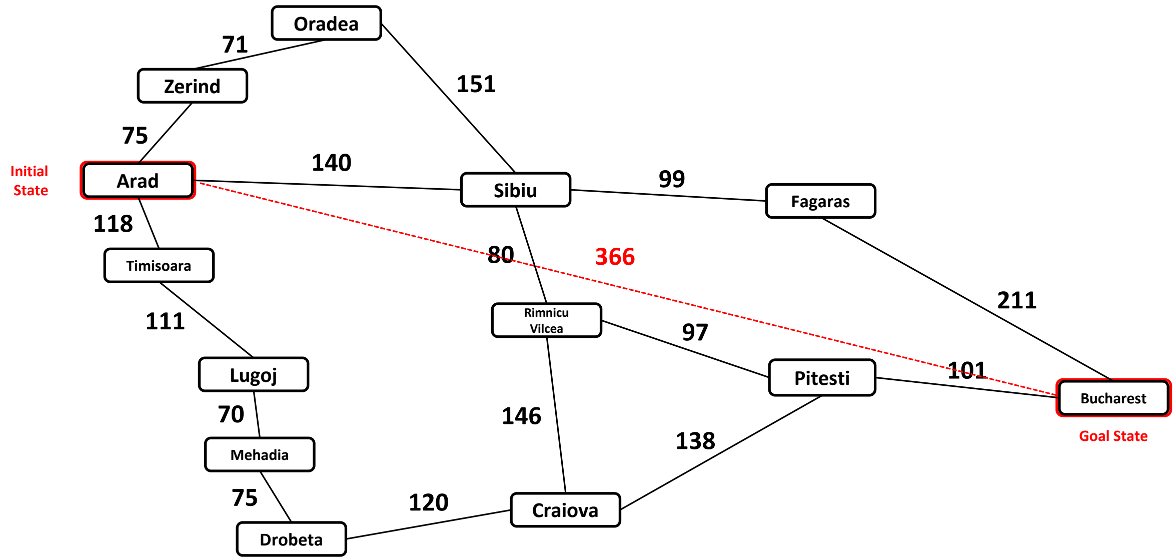
$$f(n) = \mathbf{h(State_n)}$$

A state n with minimum (or maximum) f(n) should be chosen for expansion

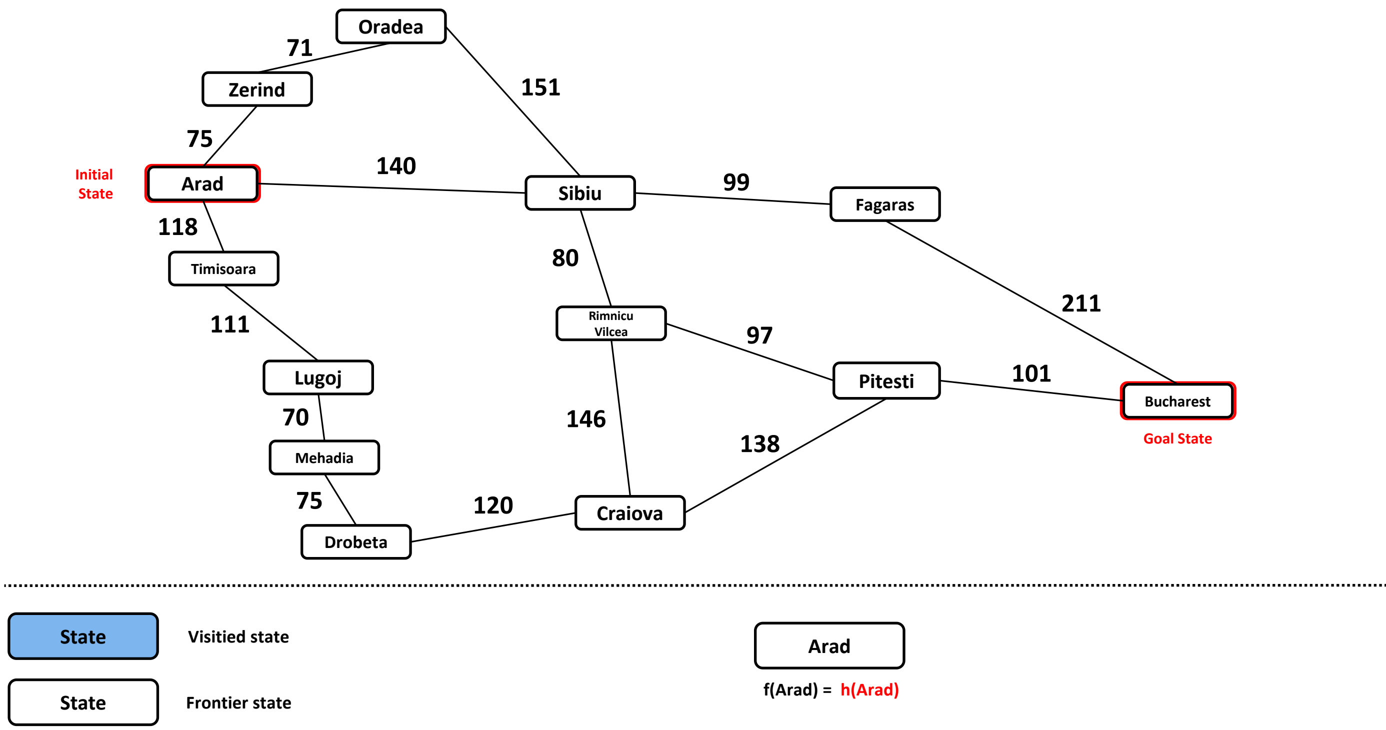
Dracula's Roadtrip: Heuristics h(n)

For this particular problem the heuristic function h(n) is defined by a straight-line (Euclidean) distance between two states (cities).

"As the crows flies" in other words.



Dracula's Roadtrip: Greedy Best First



Straight-line distance to Bucharest (h(State)):

Arad	366
Bucharest	0
Craiova	160
Drobeta	242
Eforie	161
Fagaras	176
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Hirsova	151
Iasi	226
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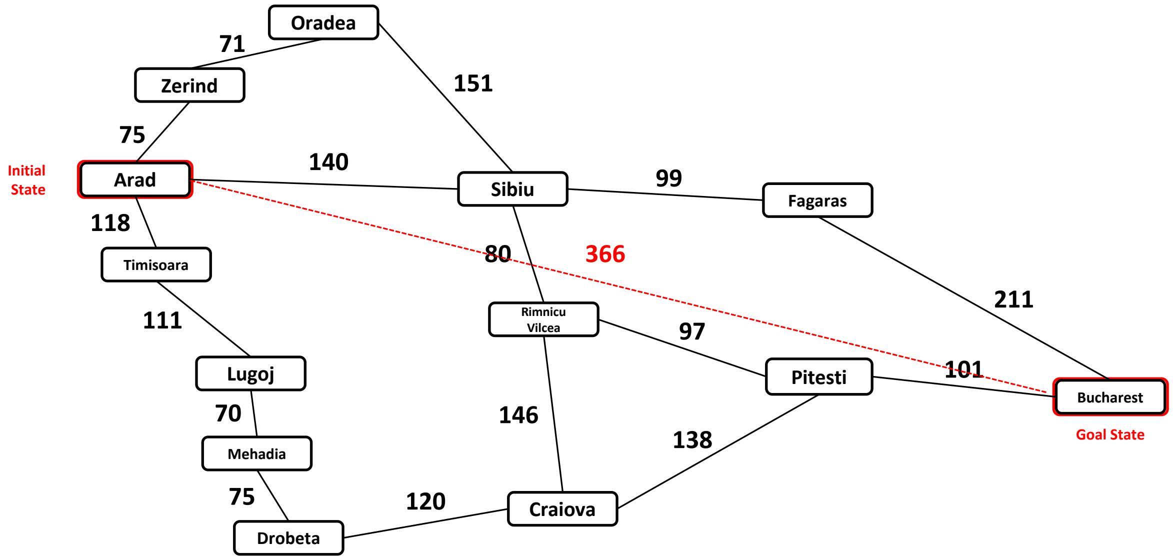
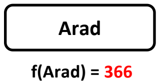
Dracula’s Roadtrip: Greedy Best First



State	Visitied state
State	Frontier state



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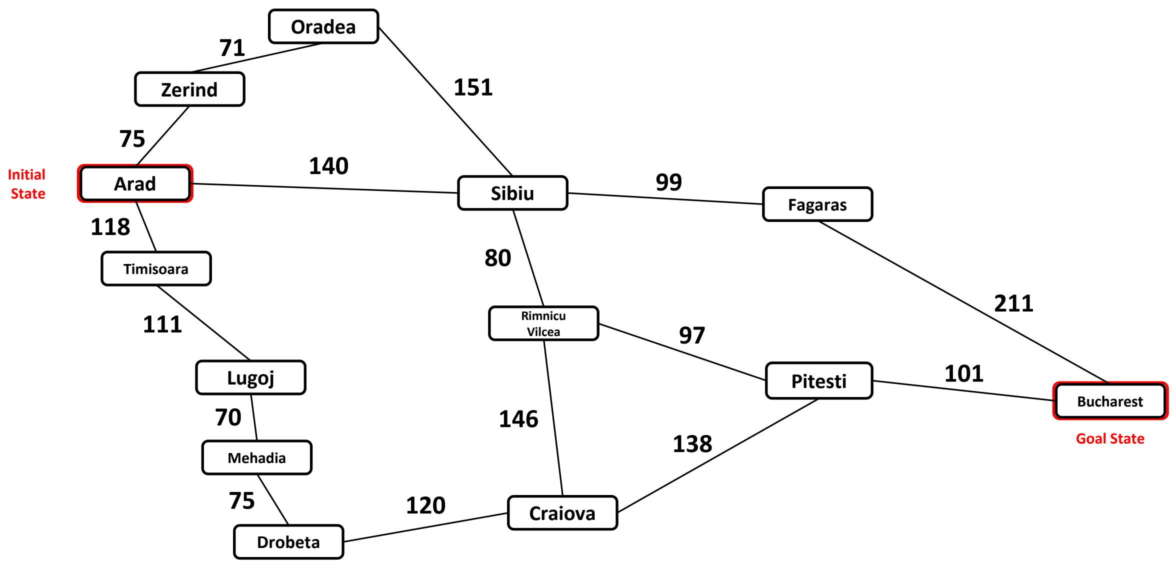

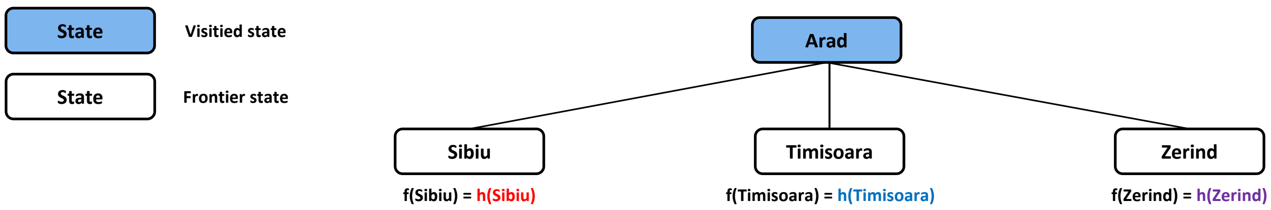

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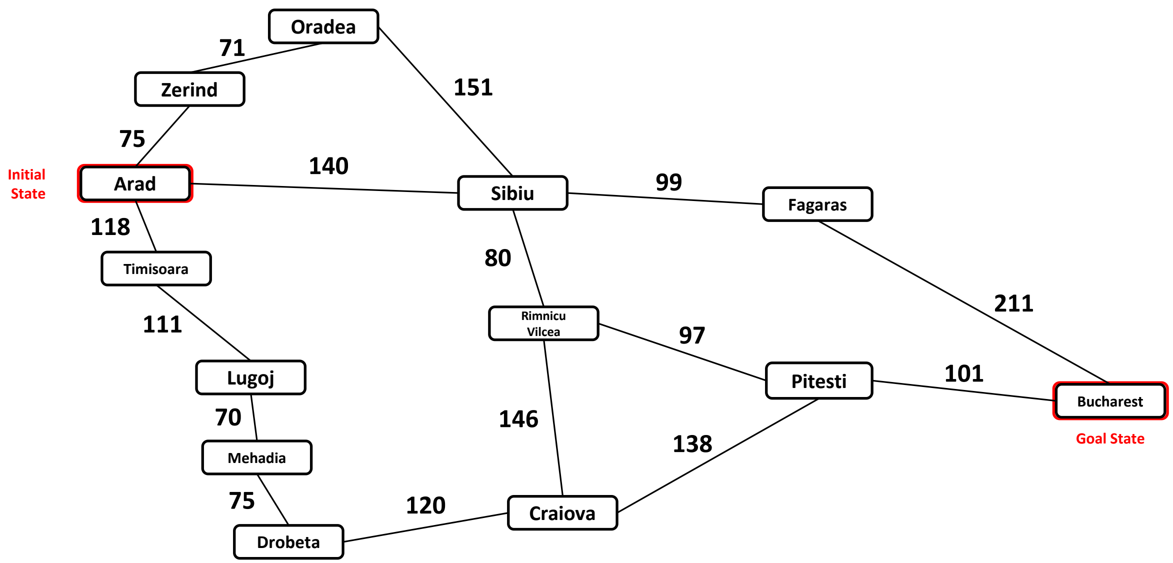

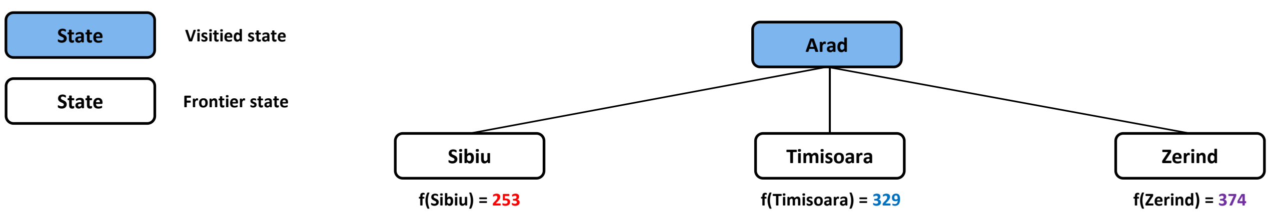

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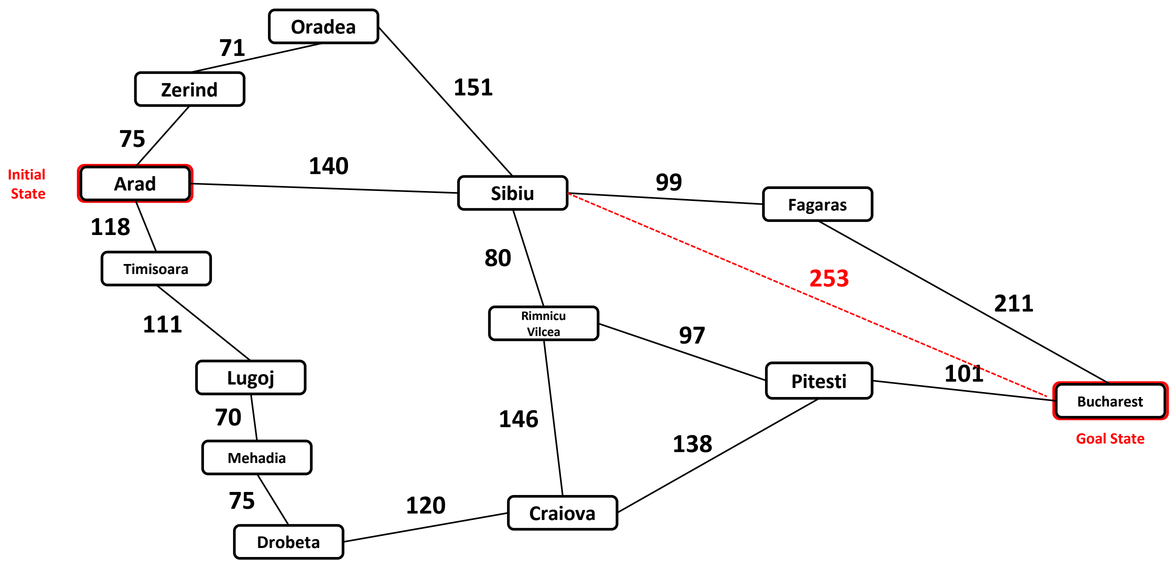

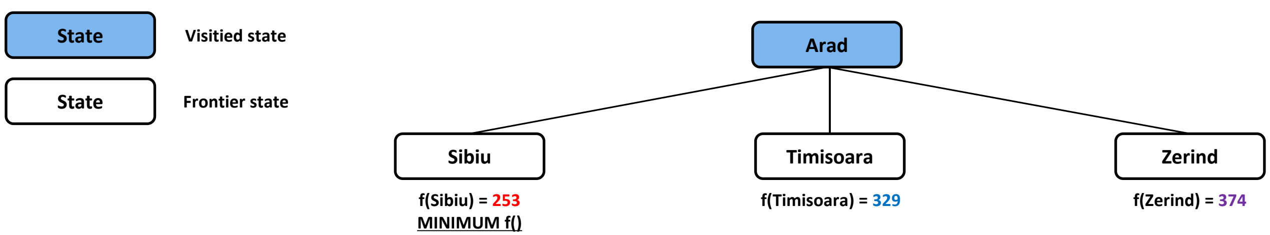

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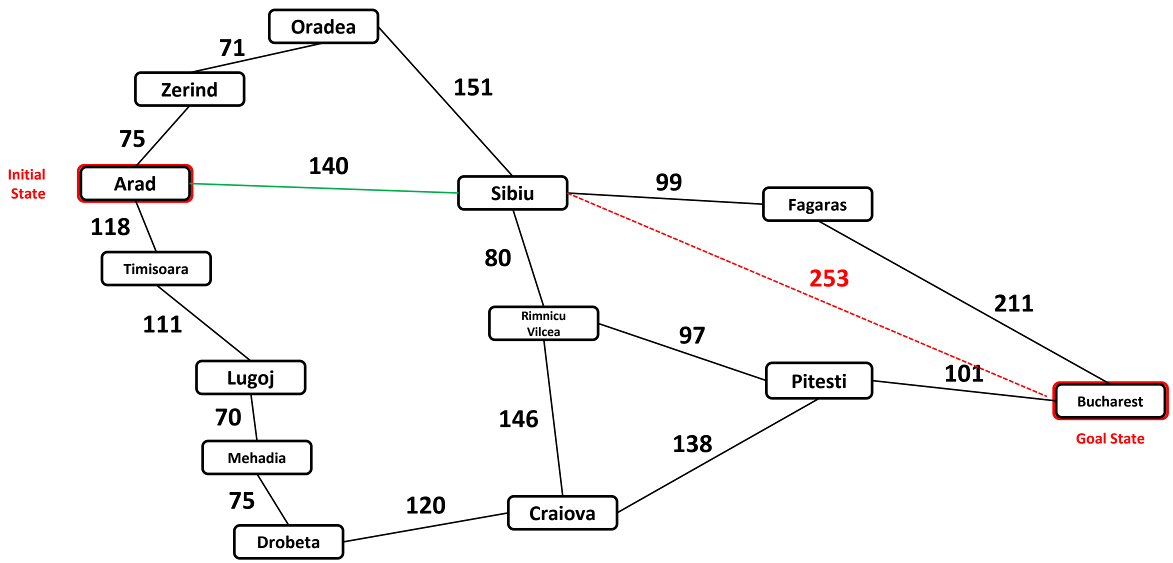

