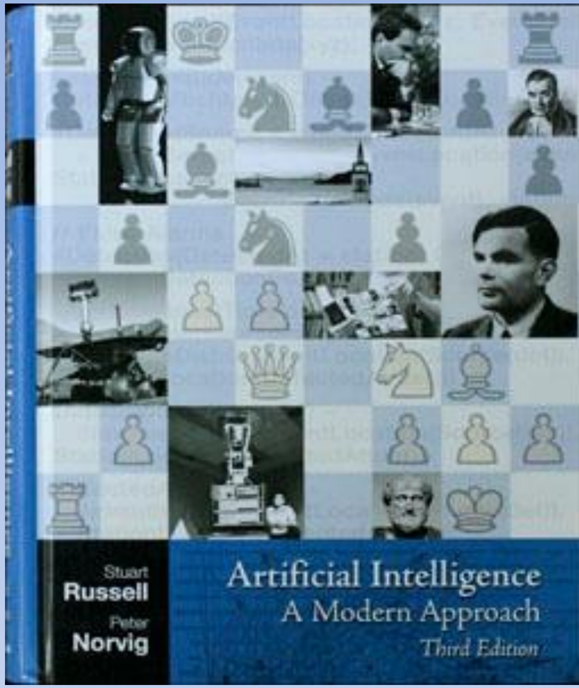



# Chapter 3: Solving Problems by Searching

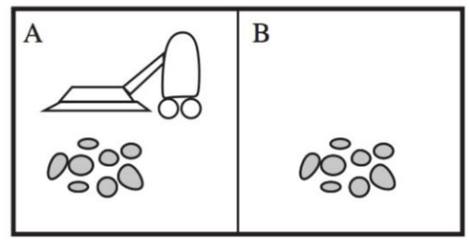



**Figure 2.2** A vacuum-cleaner world with just two locations.

| Percept sequence | Action |
|---|---|
| $[A, Clean]$ | *Right* |
| $[A, Dirty]$ | *Suck* |
| $[B, Clean]$ | *Left* |
| $[B, Dirty]$ | *Suck* |
| $[A, Clean], [A, Clean]$ | *Right* |
| $[A, Clean], [A, Dirty]$ | *Suck* |
| ⋮ | ⋮ |
| $[A, Clean], [A, Clean], [A, Clean]$ | *Right* |
| $[A, Clean], [A, Clean], [A, Dirty]$ | *Suck* |
| ⋮ | ⋮ |

**Figure 2.3** Partial tabulation of a simple agent function for the vacuum-cleaner world shown in Figure 2.2.

# Chapter 3: Solving Problems by Searching

- Introducing **Problem-Solving Agent**
  - A Goal-Based Agent
- Use ATOMIC Representations
  - States of the world have no INTERNAL STRUCTURE
  - Later Planning Agents (Ch#7-10) have factored or structured representations.
- GOAL used to help simplify maximizing performance measure.

# Romania Example

- I’m in Arad, Romania!
  - Sight Seeing
  - Photos

WAIT:
I have a non-refundable ticket leaving out of Bucharest tomorrow!!!

# Romania Example

- I’m in Arad, Romania!
- I have a non-refundable ticket leaving out of Bucharest tomorrow!!!
- Better Adopt Goal: IN BUCHAREST!

# Romania Example

- Goal Formulation:
  – Given: Current Situation, Performance Measure
  – Generate: Goal
  – First Step in Problem Solving
- Problem Formulation:
  – Given: Goal
  – Decide: Actions and States to consider.

