Artificial Intelligence

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CHAPTER 3: SOLVING PROBLEMS BY SEARCHING

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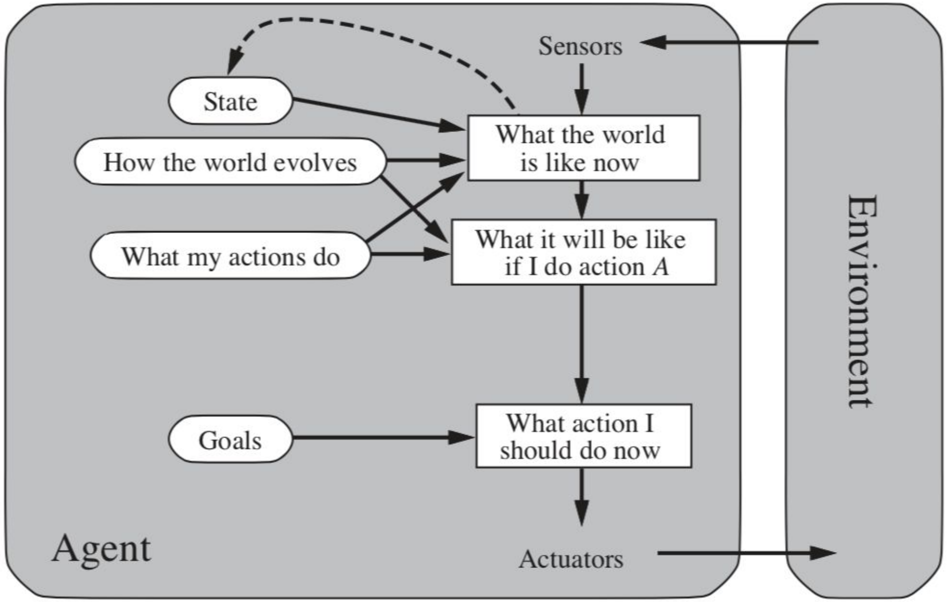
3.1 Problem-Solving Agents

3.1 Problem-Solving Agents

- A problem-solving agent is one kind of goal-based agent



3.1 Problem-Solving Agents

- A simple problem-solving agent:
  - FORMULATION: formulates a goal and a problem
  - SEARCH: searches for a sequence of actions to solve the problem / searches solutions
  - EXECUTION: executes the actions one at a time

function SIMPLE-PROBLEM-SOLVING-AGENT(*percept*) **returns** an action
  persistent: *seq*, an action sequence, initially empty
        state, some description of the current world state
        goal, a goal, initially null
        problem, a problem formulation

  state ← UPDATE-STATE(*state*, *percept*)
  if *seq* is empty **then**
    goal ← FORMULATE-GOAL(*state*)
    problem ← FORMULATE-PROBLEM(*state*, *goal*)
    seq ← SEARCH(*problem*)
    if *seq* = *failure* **then return** a null action
  action ← FIRST(*seq*)
  seq ← REST(*seq*)
  return *action*

3.1 Problem-Solving Agents

A problem can be defined by 5 components:

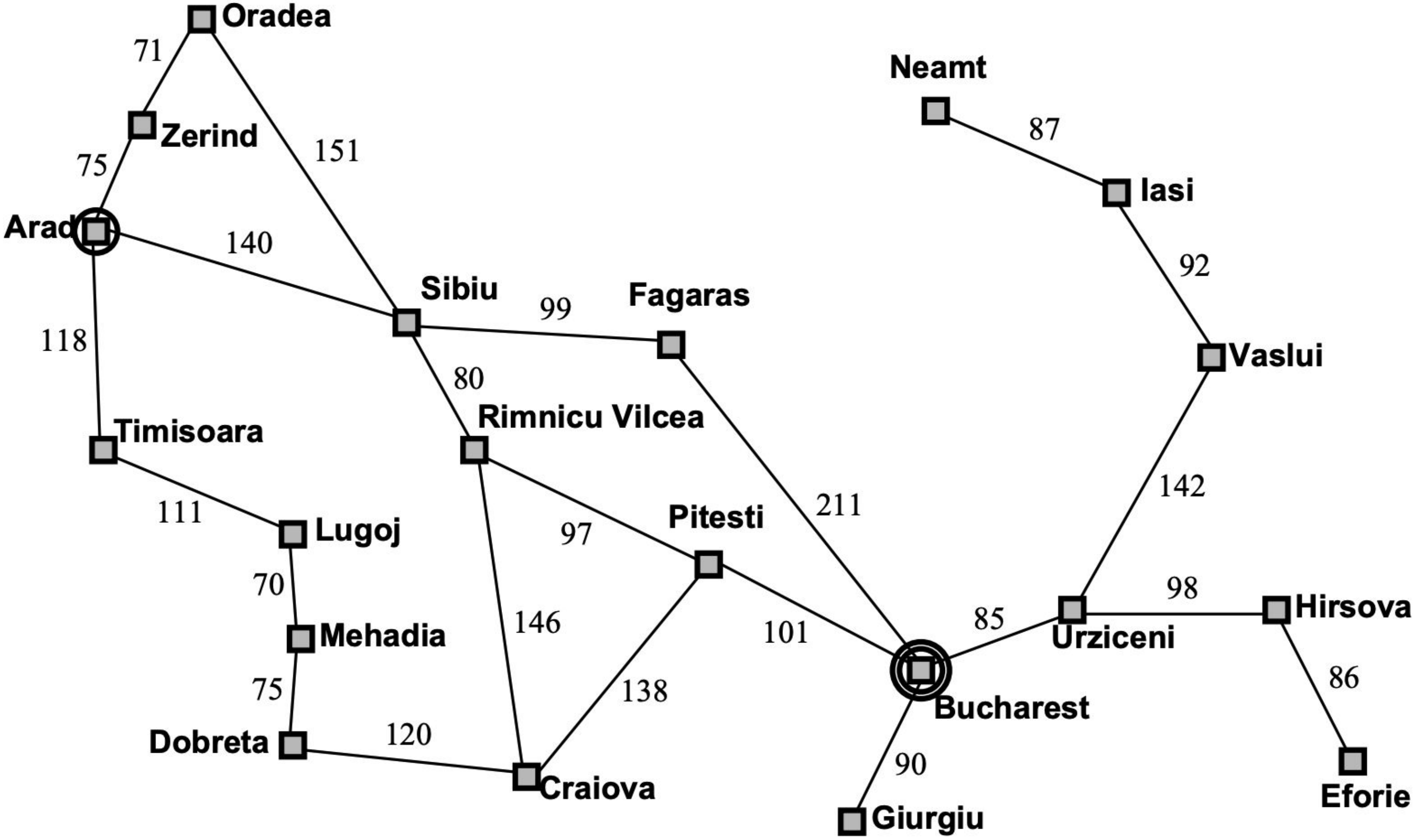
- **initial state:** the **state** that the agent starts in
- **possible actions** available to the agent.
  - Given a particular state s, **ACTIONS**(s) returns the set of actions that can be executed in s.
- **transition model:** specified by a function **RESULT**(s,a) that returns the state that results from doing action a in state s
- ***state space***: the set of all states reachable from the initial state
  - the state space forms a **graph** in which
    the ***nodes*** are ***states***, the ***arcs*** between nodes are ***actions***.
  - a **path** in the state space is ***a sequence of states*** connected by a sequence of actions
- **goal test**: decide whether a given state is a goal state
- **path cost function (~performance measure)**: assigns a numeric cost to each path
  - **step cost**: taking action a to go from state x to state y is denoted by $c(x,a,y)$.
  - **solution**: an action sequence that leads from the initial state to a goal state.
  - **optimal solution**: the lowest path cost among all solutions