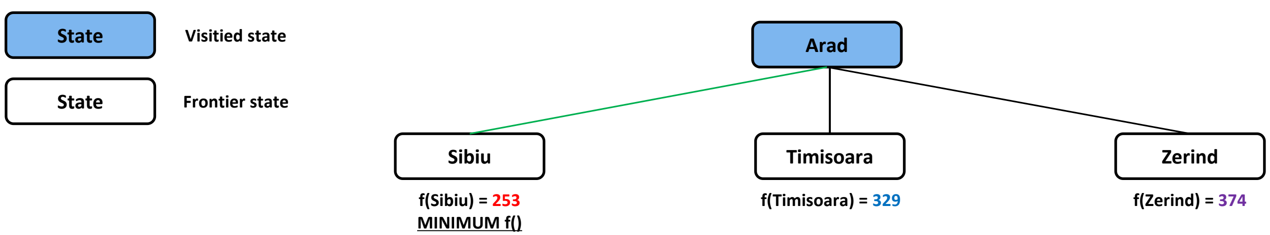

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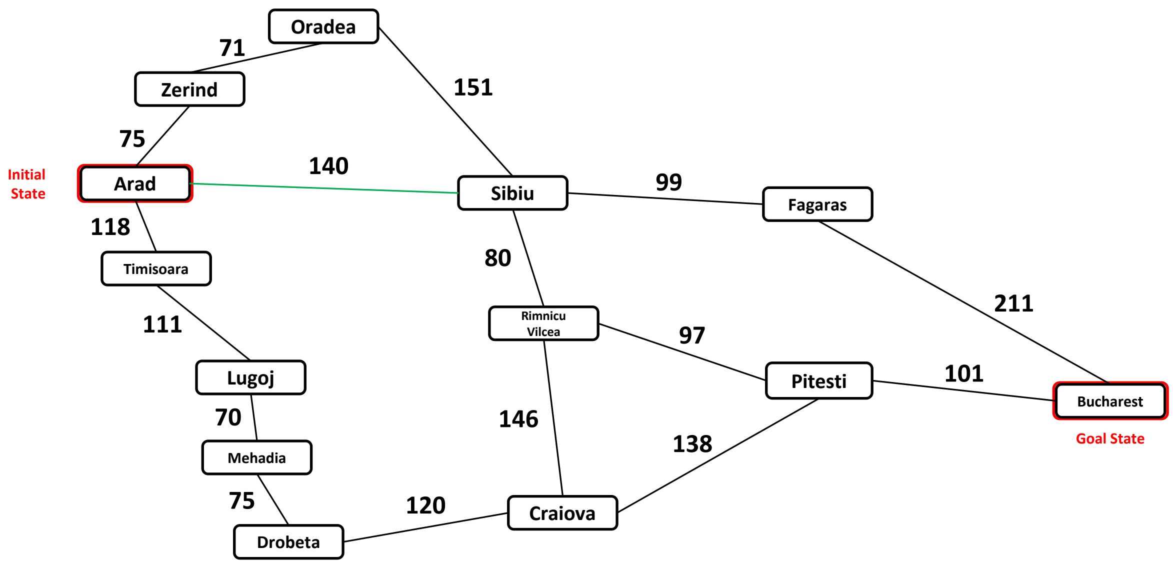

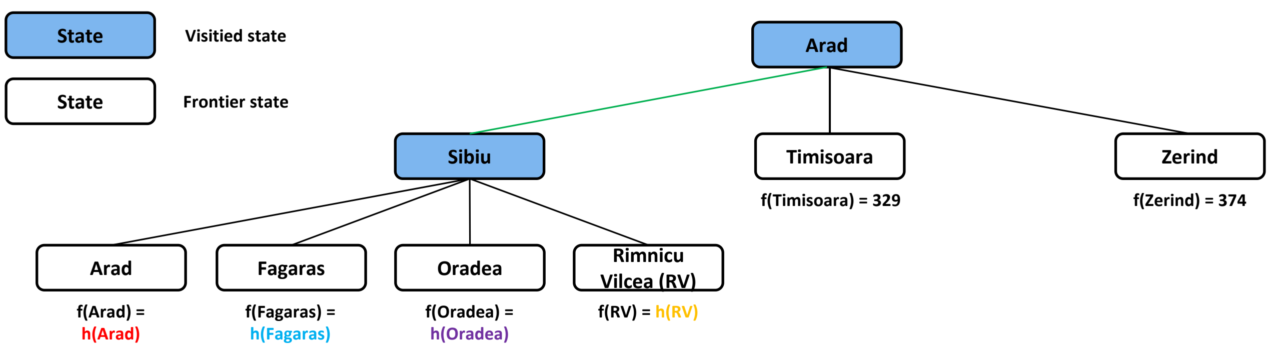

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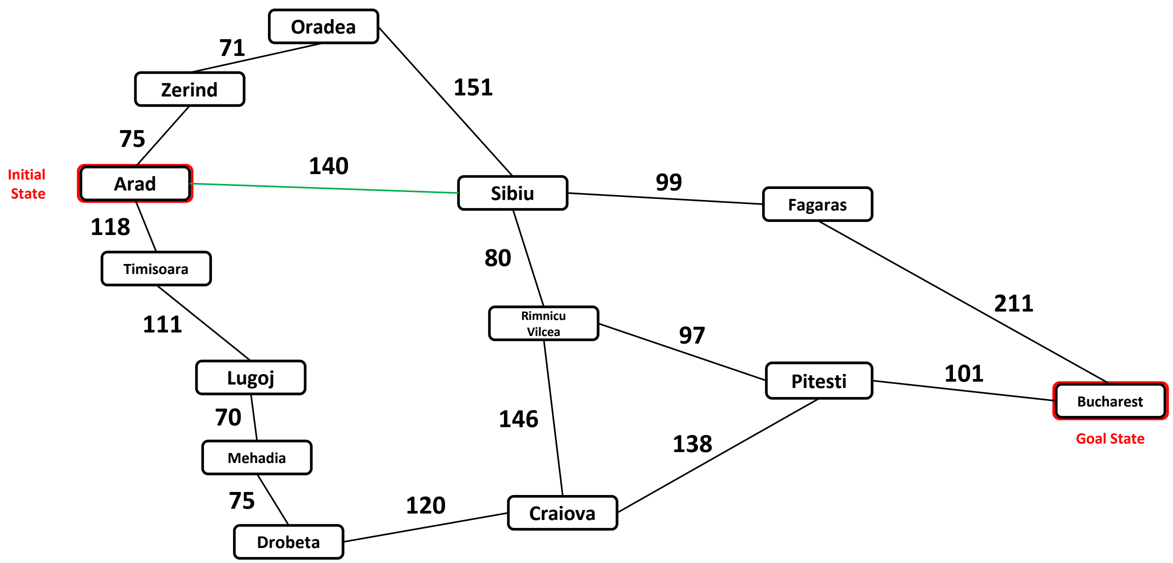

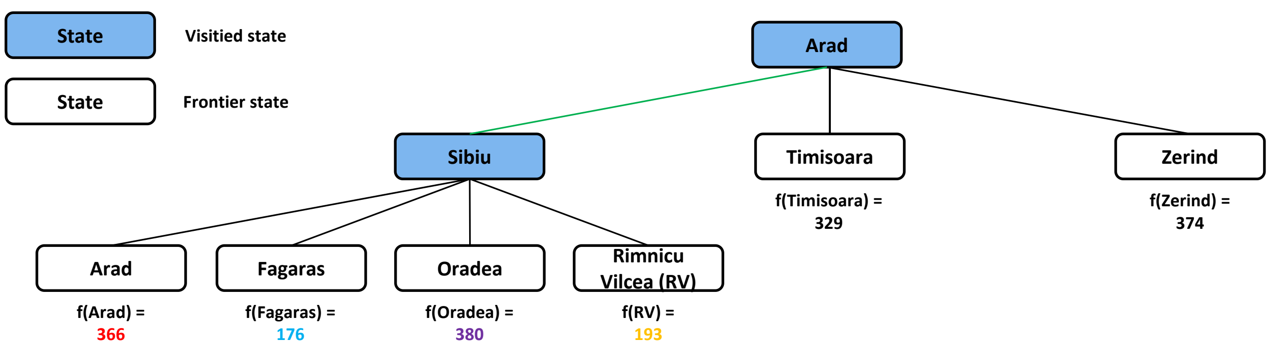

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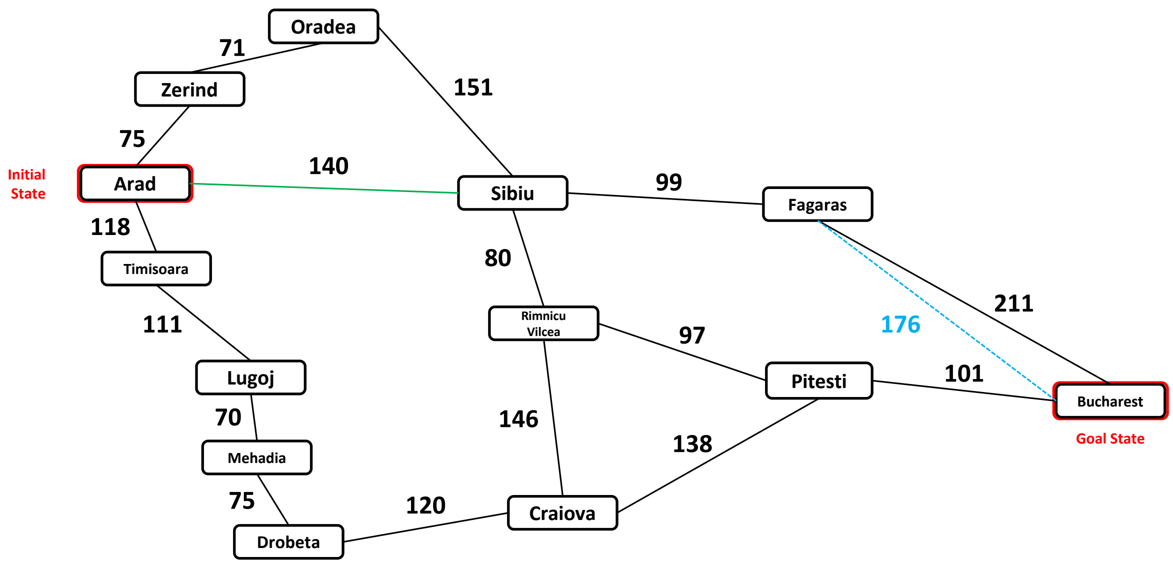

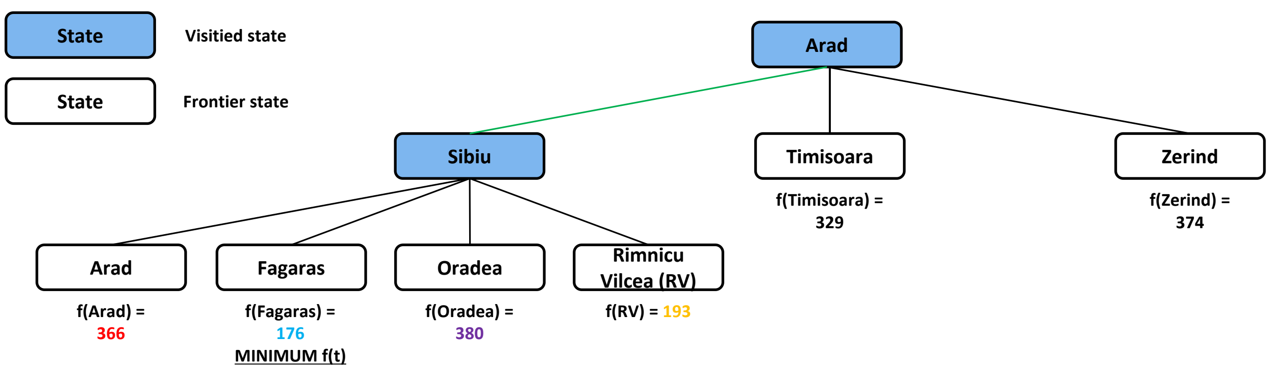

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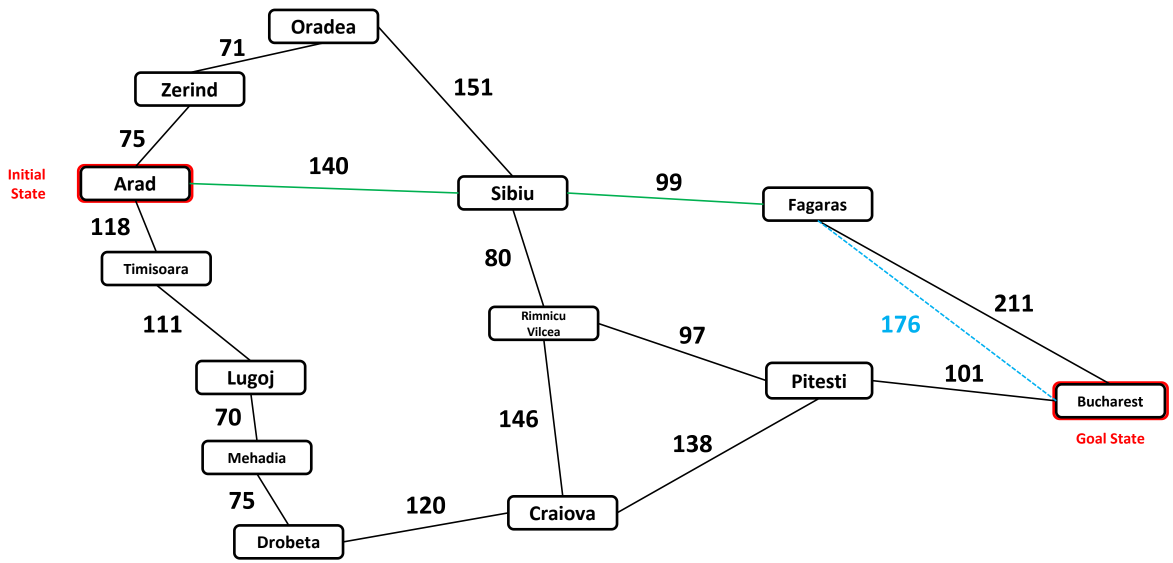

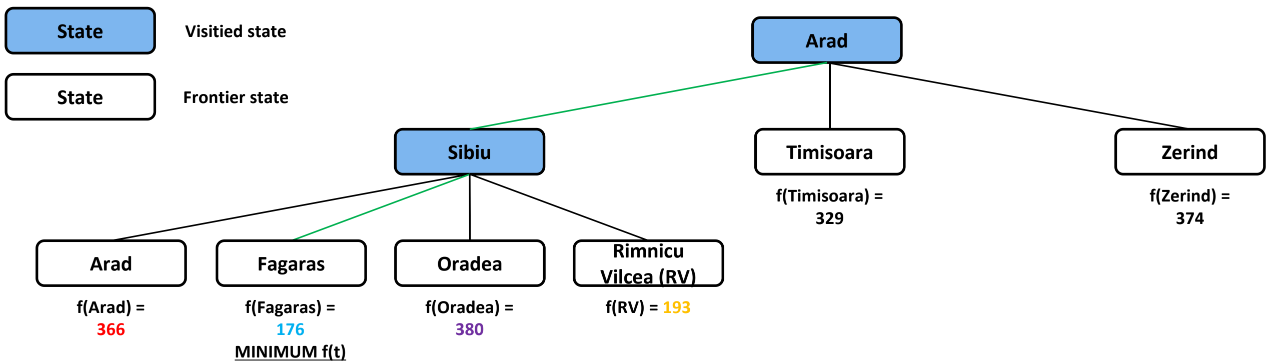

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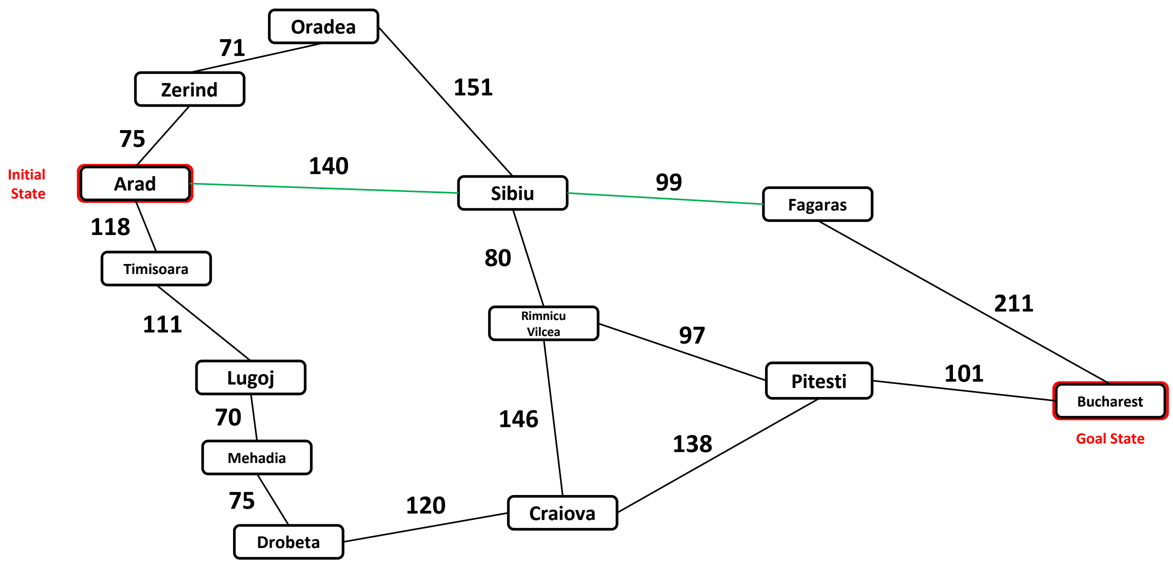