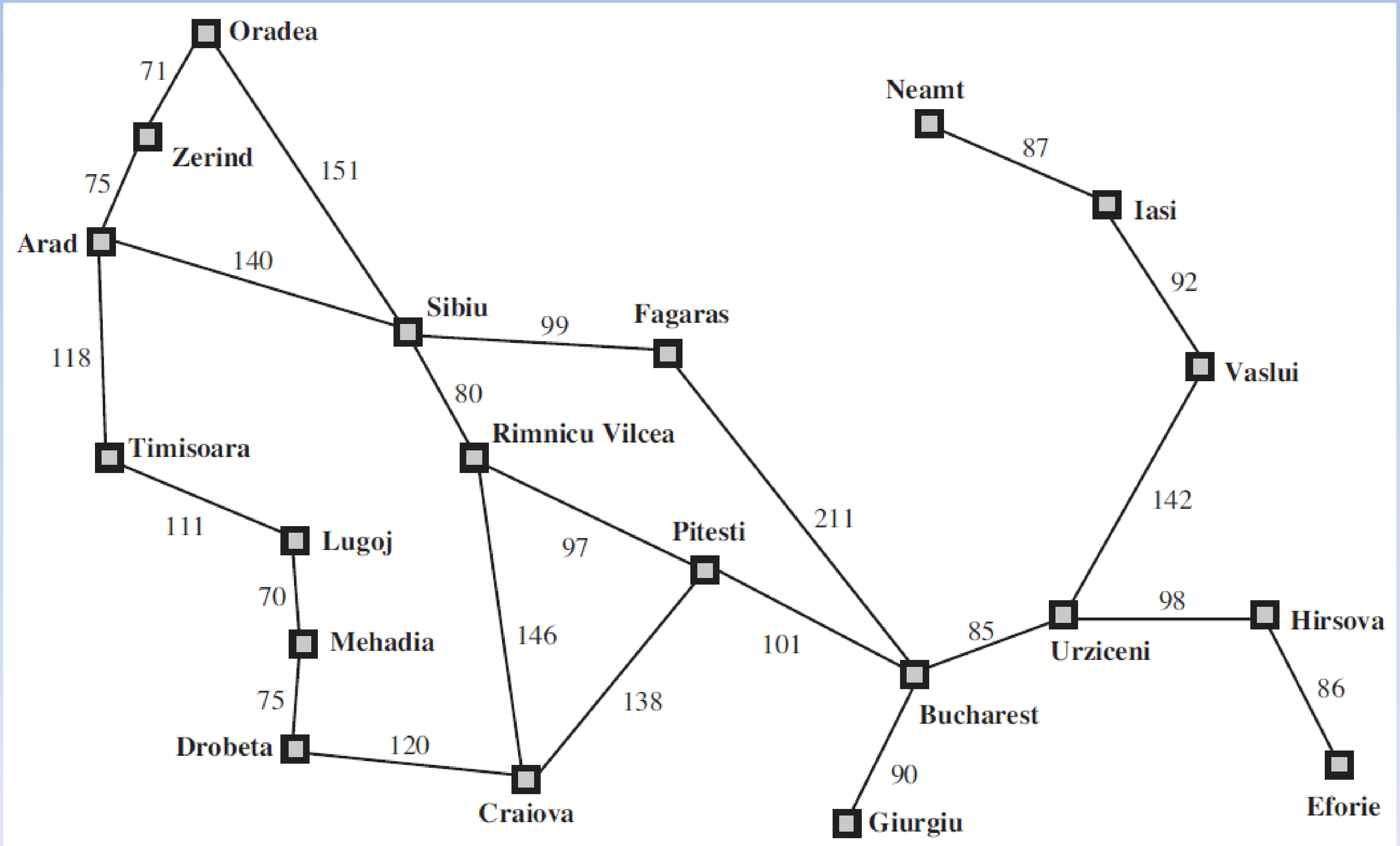
# Simple Problem-Solving Agent

- Agent's Dilemma:
  - Given several immediate options (High Road, Low Road, …)
  - Which options leads to my goal
- Agent examines the results of available actions to find a sequence leading to goal.

# Simple Problem-Solving Agent Assumptions

- Environment is OBSERVABLE
  - Agent always know where it is.
  - I’m in Fresno, Agent in Arad.
- Environment is DISCRETE
  - Finite number of actions from any state.
- Environment is KNOWN
  - We have a map.
- Environment is DETERMINISTIC
  - Roads don’t magically deliver us to different destinations.
- SEARCH:
  - Process of looking for the sequence of actions that lead to goal.

# Map



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Drobeta
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Giurgiu
Eforie

# Simple Problem-Solving Agent Search

- SEARCH:
  - Process of looking for the sequence of actions that lead to goal.
- Thinking (Searching) Agent closes eyes to the world.
- Executes solution (sequence of actions) found one step at a time.