3.2 Example

3.2 Example

- On holiday in Romania; currently in Arad.
- Flight leaves tomorrow from Bucharest
- Formulate goal: be in Bucharest
- Formulate problem:
  - states: various cities
  - actions: drive between cities
- Find solution:
  - sequence of cities, e.g., Arad, Sibiu, Fagaras, Bucharest

3.2 Example



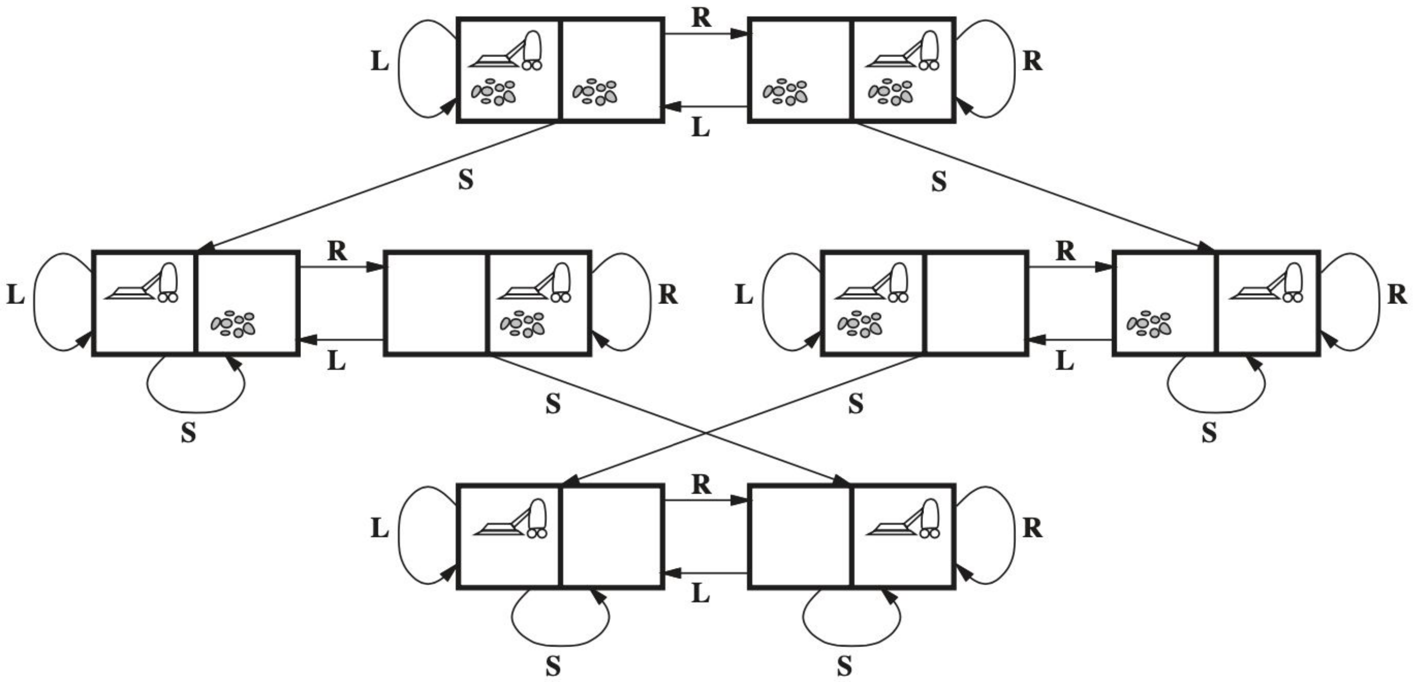
Oradea
71
Zerind
151
75
Arad
140
Sibiu
99
Fagaras
118
80
Rimnicu Vilcea
Timisoara
111
Lugoj
97
Pitesti
211
70
Mehadia
146
101
75
138
Dobreta
120
Craiova
Neamt
87
Iasi
92
Vaslui
142
98
Hirsova
85
Urziceni
86
Bucharest
90
Giurgiu
Eforie