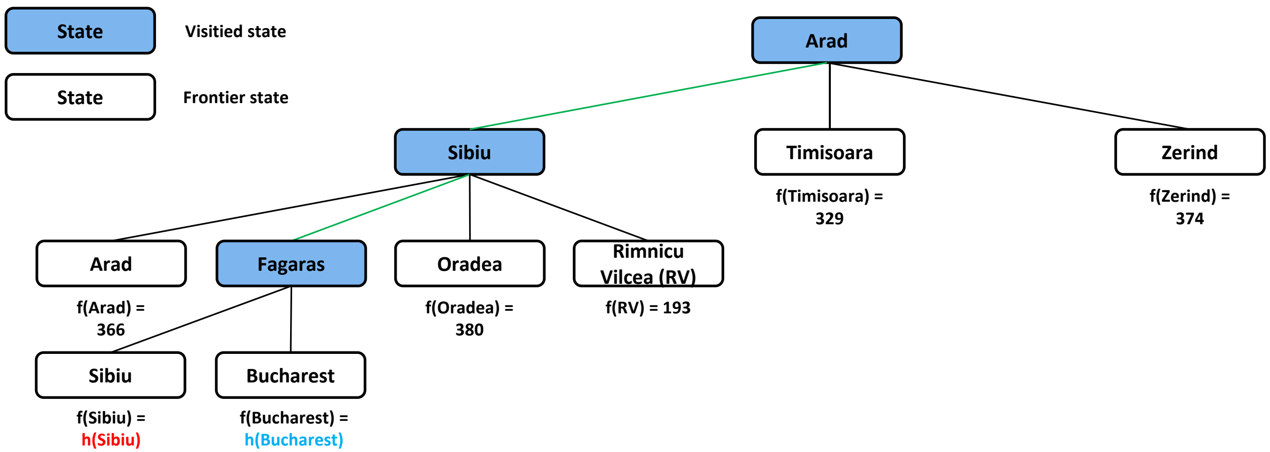

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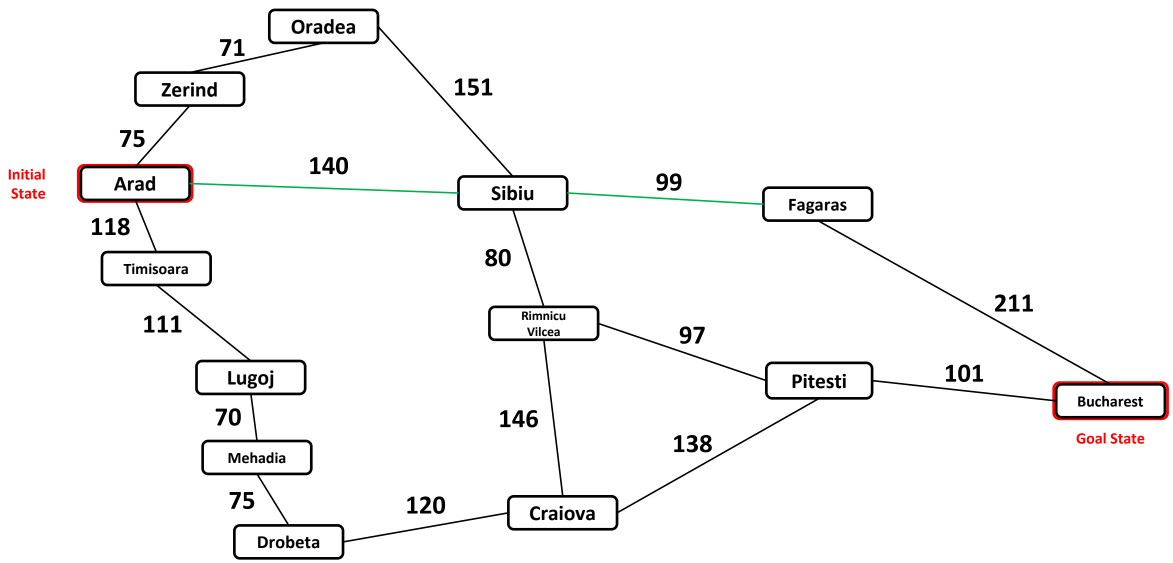

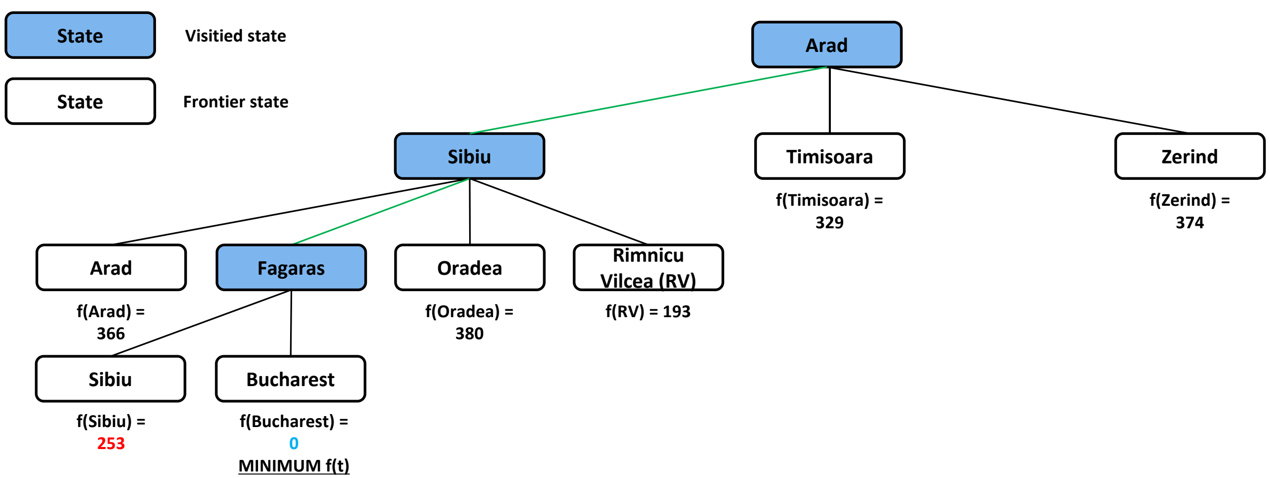

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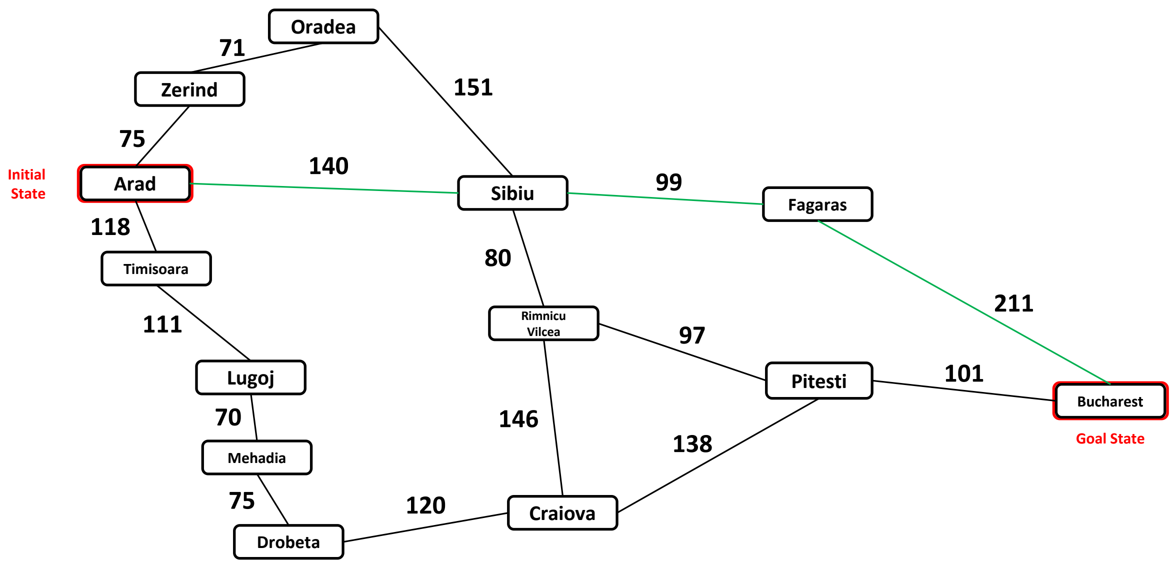

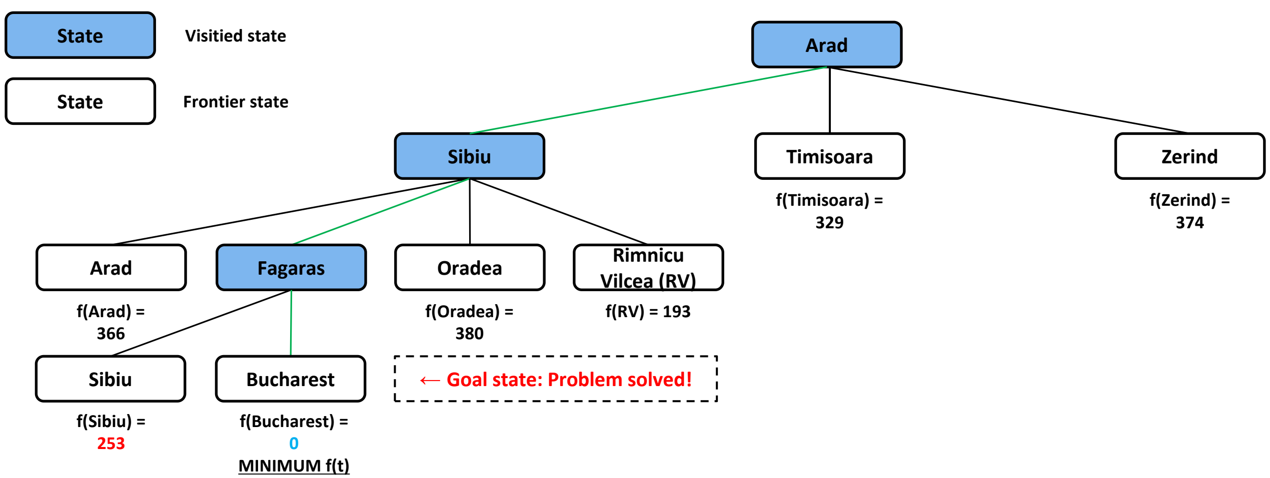

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A* Algorithm: Evaluation Function

Calculate / obtain:

$f(n) = \mathbf{g(State_n)} + \mathbf{h(State_n)}$

where:

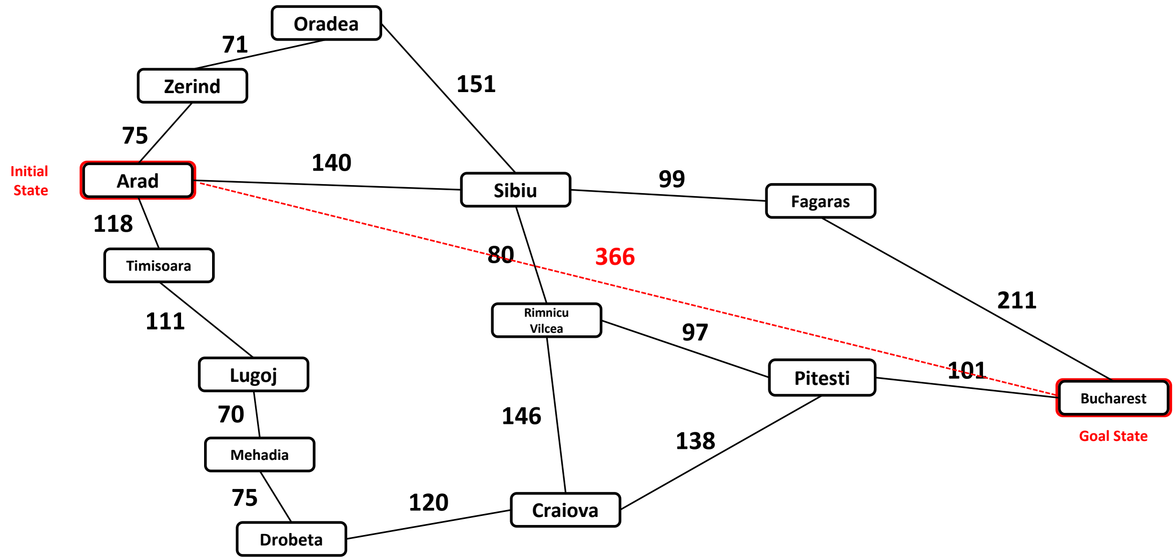
- **g(n) - initial node to node n path cost**
- **h(n) - estimated cost of the best path that continues from node n to a goal node**

A state n with minimum (maximum) f(n) should be chosen for expansion

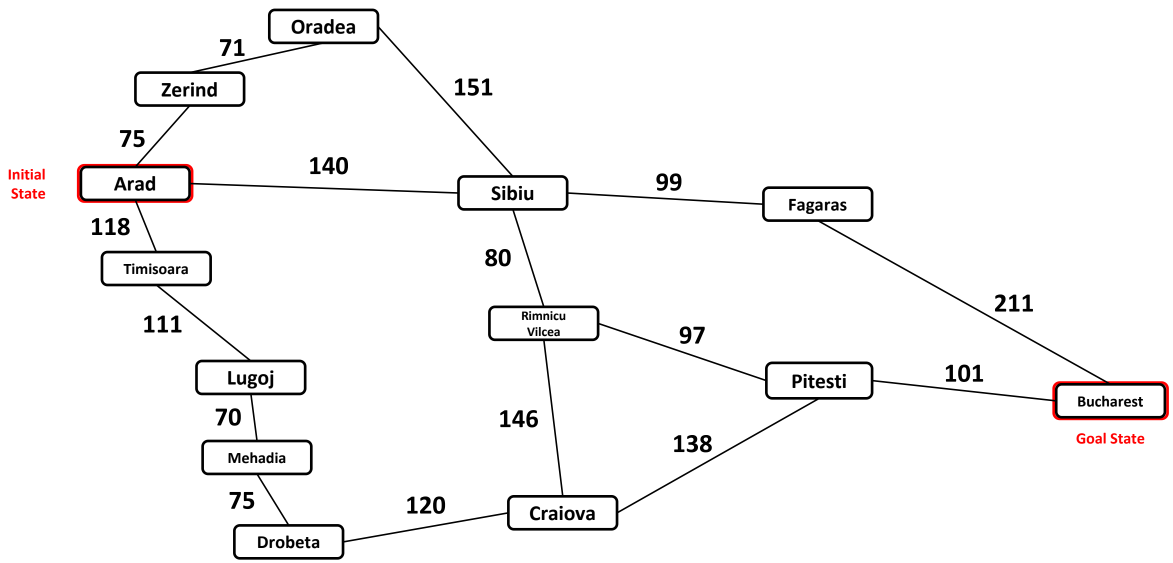
Dracula’s Roadtrip: Heuristics h(n)

For this particular problem the heuristic function h(n) is defined by a **straight-line (Euclidean) distance** between two states (cities).

“As the crows flies” in other words.