3.2 Example

Example:

- initial state, e.g., In(Arad)
- possible actions
  - Actions(In(Arad)) = {Go(Sibiu),Go(Timisoara),Go(Zerind)}
- transition model
  - RESULT(In(Arad),Go(Zerind)) = In(Zerind) .
- goal test
  - explicit, e.g., x = In(Bucharest)
- path cost (additive)
  - e.g., sum of distances, number of actions executed, etc.
  - the step cost: c(x, a, y), assumed to be ≥ 0

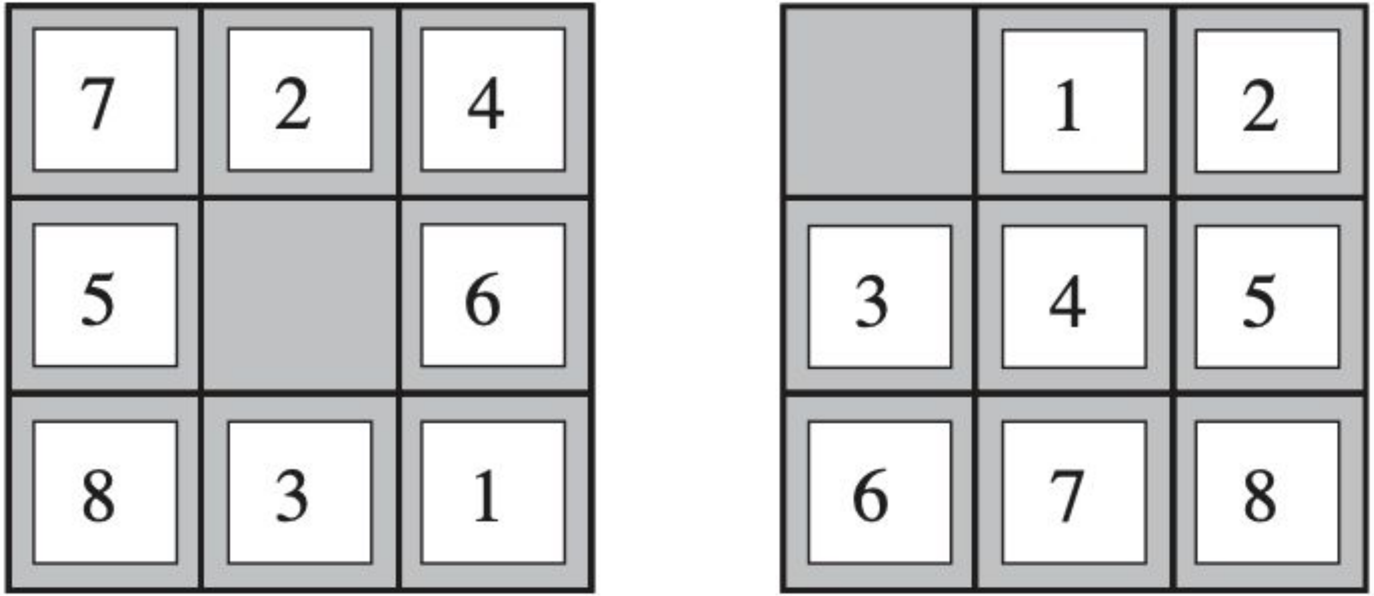
3.2 Example: vacuum world



3.2 Example: vacuum world

- States: location and contents, e.g., [A, Dirty], $2 \times 2^2 = 8$ possible world states
- Initial state: Any state can be designated as the initial state.
- Actions: 3 actions: Left, Right, and Suck.
- Transition model: The actions have their expected effects, except that moving Left in the leftmost square, moving Right in the rightmost square, and Sucking in a clean square have no effect.
- Goal test: This checks whether all the squares are clean.
- Path cost: Each step costs 1, so the path cost is the number of steps in the path.

3.2 Example: vacuum world



Start State   Goal State

3.2 Real-world problems

- Route-finding problem: travel-planning, in-car systems
- Touring problems
- Traveling Salesperson Problem (TSP) is a touring problem in which each city must be visited exactly once. The aim is to find the shortest tour.
- Robot navigation

3.3 Searching For Solutions

3.3 Tree search algorithms - basic idea

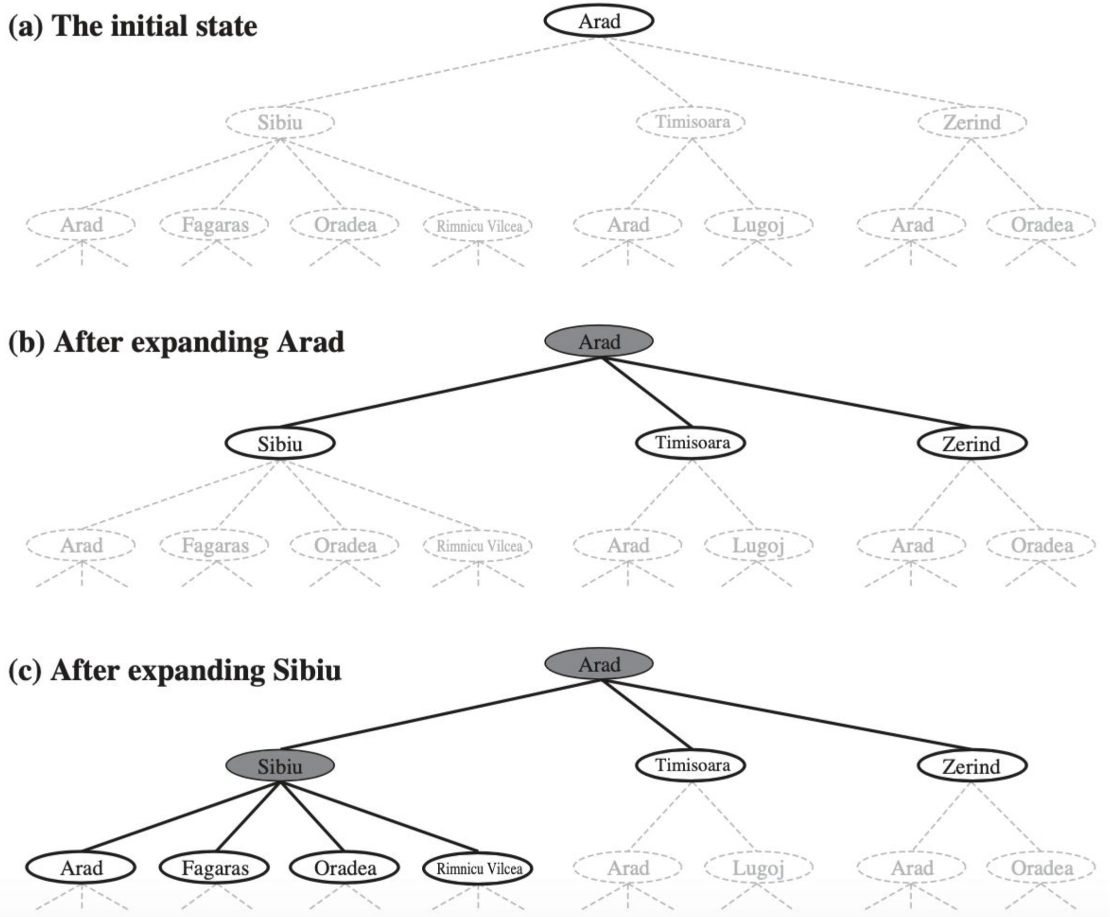
- Search tree with
  - the initial state at the root
  - the branches are actions
  - the nodes correspond to states in the state space of the problem.
- **Expanding** the current state;
  - applying each legal action to the current state, thereby generating a new set of states.
- The set of all leaf nodes available for expansion at any given point is called the **frontier** or **open list**.

3.3 Searching For Solutions

Tree search algorithms - basic idea

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

3.3 Searching For Solutions



3.3 Searching For Solutions

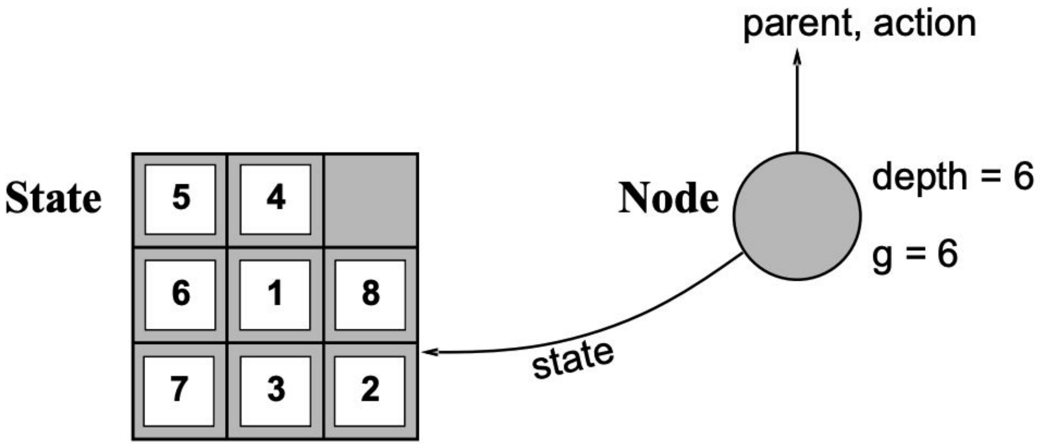
The explored set (also known as the closed list): set of all explored nodes

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 the frontier or explored set

3.3.1 Data structure

For each node n of the tree, we have a structure that contains four components:

- 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, as indicated by the parent pointers.