Dracula's Roadtrip: A* Search



State	Visitied state
State	Frontier state

Arad

f(Arad) = g(Arad) + h(Arad)

Straight-line distance to Bucharest (h(State)):

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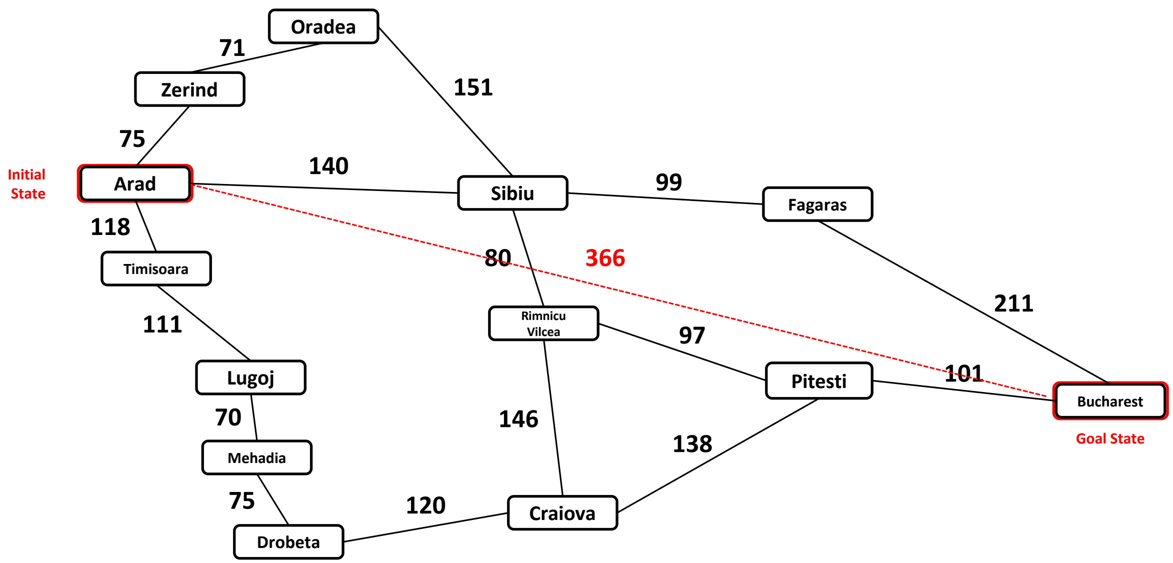
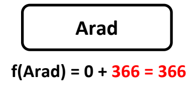


State — Visitied state

State — Frontier state



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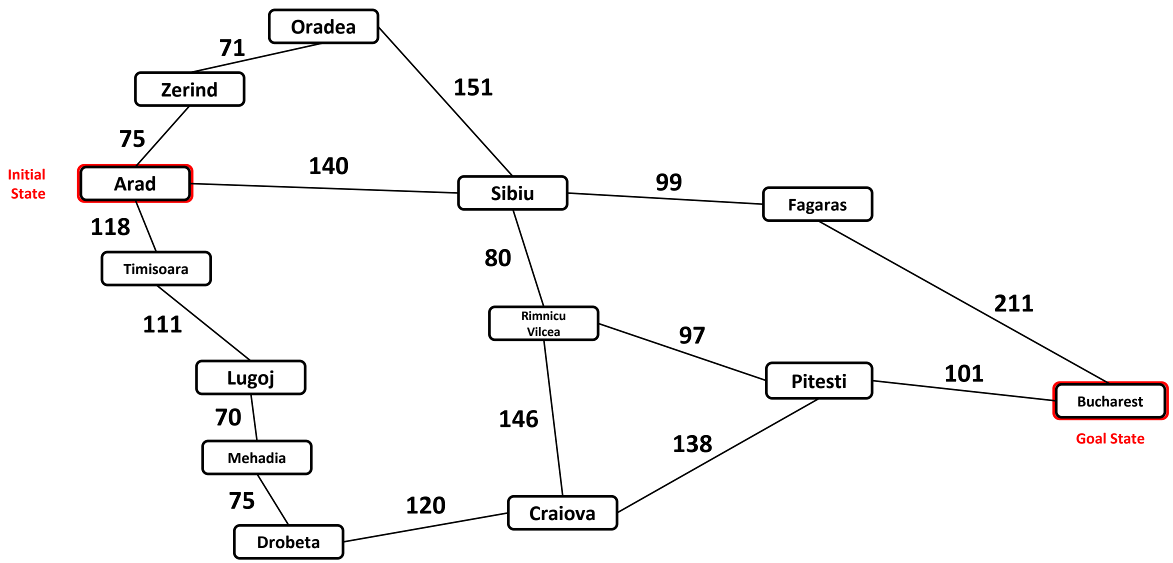

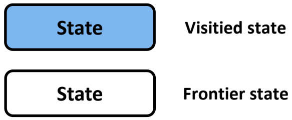

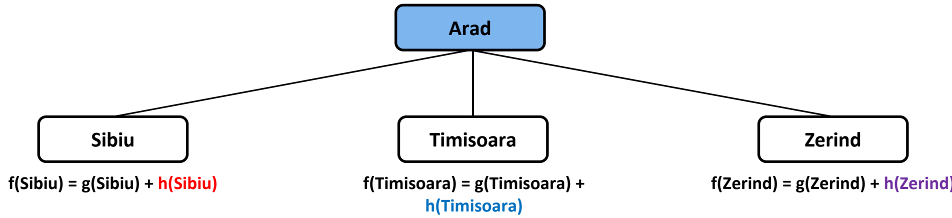

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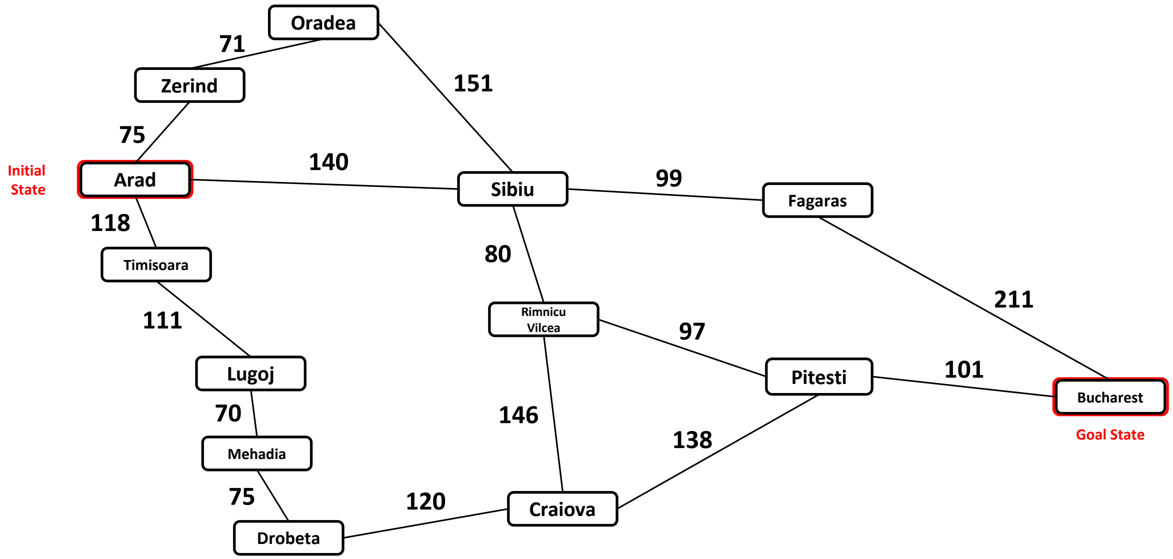

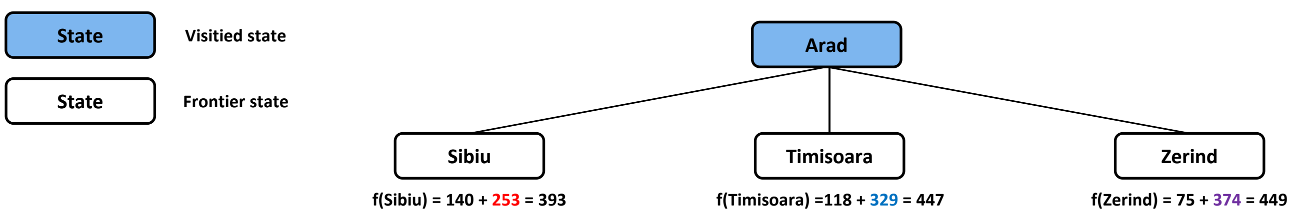

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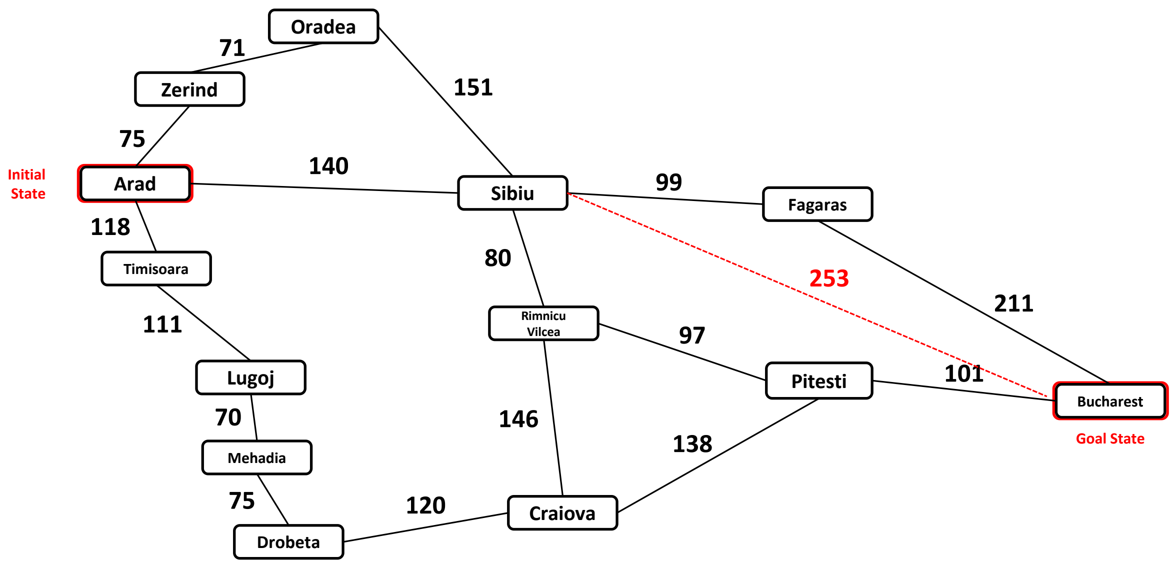
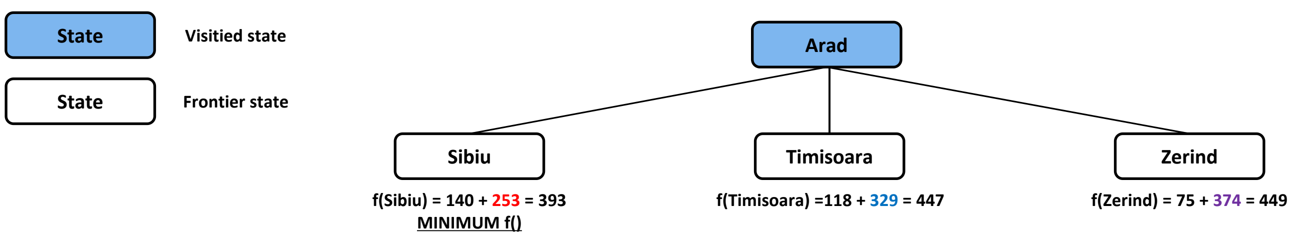
Dracula's Roadtrip: A* Search





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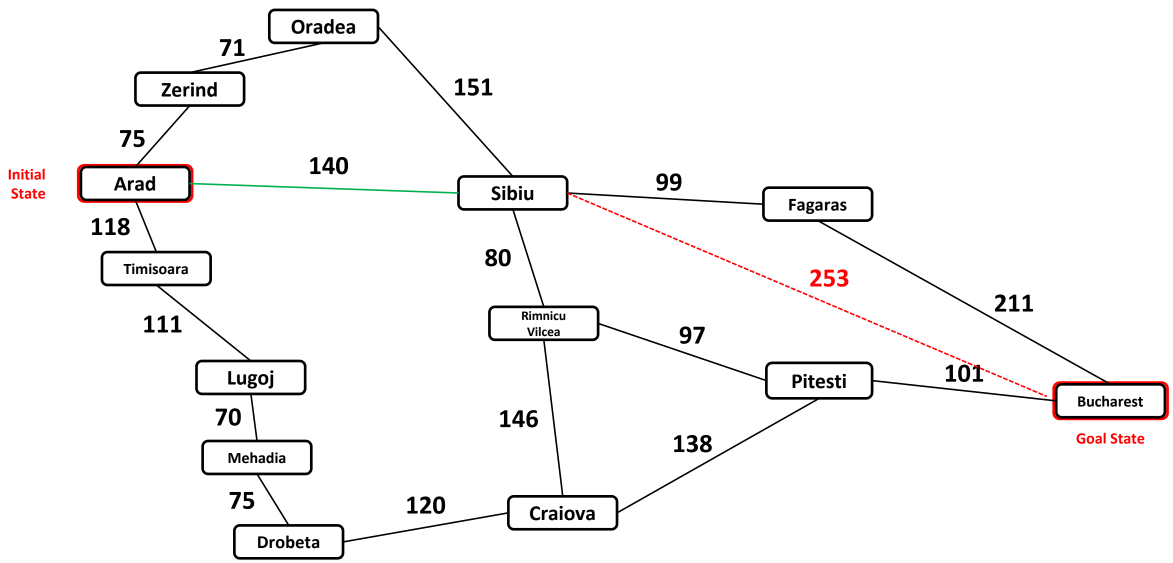

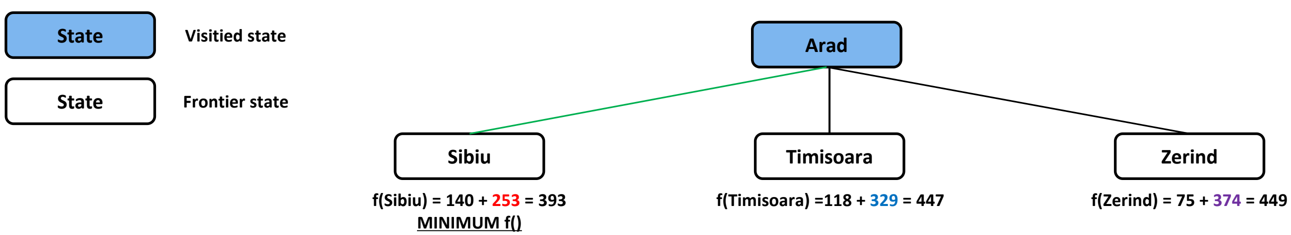

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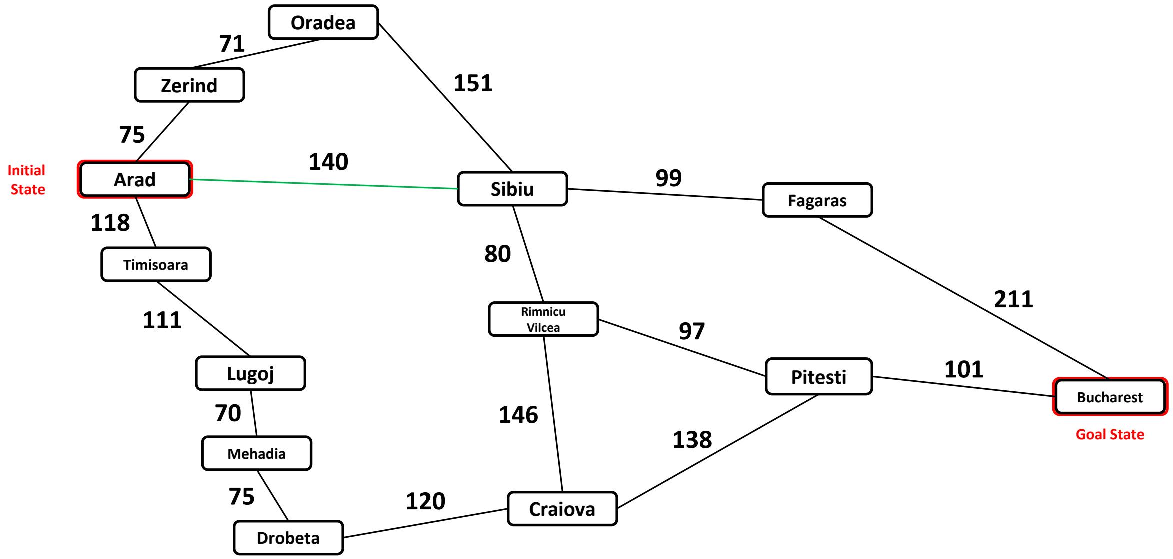

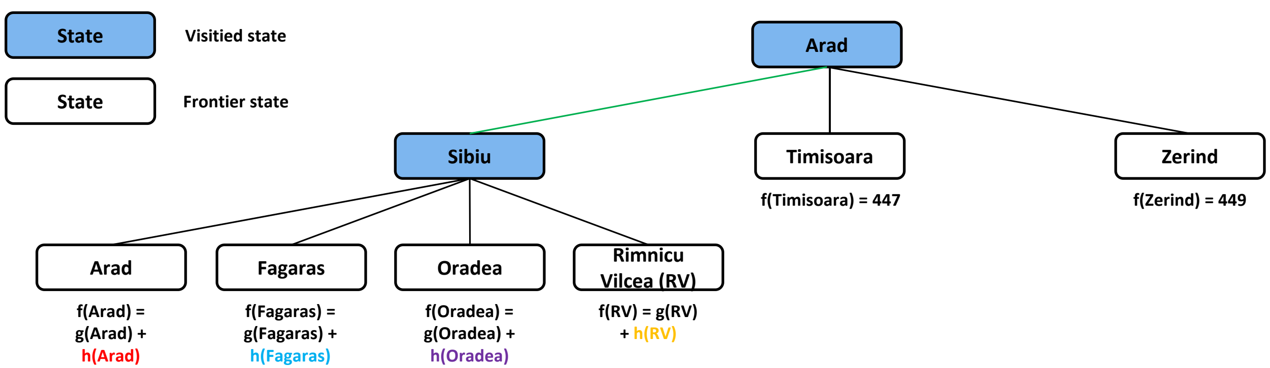

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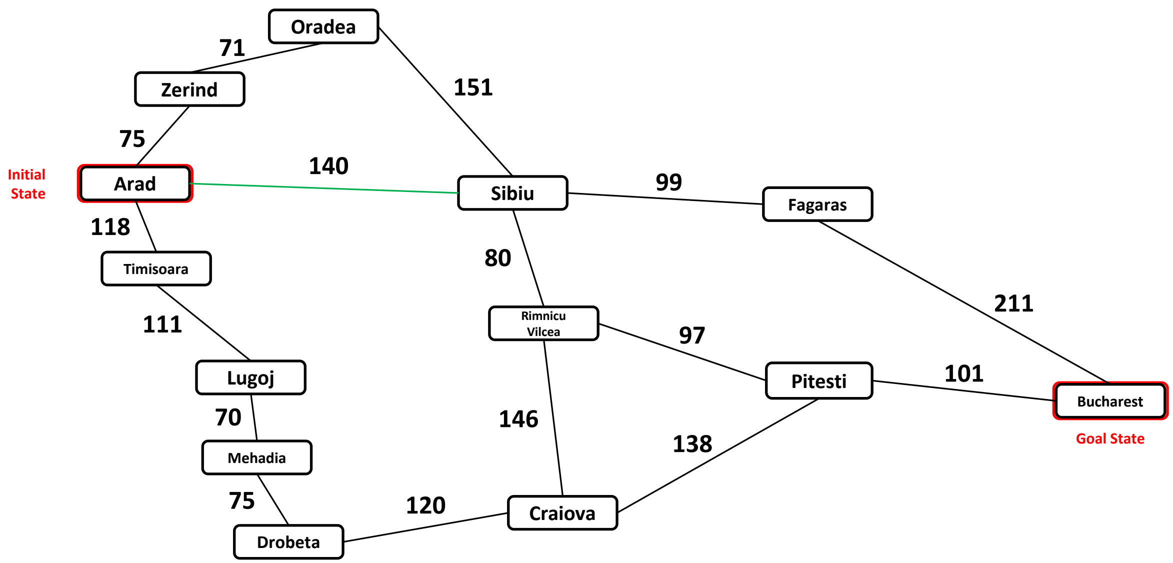