3.3.2 Measuring problem-solving performance

Measuring problem-solving performance

- Completeness: Is the algorithm guaranteed to find a solution when there is one?
- Optimality: Does the strategy find the optimal solution?
- Time complexity: How long does it take to find a solution?
- Space complexity: How much memory is needed to perform the search?
  (page 1053 textbook)

Complexity is expressed in terms of:

- b: the branching factor or maximum number of successors of any node;
- d: the depth of the shallowest goal node
- m: the maximum length of any path in the state space

3.4 Uninformed search strategies

Uninformed strategies use only the information available in the problem definition

- ***Breadth-first search: BFS***
- Uniform-cost search
- ***Depth-first search: DFS***
- Depth-limited search
- Iterative deepening search

3.4 Uninformed search strategies

3.4.1 Breadth-first search

- BFS expands the shallowest nodes first
  - the root node is expanded -> its successors -> their successors, and so on.
- Implementation:
  - frontier: FIFO queue, i.e., new successors go at end

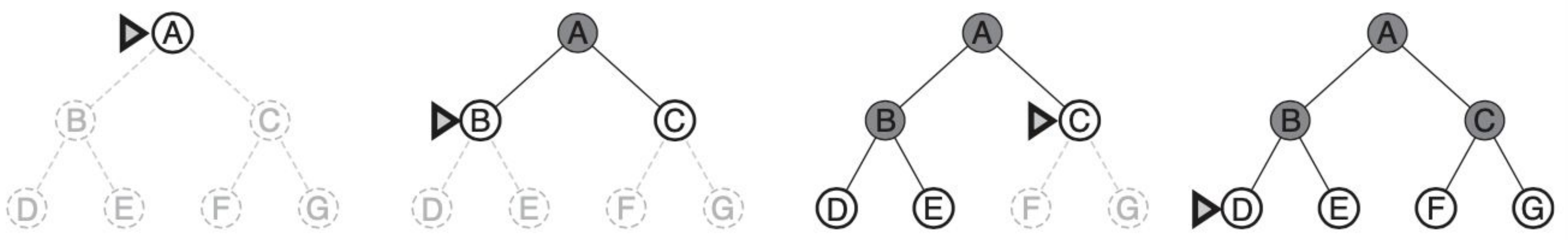


Figure 3.12 Breadth-first search on a simple binary tree. At each stage, the node to be expanded next is indicated by a marker.

3.4 Uninformed search strategies

```
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)
        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 not in explored or frontier then
                frontier <- INSERT(child, frontier)
```

3.4 Uninformed search strategies

3.4.1 Breadth-first search

- Complete: yes if b is finite
- Time: $O(b^d)$
- Space: $O(b^d)$
- Optimal: yes if step costs all equal (shallowest path is lowest path cost)

(page 82 textbook)

Complexity is expressed in terms of 4 quantities:

- b: the branching factor or maximum number of successors of any node
- d: the depth of the shallowest solution
- m: the maximum length of any path in the state space

3.4 Uninformed search strategies

3.4.1 Breadth-first search

- Time: $O(b^d)$
    - The root of the search tree generates b nodes at the first level, each of which generates b more nodes, for a total of b^2 at the second level.
    - Each of these generates b more nodes, yielding b^3 nodes at the third level, and so on.
    - Now suppose that the solution is at depth d.
    - Then the total number of nodes generated is

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

3.4 Uninformed search strategies

3.4.1 Breadth-first search

- Space: $O(b^d)$
- For breadth-first graph search in particular, every node generated remains in memory.
- There will be $O(b^{d-1})$ nodes in the explored set and $O(b^d)$ nodes in the frontier, so the space complexity is $O(b^d)$

3.4 Uninformed search strategies

3.4.2 Uniform-cost search

- Expand least-cost unexpanded node
- Equivalent to breadth-first if step costs all equal

3.4 Uninformed search strategies

```
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 ordered 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 not in explored or frontier then
              frontier ← INSERT(child, frontier)
          else if child.STATE is in frontier with higher PATH-COST then
              replace that frontier node with child
```

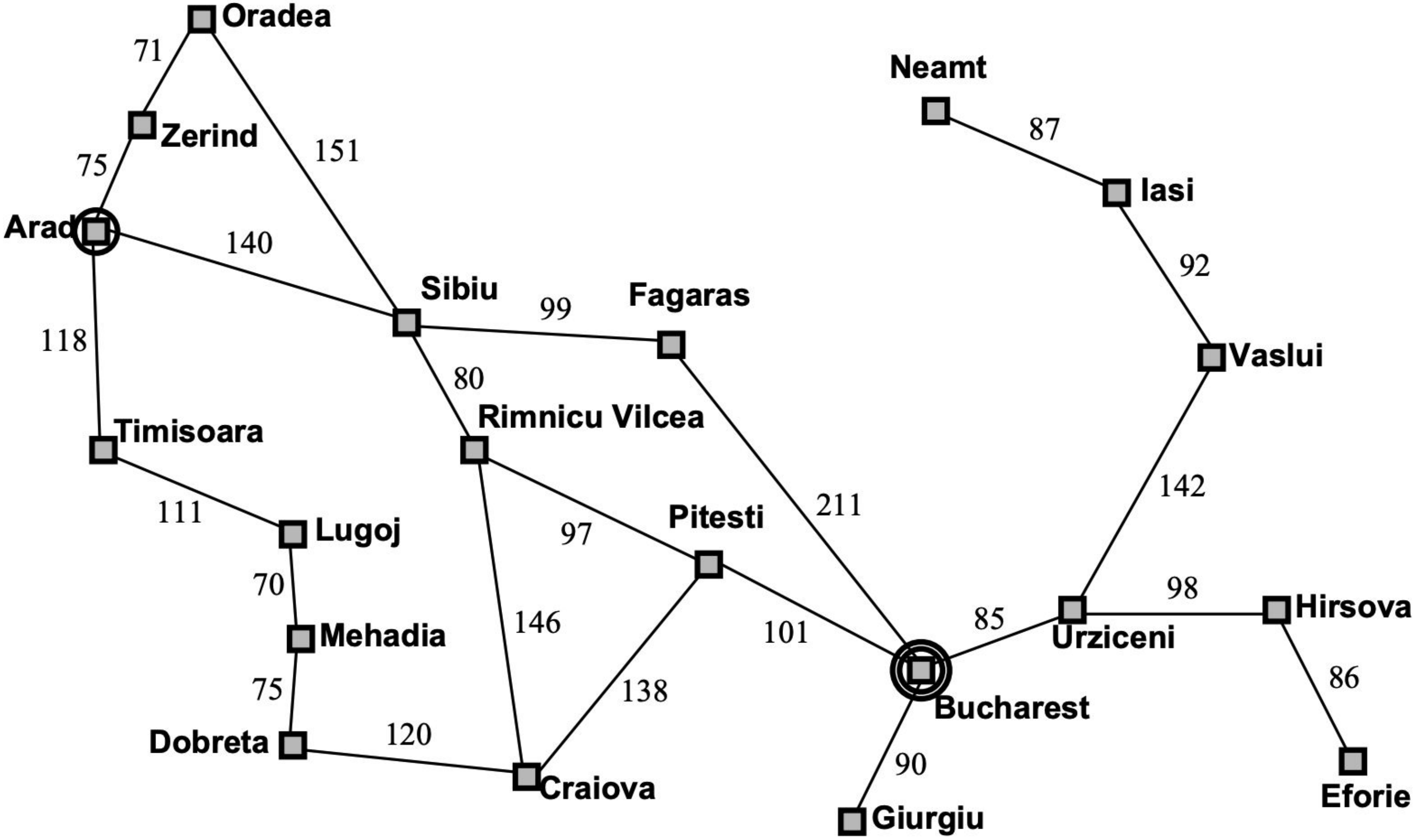
3.4 Uninformed search strategies

3.4.2 Uniform-cost search

- Complete: yes, if step cost $\geq \varepsilon$
- Optimal: yes, nodes expanded in increasing order of path cost
- Time, space: uniform-cost search is guided by path costs rather than depths, so its complexity cannot be characterized in terms of b and d
  - C* be the cost of the optimal solution, step cost $\geq \varepsilon$
  - the algorithm worst-case time and space complexity

$$O(b^{1+\lfloor C^*/\epsilon \rfloor})$$

3.4 Uninformed search strategies



3.4 Uninformed search strategies

3.4.3 Depth-first search

- Expand deepest unexpanded node
- Implementation:
  - frontier = LIFO queue, i.e., put successors at front

3.4 Uninformed search strategies

function DEPTH-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 LIFO queue with node as the only element**
    explored <- an empty set

    loop do
        if EMPTY?(*frontier*) **then** return failure
        node <- POP(*frontier*) // the most recently generated node is chosen for expansion
        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 not in *explored* or *frontier* **then**
                frontier <- INSERT(*child*, *frontier*)