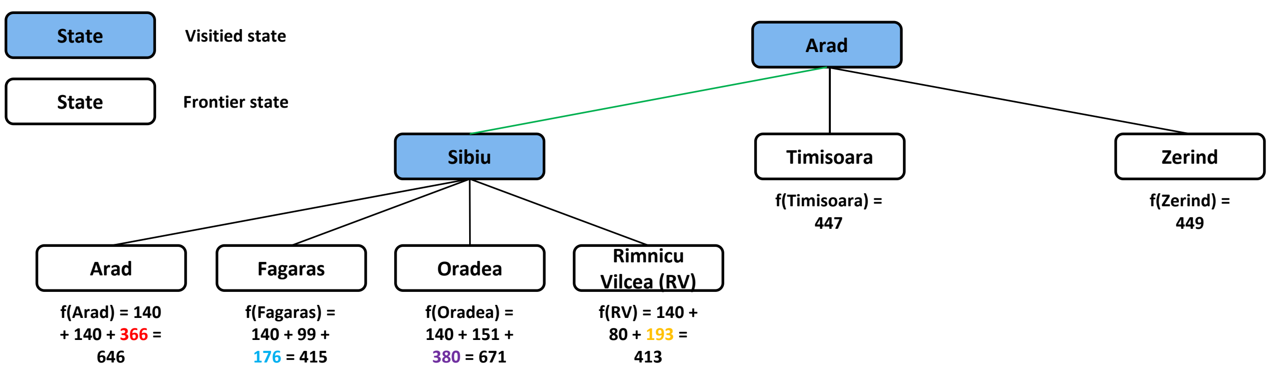

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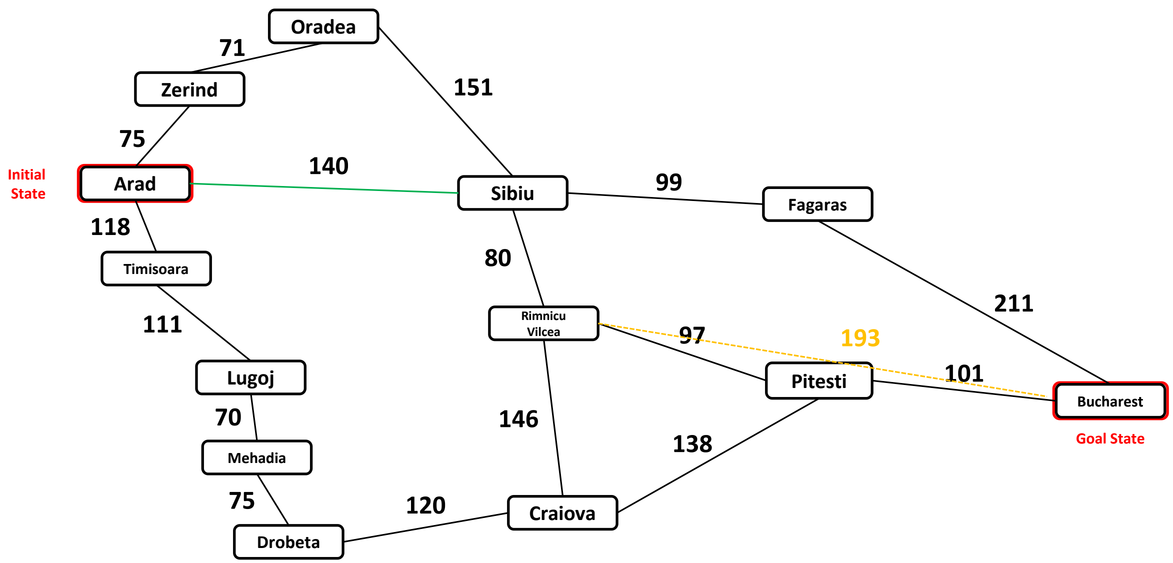

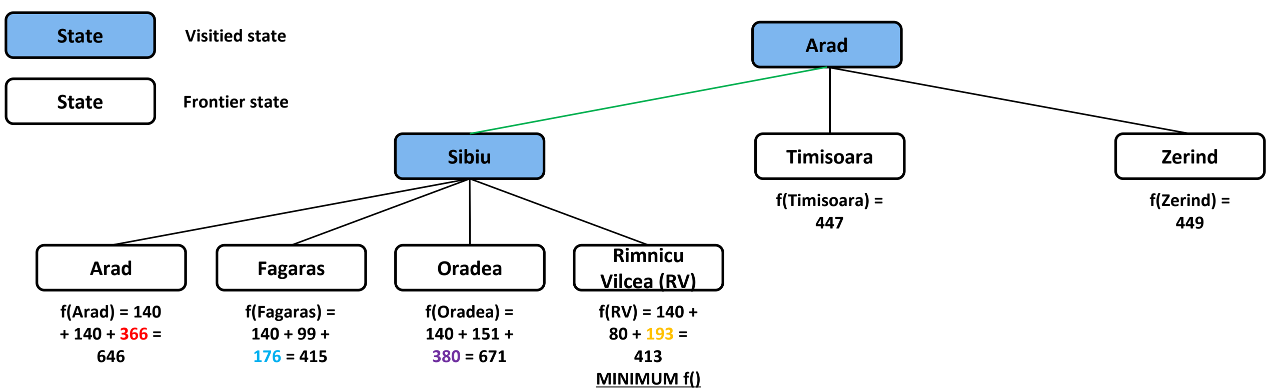

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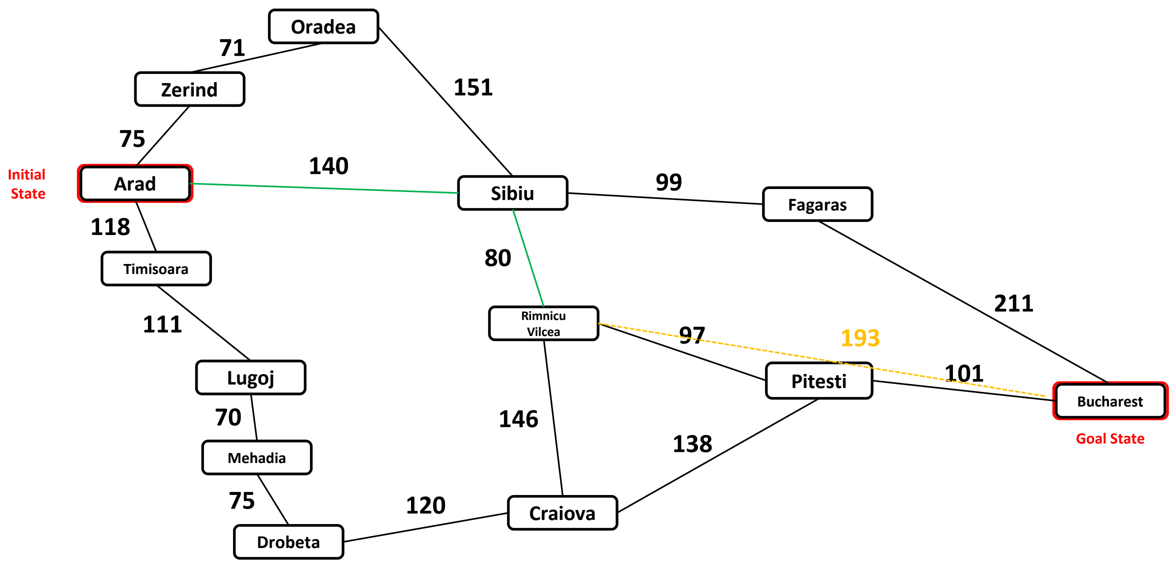

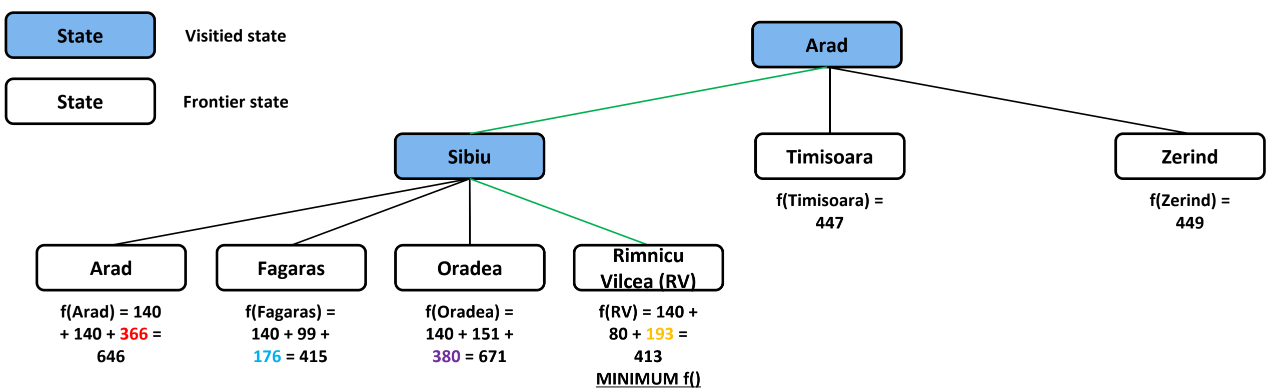

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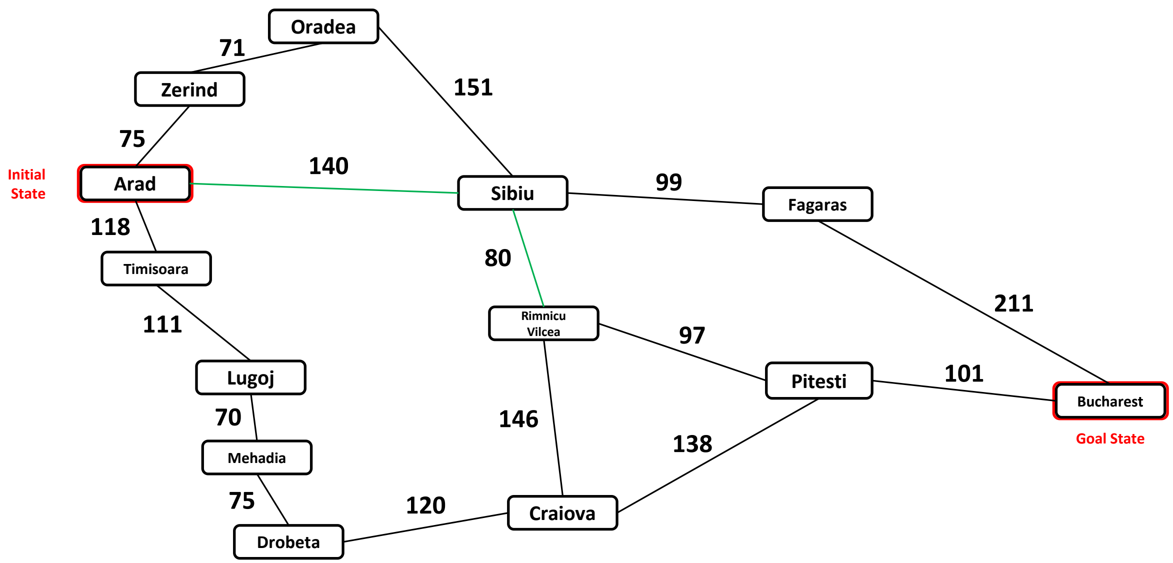

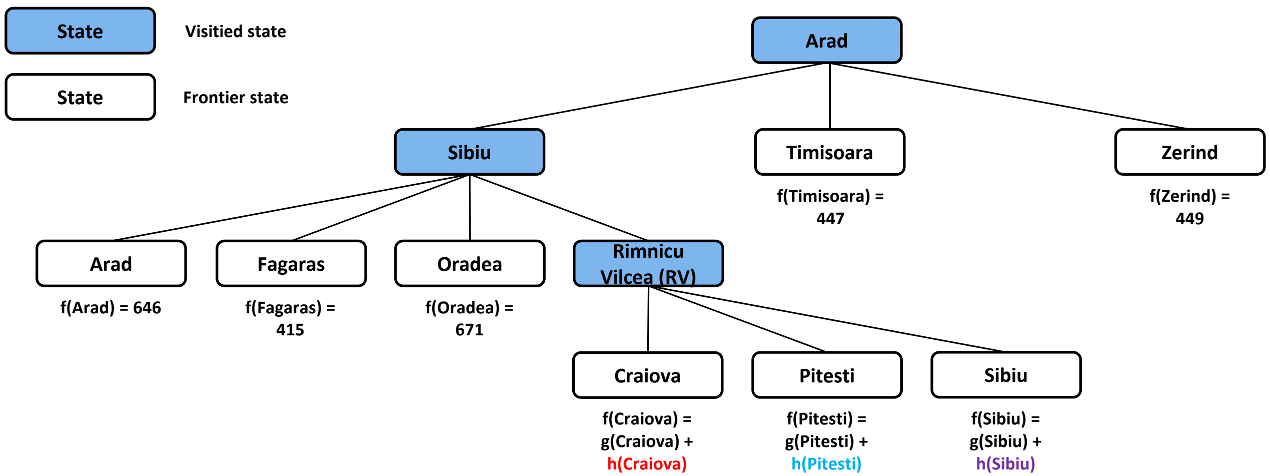

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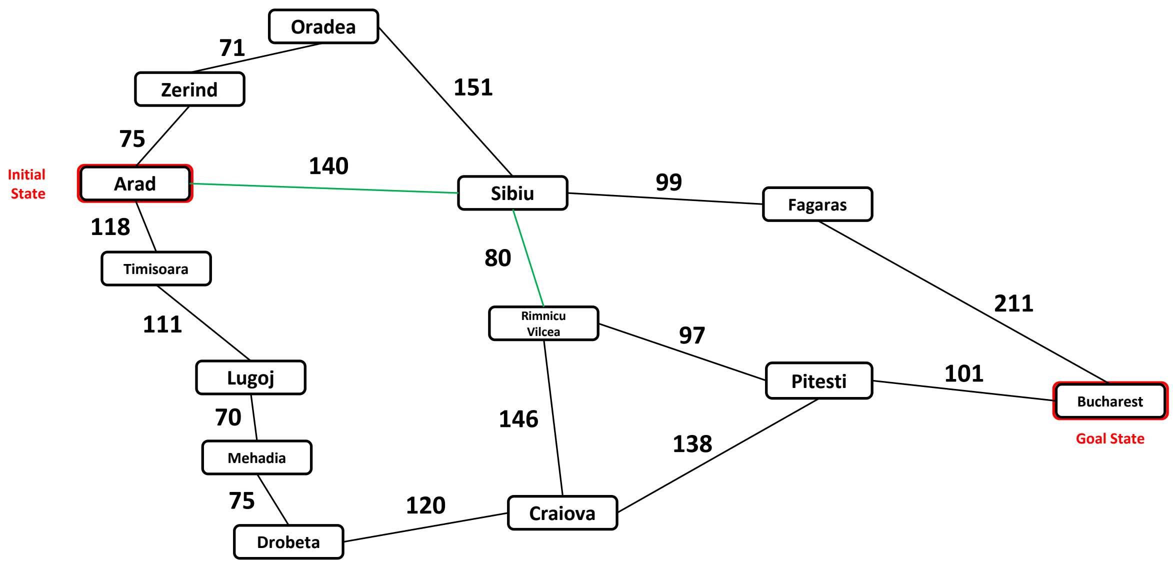

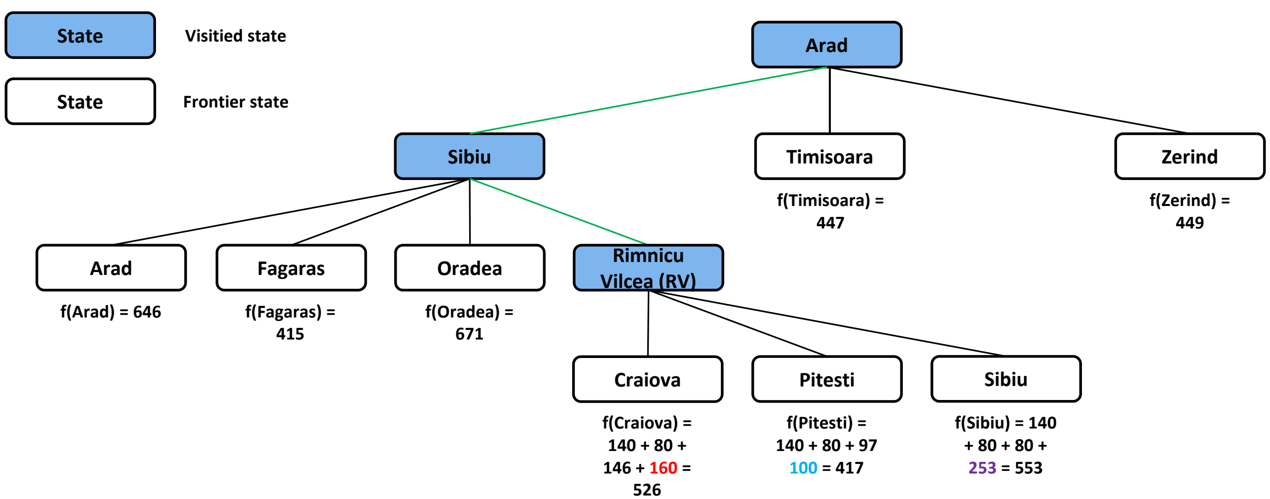

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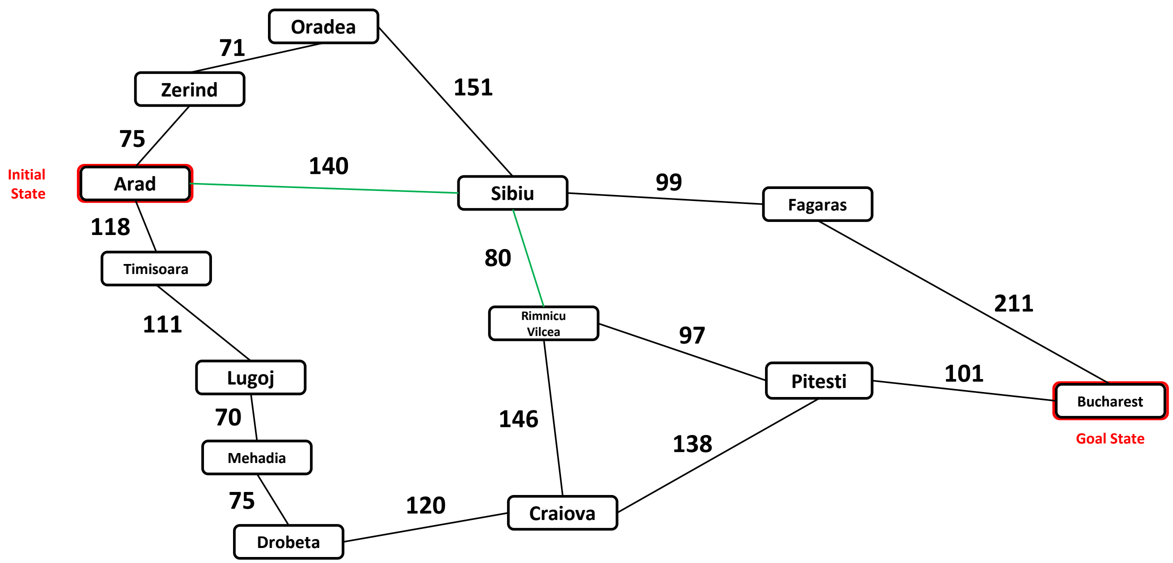