node: A
frontier: A
explored: {}

node: A
child: B
frontier: C, B
explored: A

node: B
child: D
frontier: C, E, D
explored: A, B

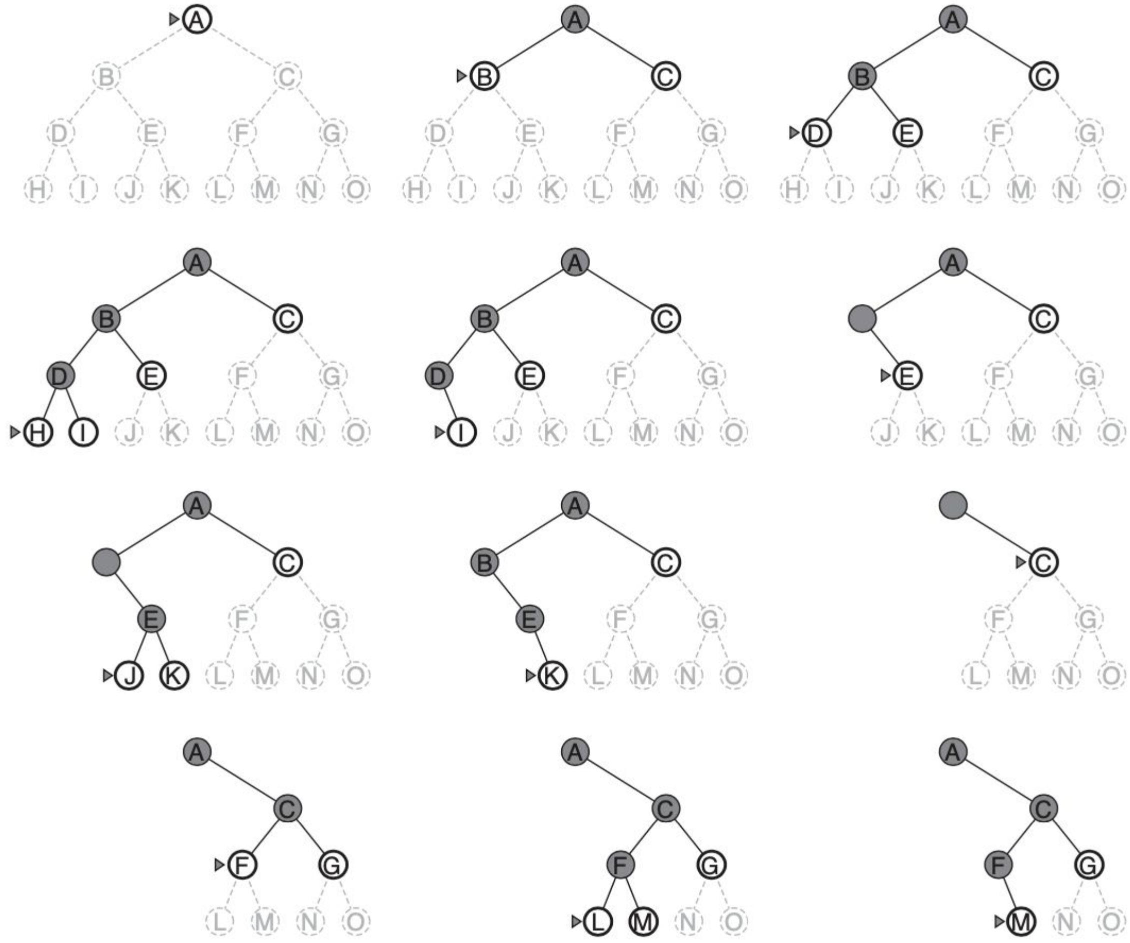


Figure 3.16 Depth-first search on a binary tree. The unexplored region is shown in light gray. Explored nodes with no descendants in the frontier are removed from memory. Nodes at depth 3 have no successors and M is the only goal node.

3.4 Uninformed search strategies

3.4.3 Depth-first search

- Complete:
  - graph-search: complete in finite state spaces.
  - tree-search: not complete
- Optimal: no, it can make a wrong choice and get stuck going down a very long path when another choice can lead to a solution near the root
- Time: $O(b^m)$, terrible if m is much larger than d
  - m: the maximum length of any path
  - d: the depth of the shallowest solution
  - b: the maximum number of successors of any node
- Space: $O(bm)$, i.e., linear space!
  - store a single path from the root to a leaf node and the unexpanded sibling nodes for each node on the path.
  - when a node has been expanded and all its descendants have been explored, it can be removed from memory.

3.4 Uninformed search strategies

node: A
limit: 1
child: C
result: cutoff

3.4.4 Depth-limited search

- depth-first search with depth limit *l*, i.e., nodes at depth *l* have no successors

function DEPTH-LIMITED-SEARCH(*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? ← 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*

node: C
limit: 0
child:
result:

3.4 Uninformed search strategies

3.4.5 Iterative deepening depth-first search

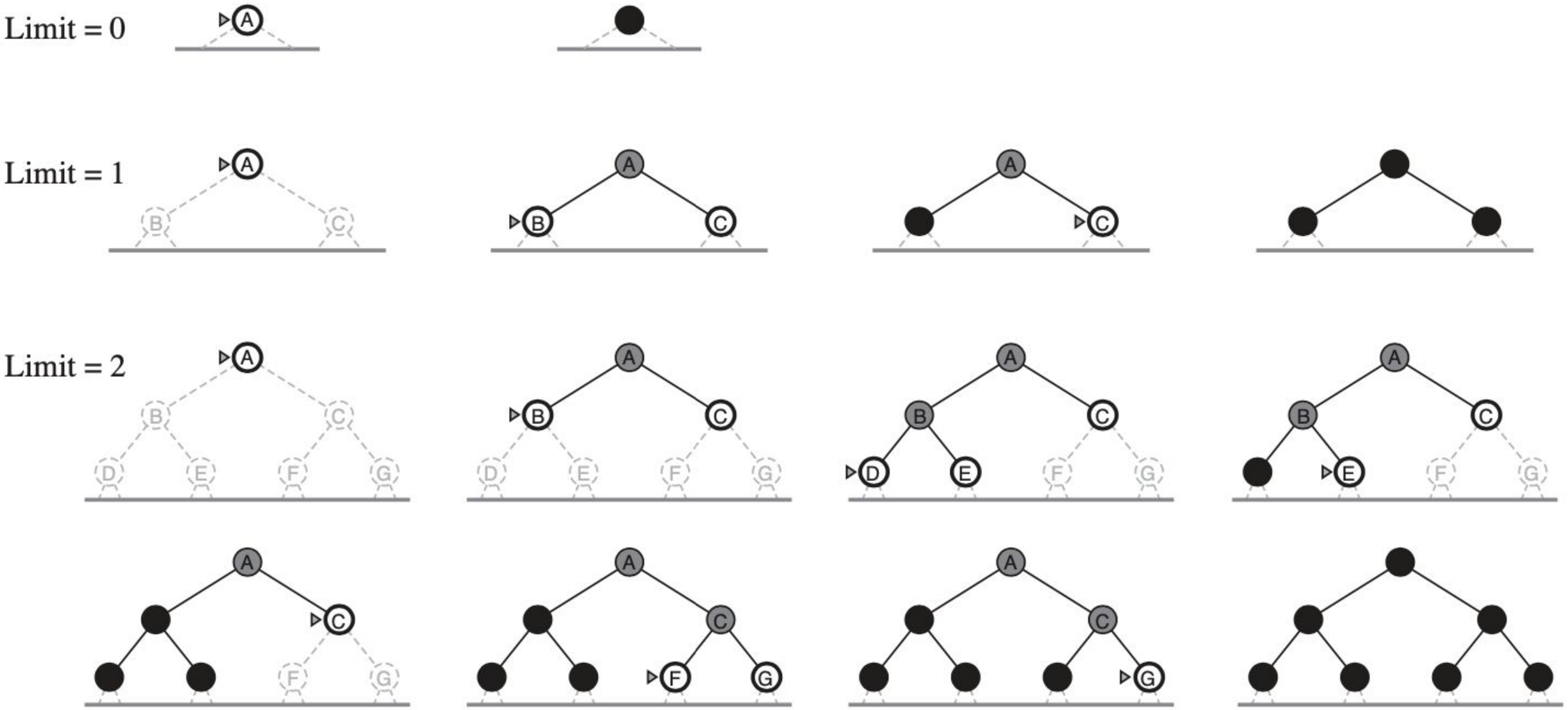
- depth-limited search with increasing limits
- terminates when a solution is found or if the depth- limited search returns failure, meaning that no solution exists.

function ITERATIVE-DEEPENING-SEARCH(*problem*) **returns** a solution, or failure
    for *depth* = 0 **to** ∞ **do**
        result $\leftarrow$ DEPTH-LIMITED-SEARCH(*problem*, *depth*)
        if *result* $\neq$ cutoff **then return** *result*

Figure 3.18 The iterative deepening search algorithm, which repeatedly applies depth-limited search with increasing limits. It terminates when a solution is found or if the depth-limited search returns *failure*, meaning that no solution exists.