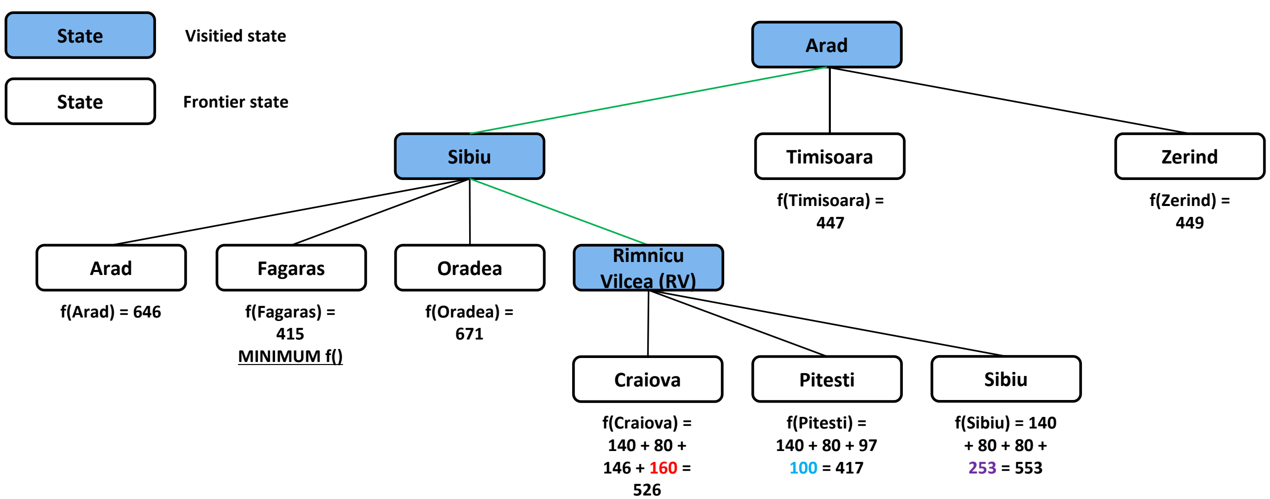

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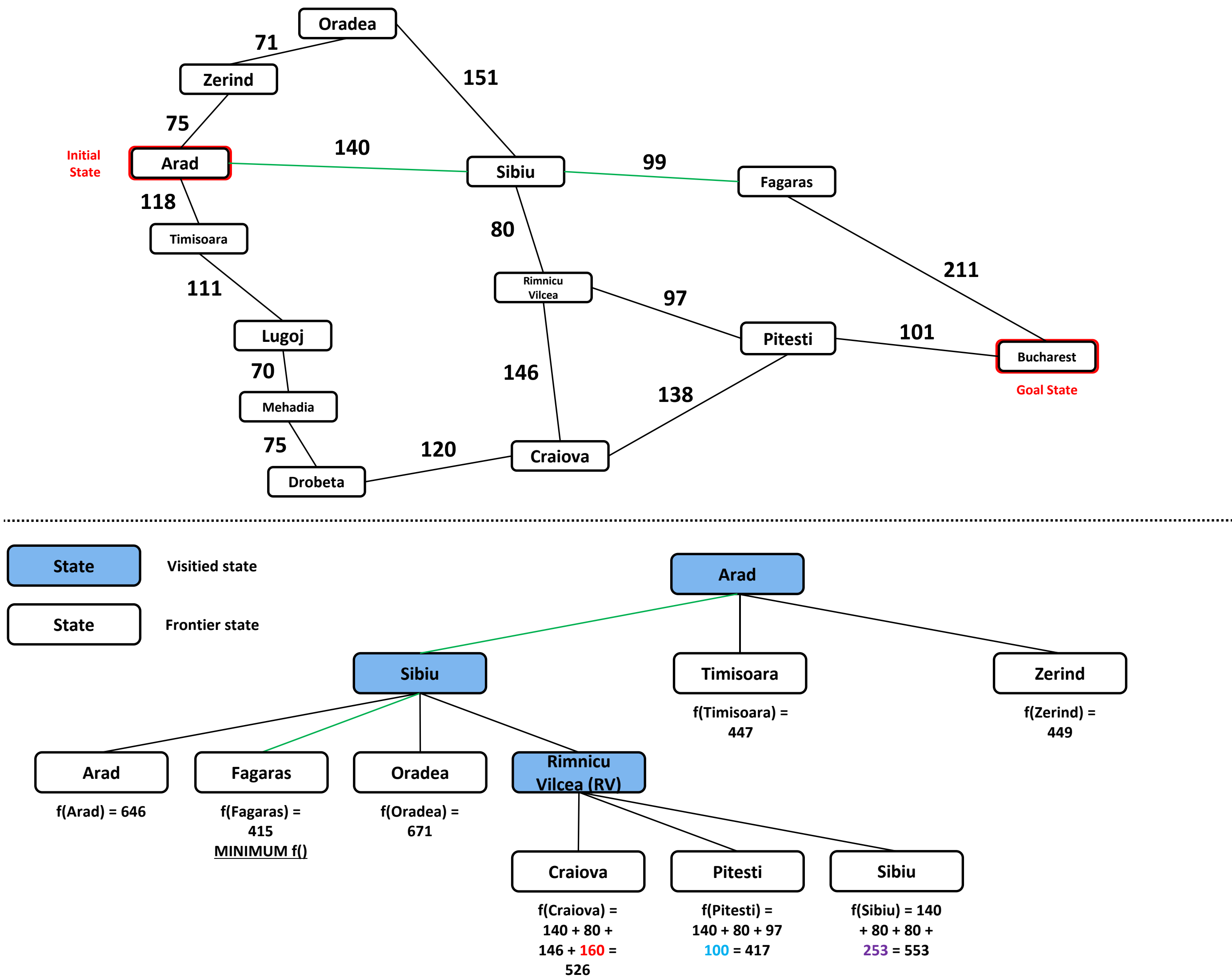

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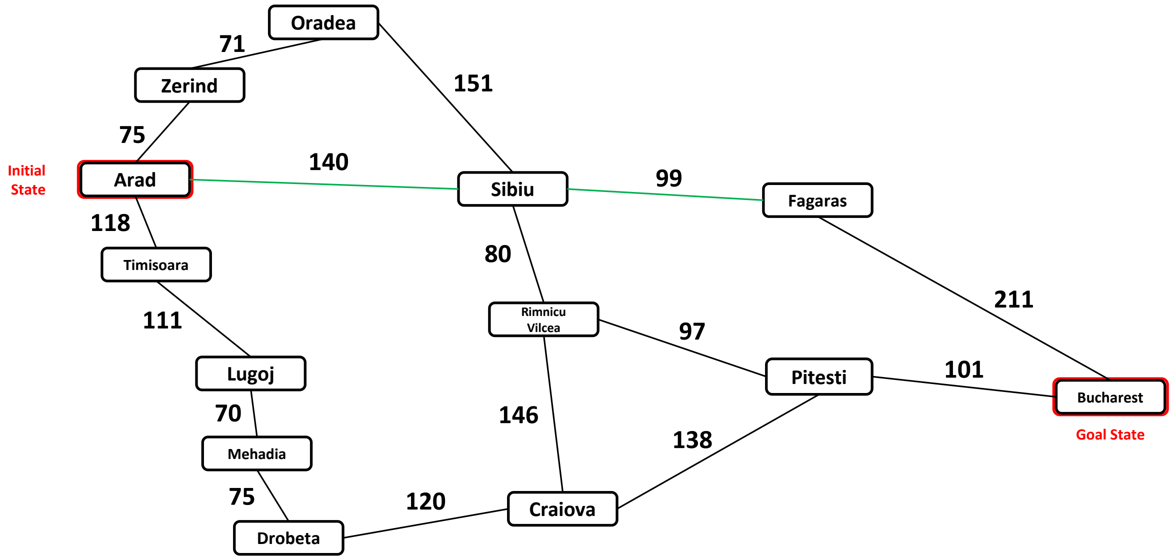

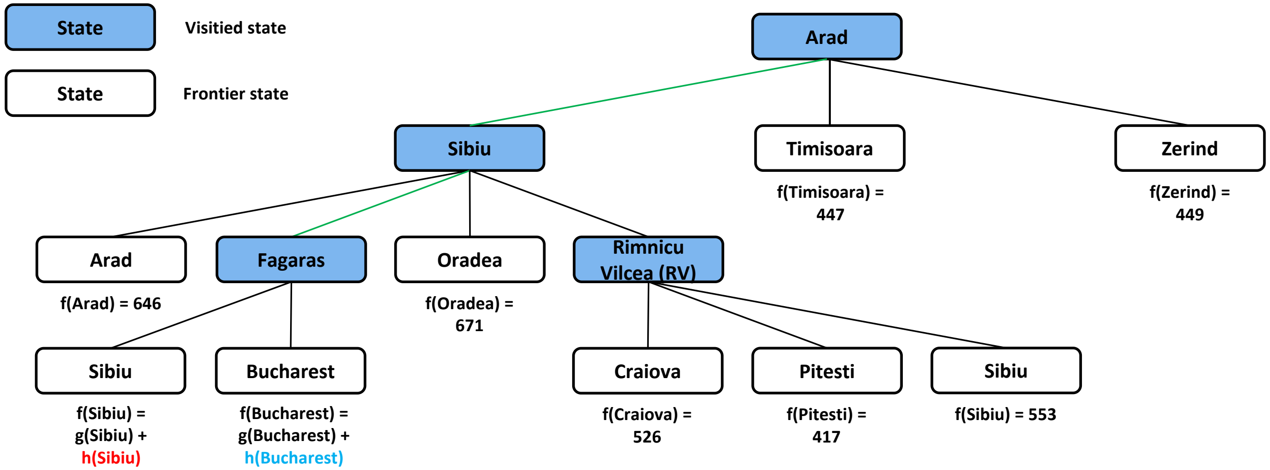

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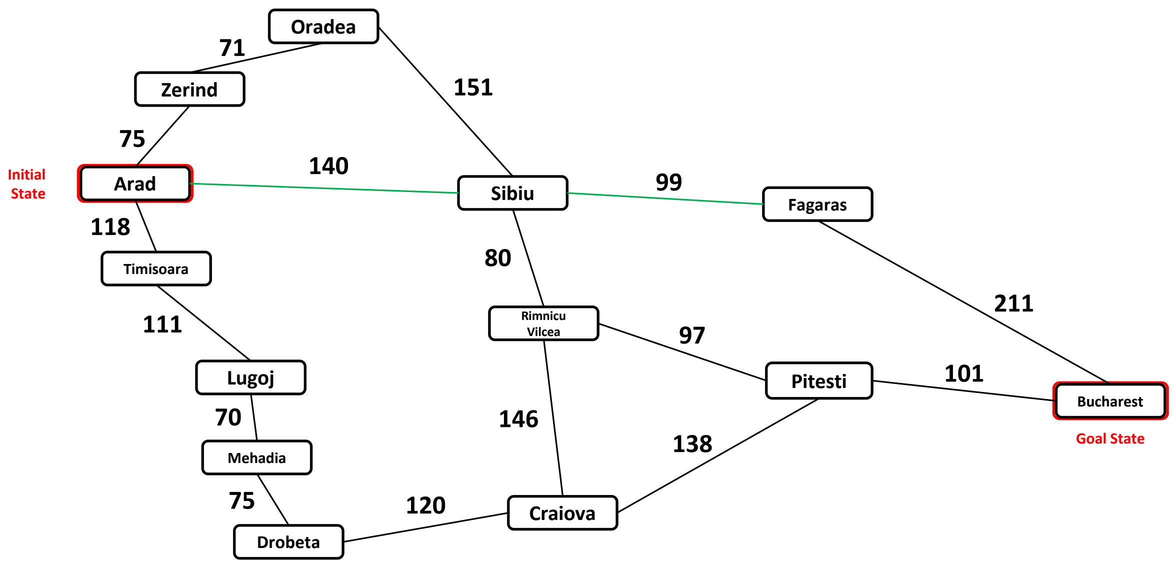

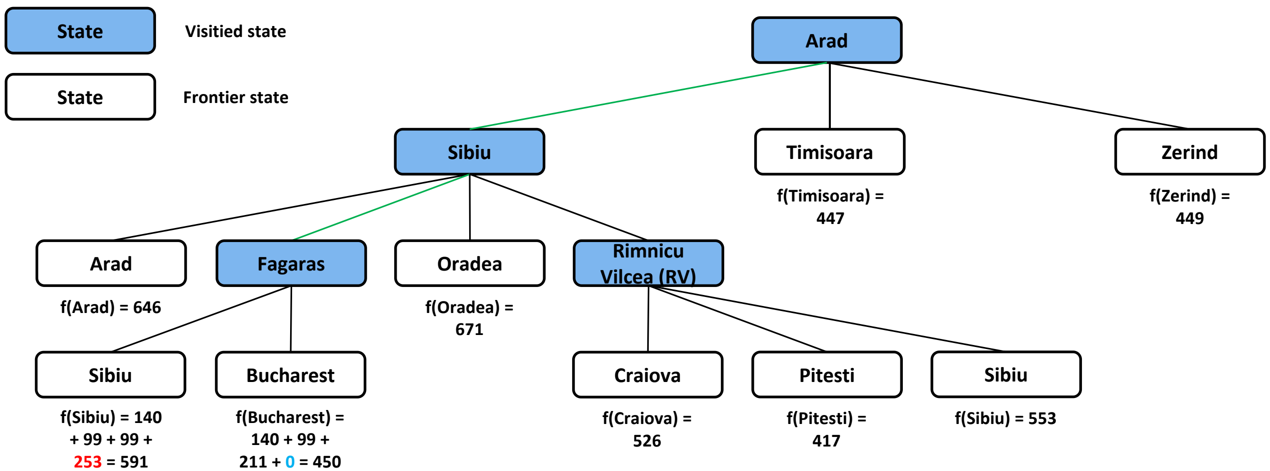

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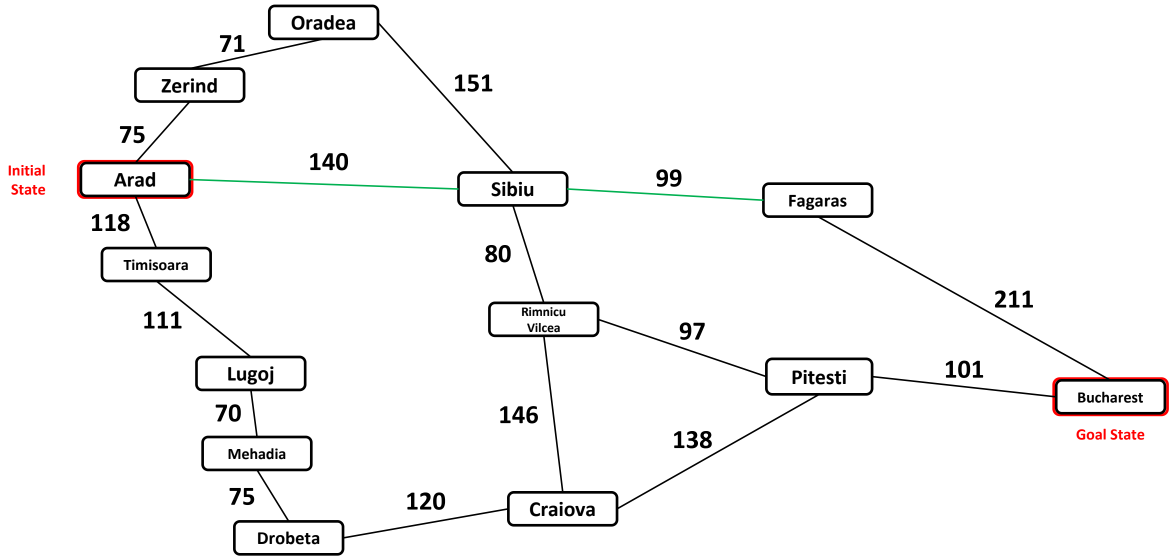

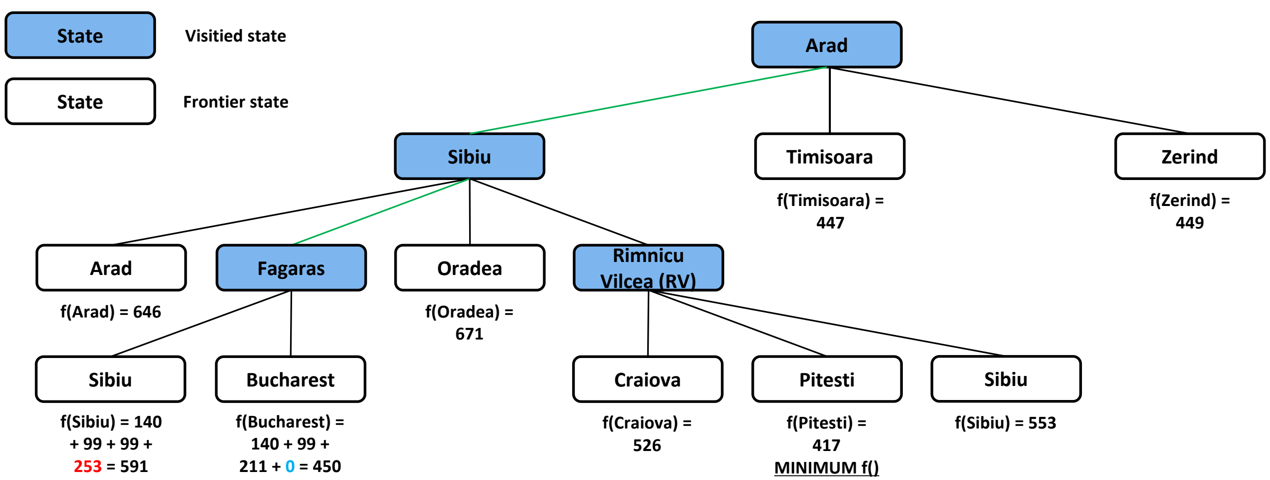

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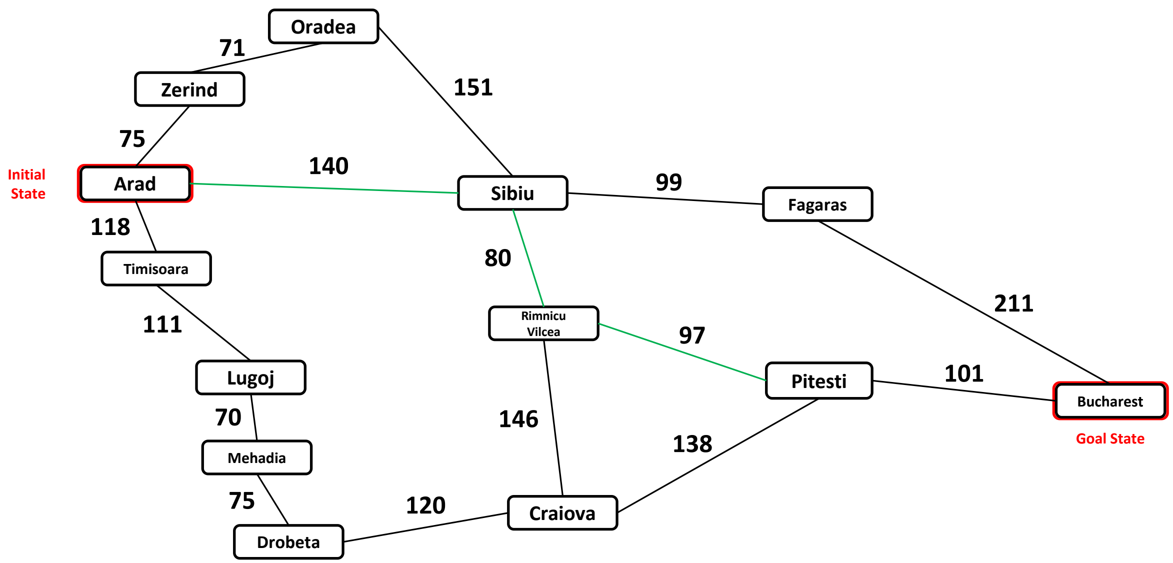

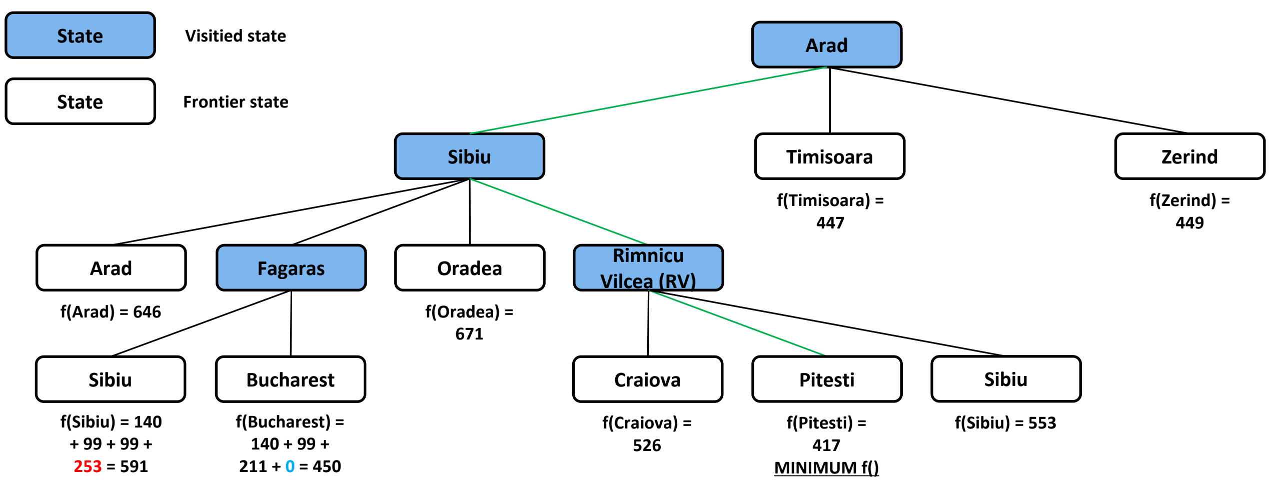

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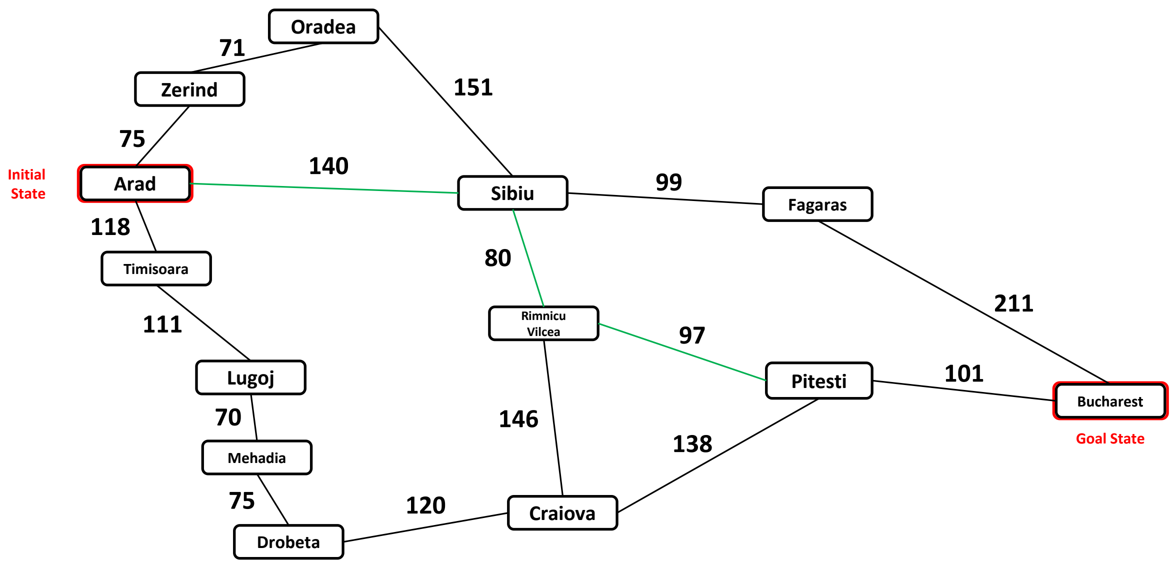

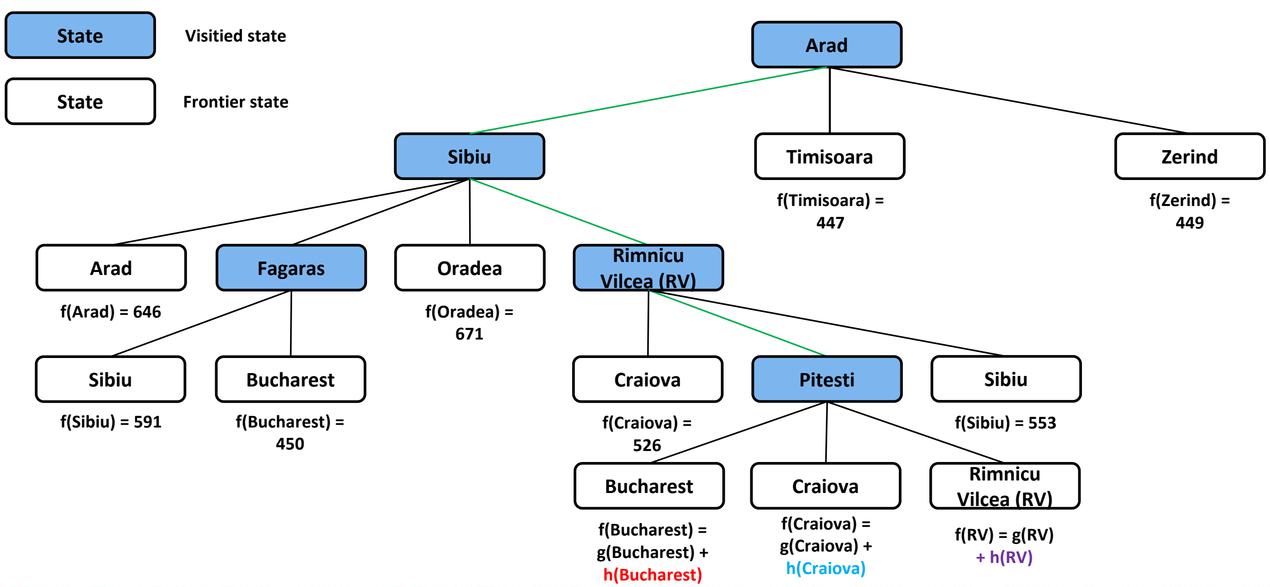

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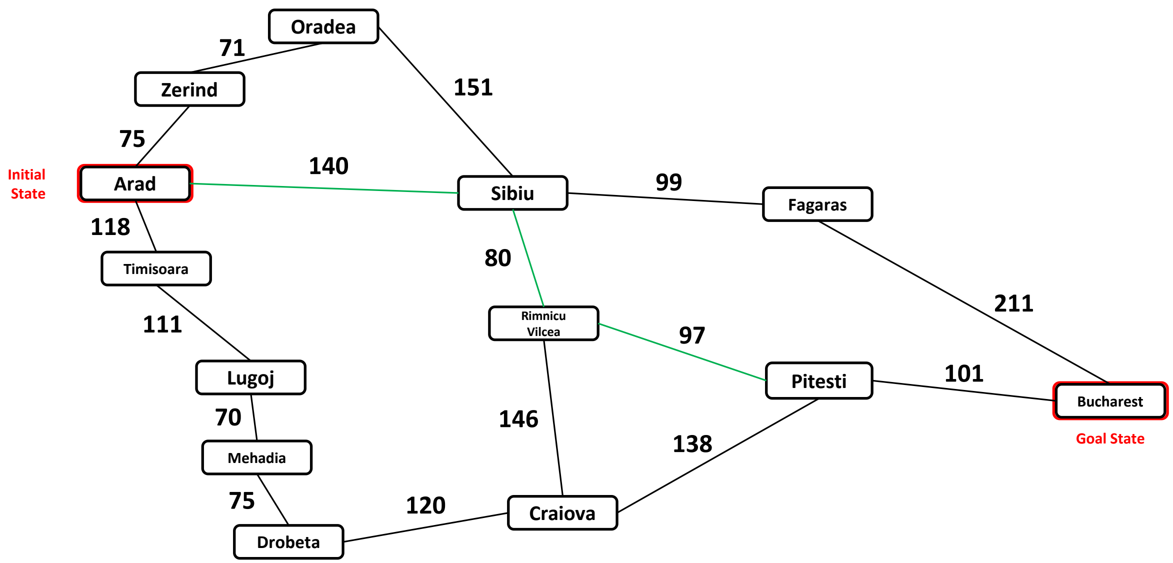

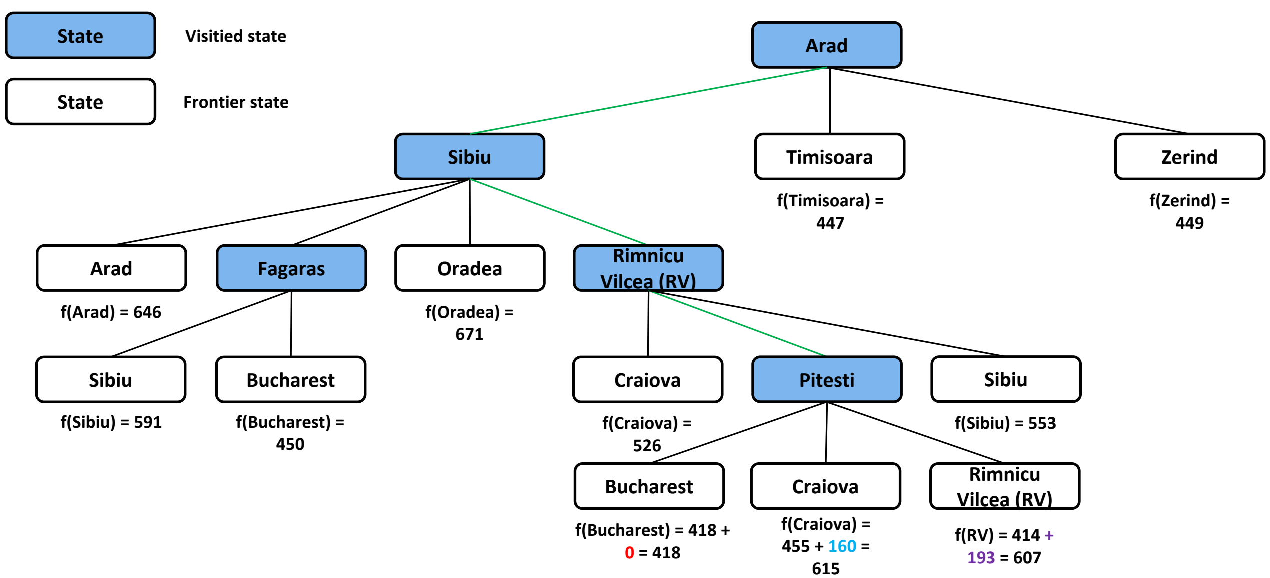

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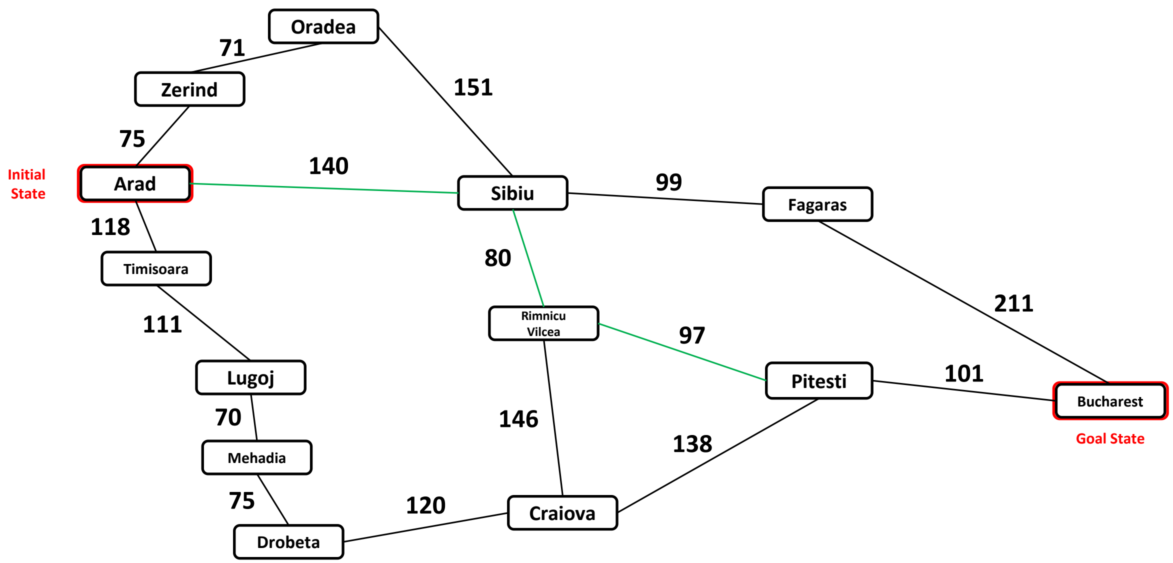

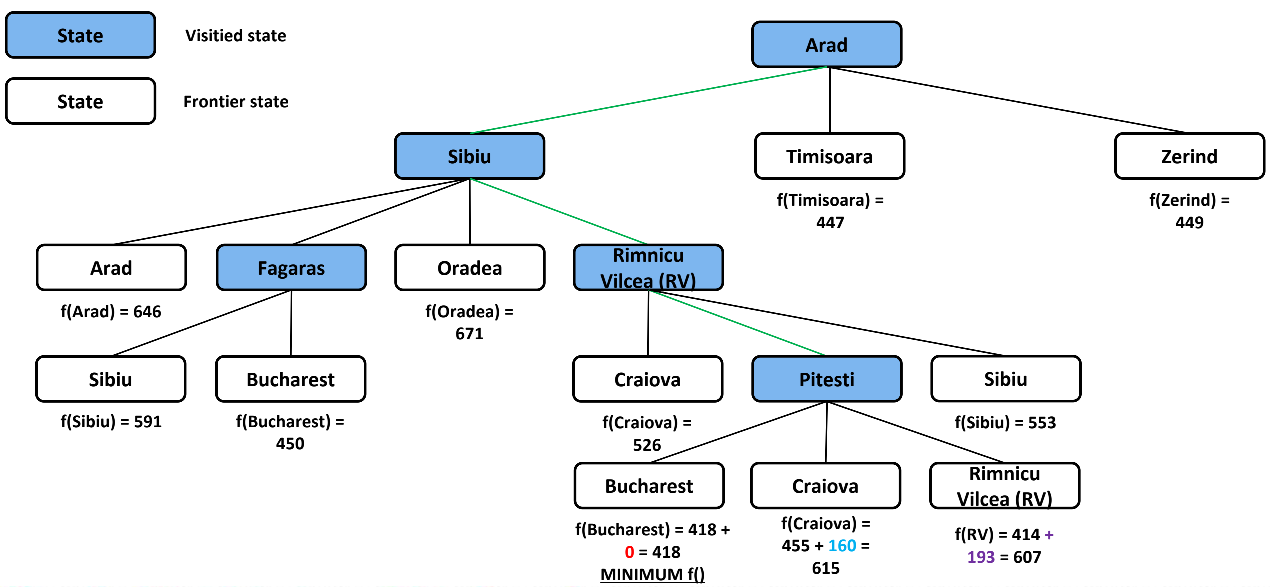

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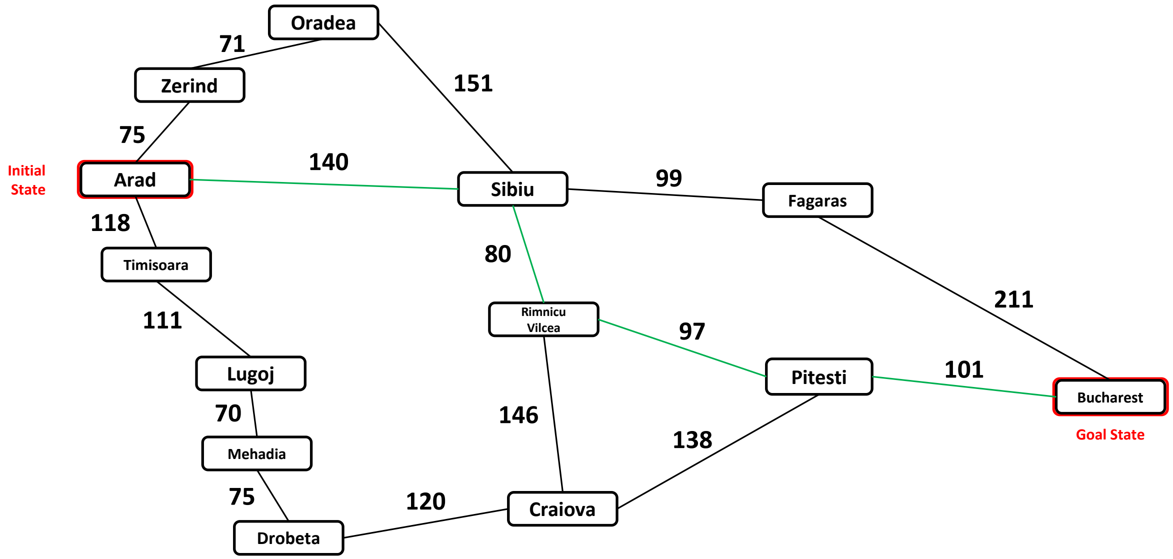