3.4 Uninformed search strategies

3.4.5 Iterative deepening depth-first search



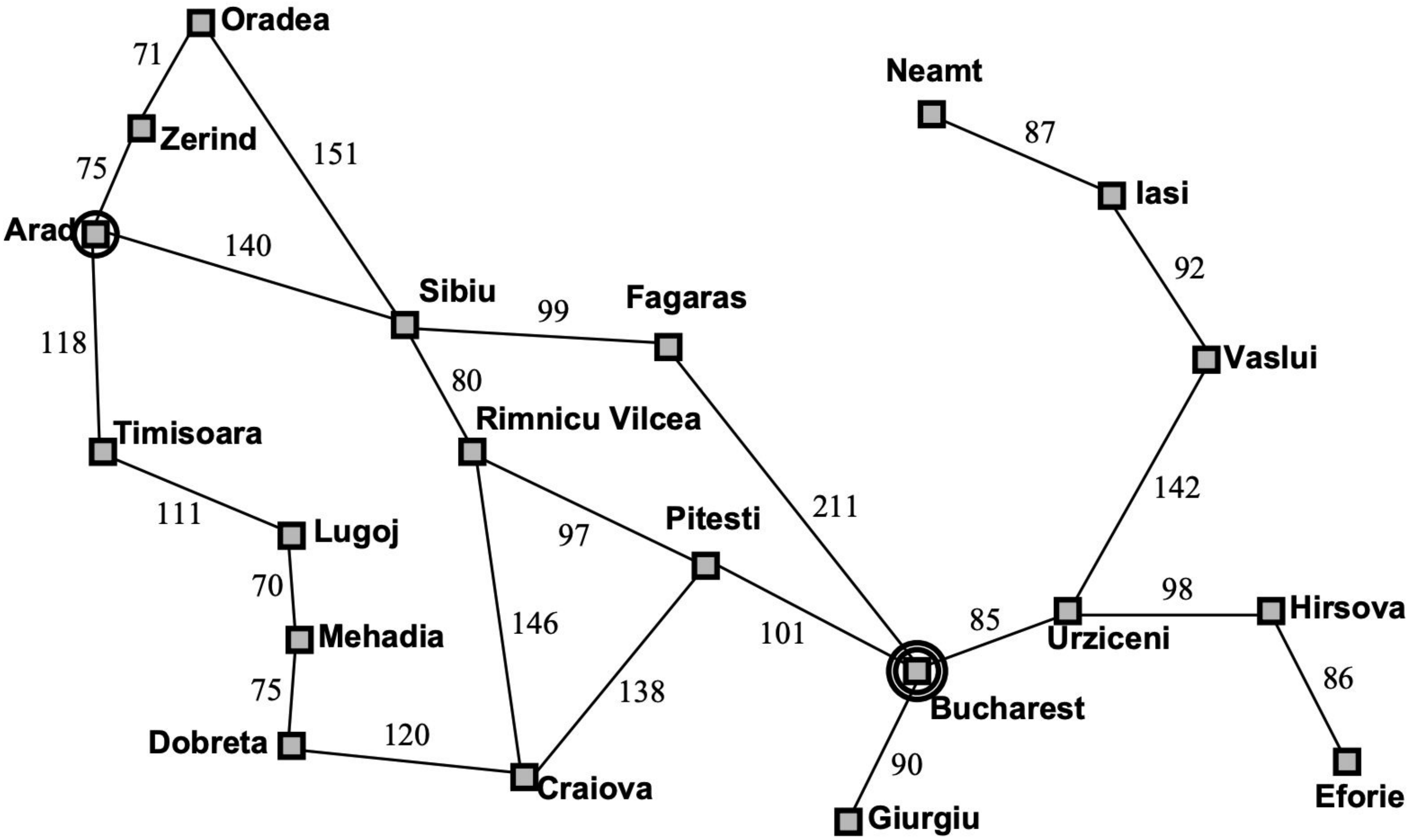
3.4 Uninformed search strategies

3.4.5 Iterative deepening depth-first search

- Complete: yes if b is finite
- Optimal: yes if step costs all equal
- Time: $O(b^d)$
    - b: the maximum number of successors of any node
    - d: the depth of the shallowest solution
- Space: $O(bd)$

IDF is the preferred uninformed search method when there is a **large search space** and **the depth** of the solution is **unknown**.

3.4 Uninformed search strategies



3.4 Uninformed search strategies

3.4.6 Comparing uninformed search strategies

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

Figure 3.21 Evaluation of tree-search strategies. b is the branching factor; d is the depth of the shallowest solution; m is the maximum depth of the search tree; l is the depth limit. Superscript caveats are as follows: ^{a} complete if b is finite; ^{b} complete if step costs $\geq \epsilon$ for positive ϵ; ^{c} optimal if step costs are all identical; ^{d} if both directions use breadth-first search.