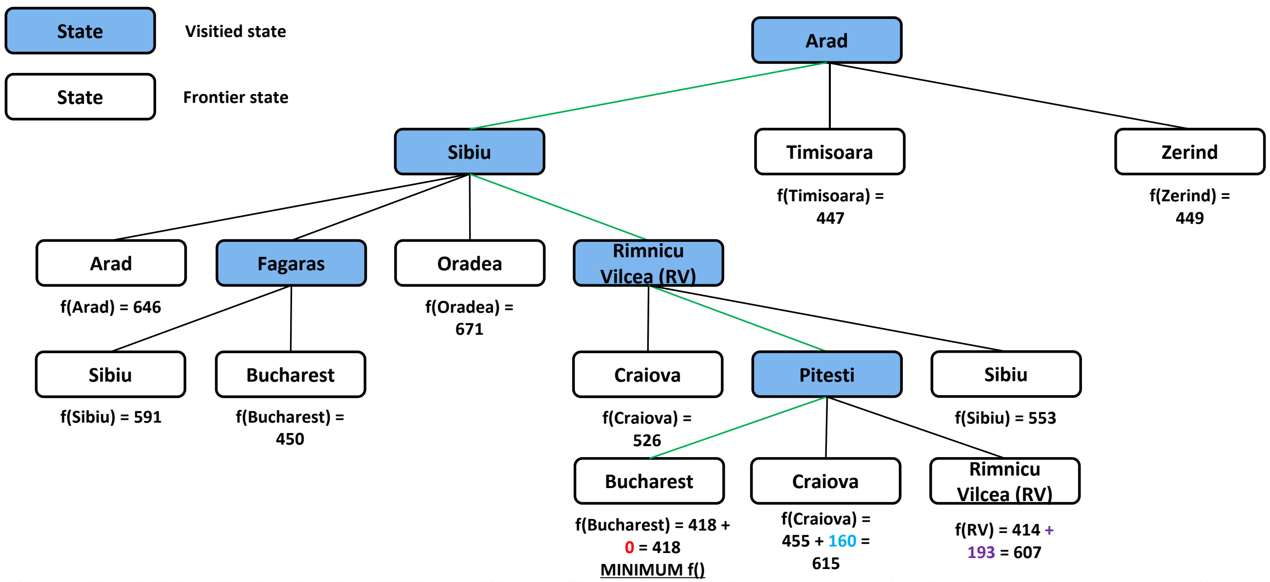

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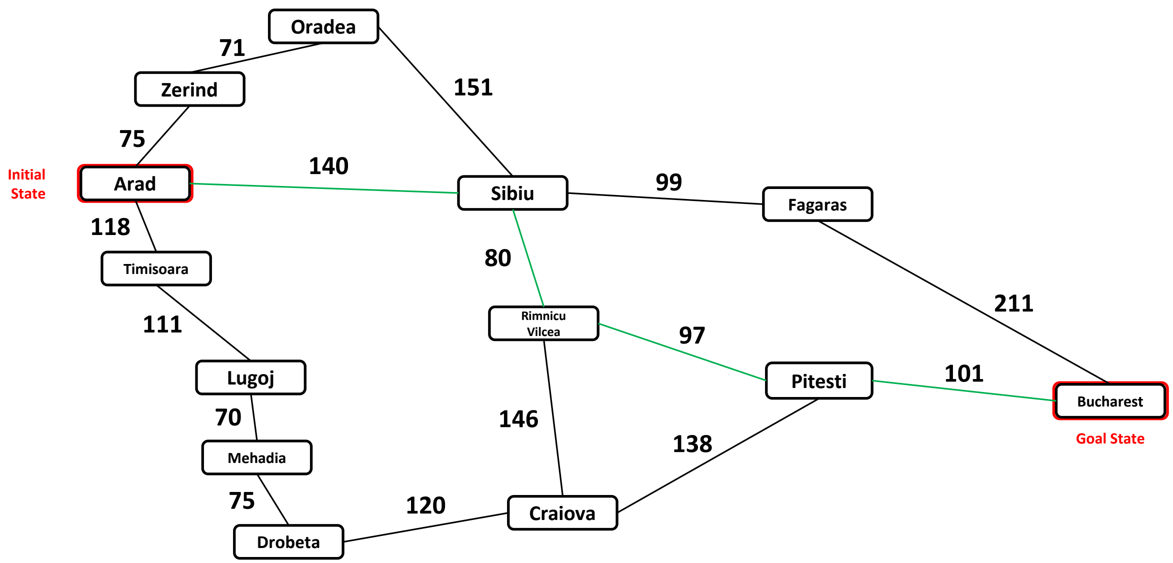

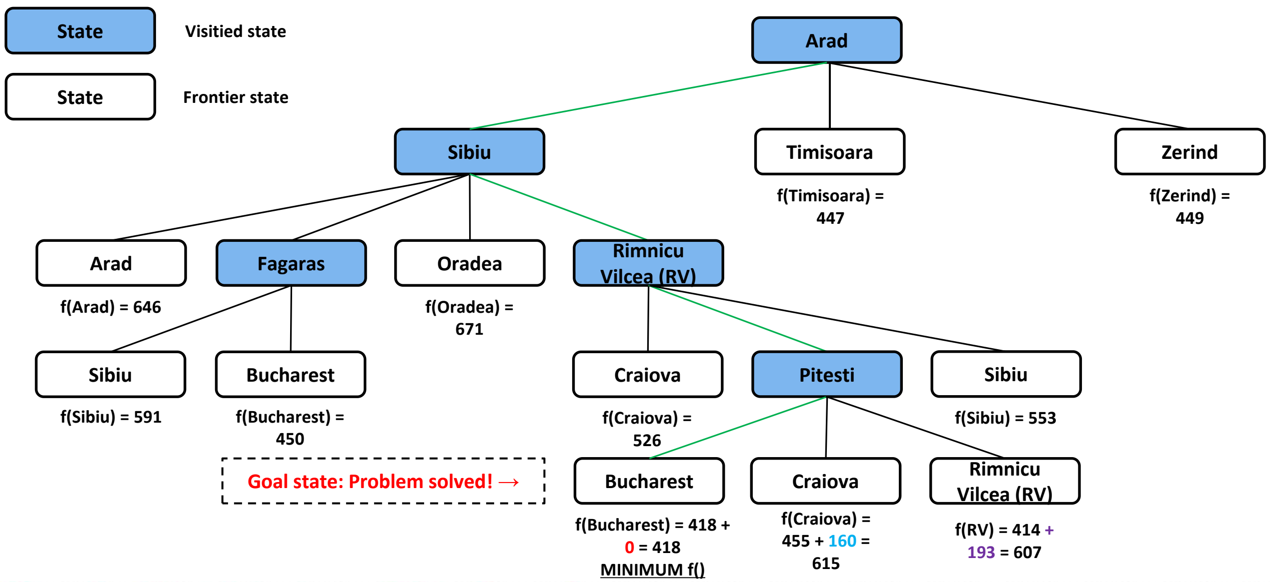

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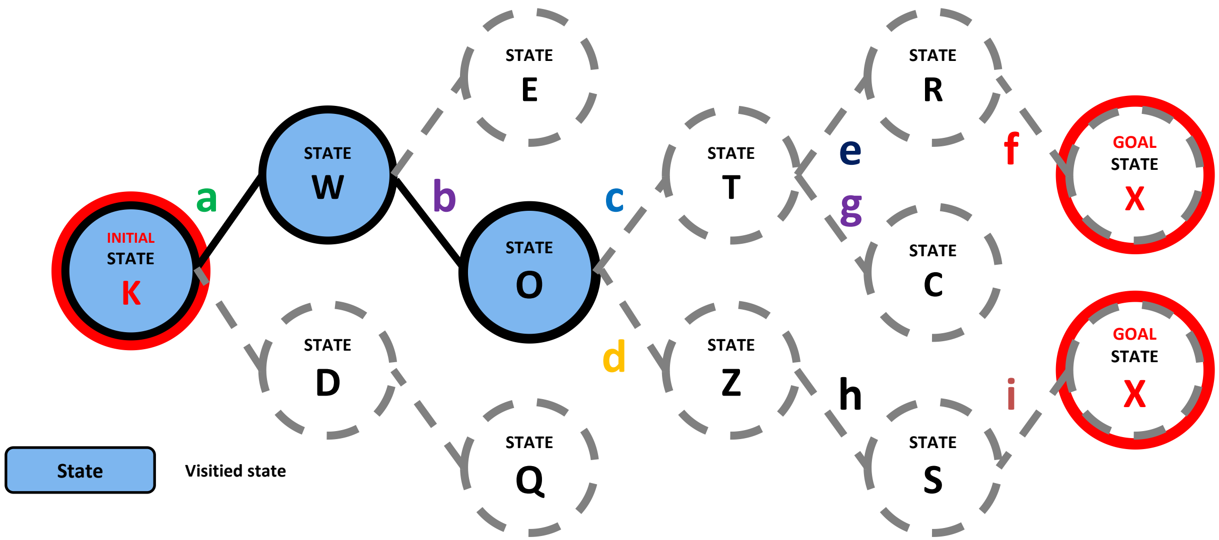
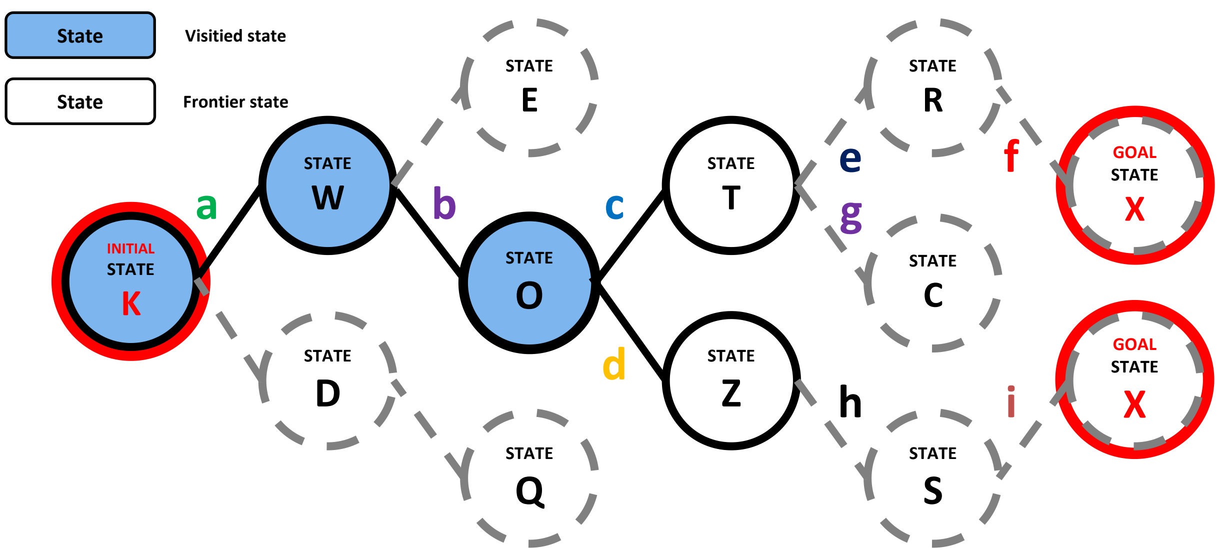
Hill Climbing Search vs. A* Search



Best First Search:
Go to T or Z?
f(T) = c

f(Z) = d

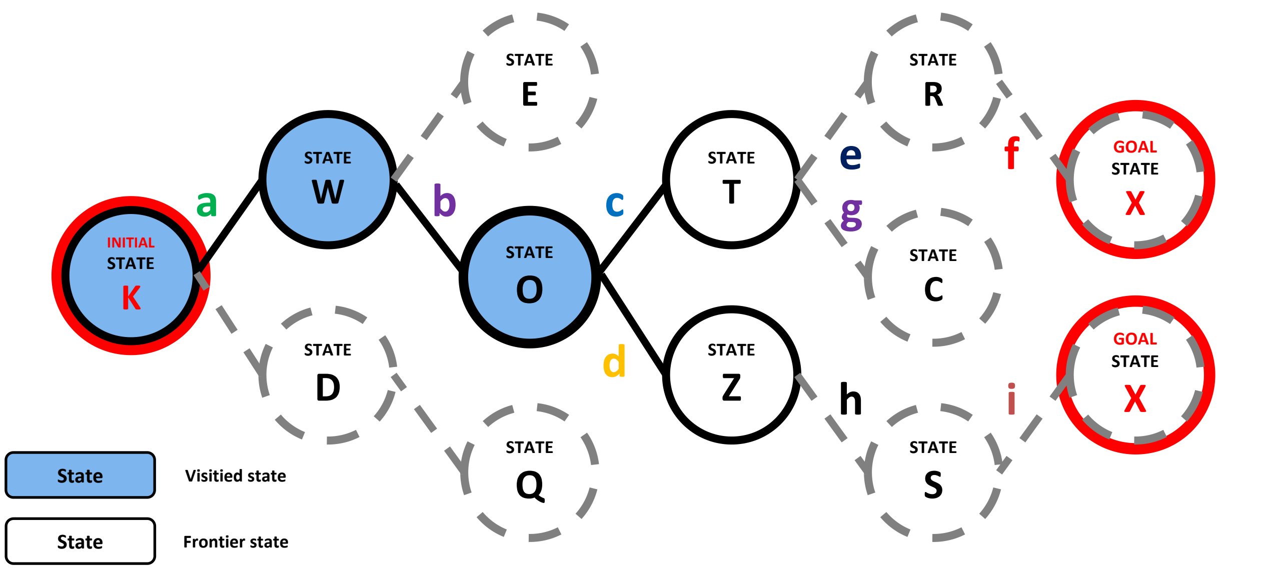
Pick state with min f()



A* Search:
Expand T or Z?
f(T) = g(T) + h(T)
f(T) = a + b + c + h(T)

f(Z) = g(Z) + h(Z)
f(T) = a + b + d + h(Z)
Pick state with min f()

Greedy Best First Search vs. A* Search



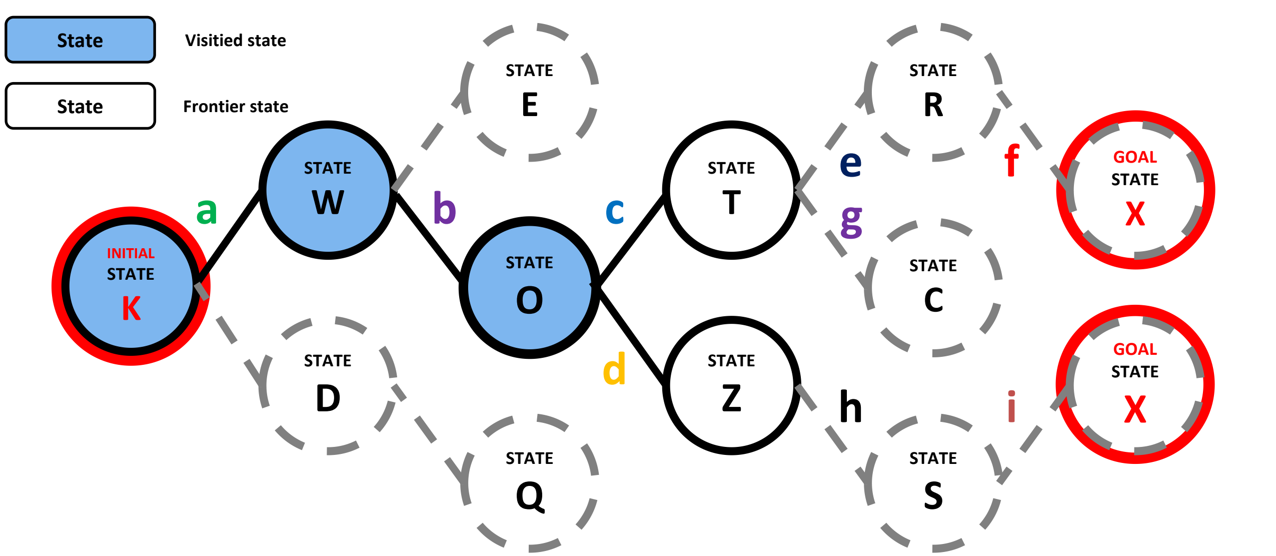
Greedy Best First:

Expand T or Z?

f(T) = h(T)

f(Z) = h(Z)

Pick state with min f()



A* Search:

Expand T or Z?

f(T) = g(T) + h(T)

f(T) = a + b + c + h(T)

f(Z) = g(Z) + h(Z)

f(T) = a + b + d + h(Z)

Pick state with min f()