# Simple Problem-Solving Agent



**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
```

**Figure 3.1** A simple problem-solving agent. It first formulates a goal and a problem, searches for a sequence of actions that would solve the problem, and then executes the actions one at a time. When this is complete, it formulates another goal and starts over.

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Contains Action Sequence

Return First Action

**Figure 3.1** A simple problem-solving agent. It first formulates a goal and a problem, searches for a sequence of actions that would solve the problem, and then executes the actions one at a time. When this is complete, it formulates another goal and starts over.

# Simple Problem-Solving Agent: Knows Action Sequence



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function SIMPLE-PROBLEM-SOLVING-AGENT(percept) returns an action
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  return action
```

Contains Action Sequence

Return First Action

**Figure 3.1** A simple problem-solving agent. It first formulates a goal and a problem, searches for a sequence of actions that would solve the problem, and then executes the actions one at a time. When this is complete, it formulates another goal and starts over.

# Simple Problem-Solving Agent: Doesn't Know Action Sequence



**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*

SEARCH

**Figure 3.1** A simple problem-solving agent. It first formulates a goal and a problem, searches for a sequence of actions that would solve the problem, and then executes the actions one at a time. When this is complete, it formulates another goal and starts over.

# Search Problem

- Initial State
- Possible Actions:
  - Actions(s) : Available actions in state ‘s’
- Action Behaviors (Transition Model)
  - Result(s, a): State that results from doing action ‘a’ in state ‘s’
- Goal Test
- Path Cost

# Successor Function

- SuccessorFN: Used by many treatments of problem solving.
- SuccessorFN: Defined with Actions(state), Result(state, action)

```
Def Successors(state):

    return [(action, Result(state, action)) for action in Actions(state)]
```

# Modeling / Abstraction

- State Space Defined by:
  - Initial State, Possible Actions, and Action Behaviors
- Abstraction required to create representation
  - Detail removed from state descriptions
  - Detail removed from action behaviors

# Modeling / Abstraction Navigation Example

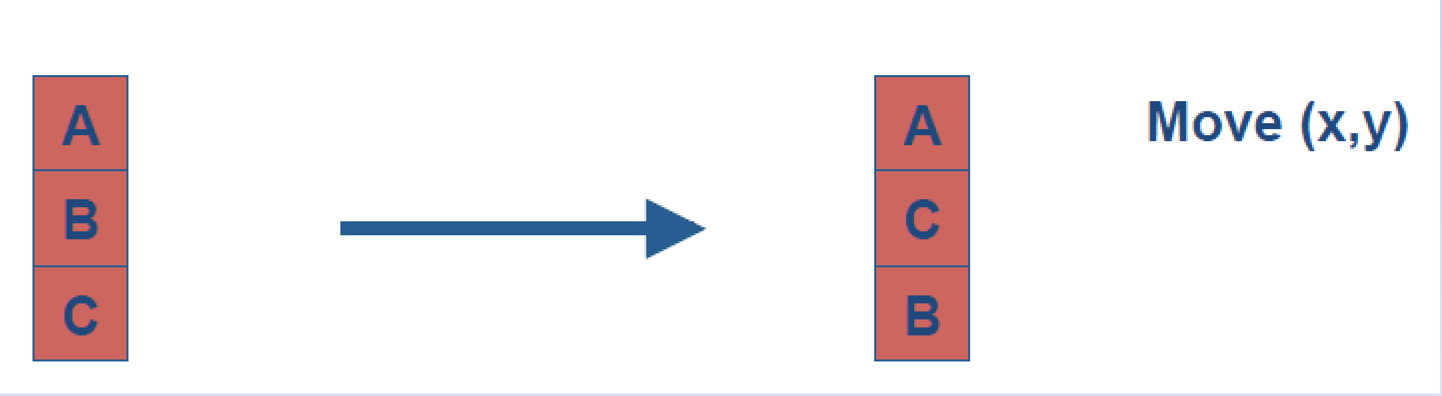
- How do we define States & Operators ?
  - First step is to abstract “the big picture”
    - i.e., solve a map problem
      - Nodes=cities,  Links=freeways/roads (high-level description)
    - This description is an abstraction of the real problem
  - Details later, like freeway onramps, refueling, etc.
- Abstraction is critical for automated problem solving
  - Approximate/simplified model of the world:
  - Good abstractions retain all important details.

# Modeling / Abstraction

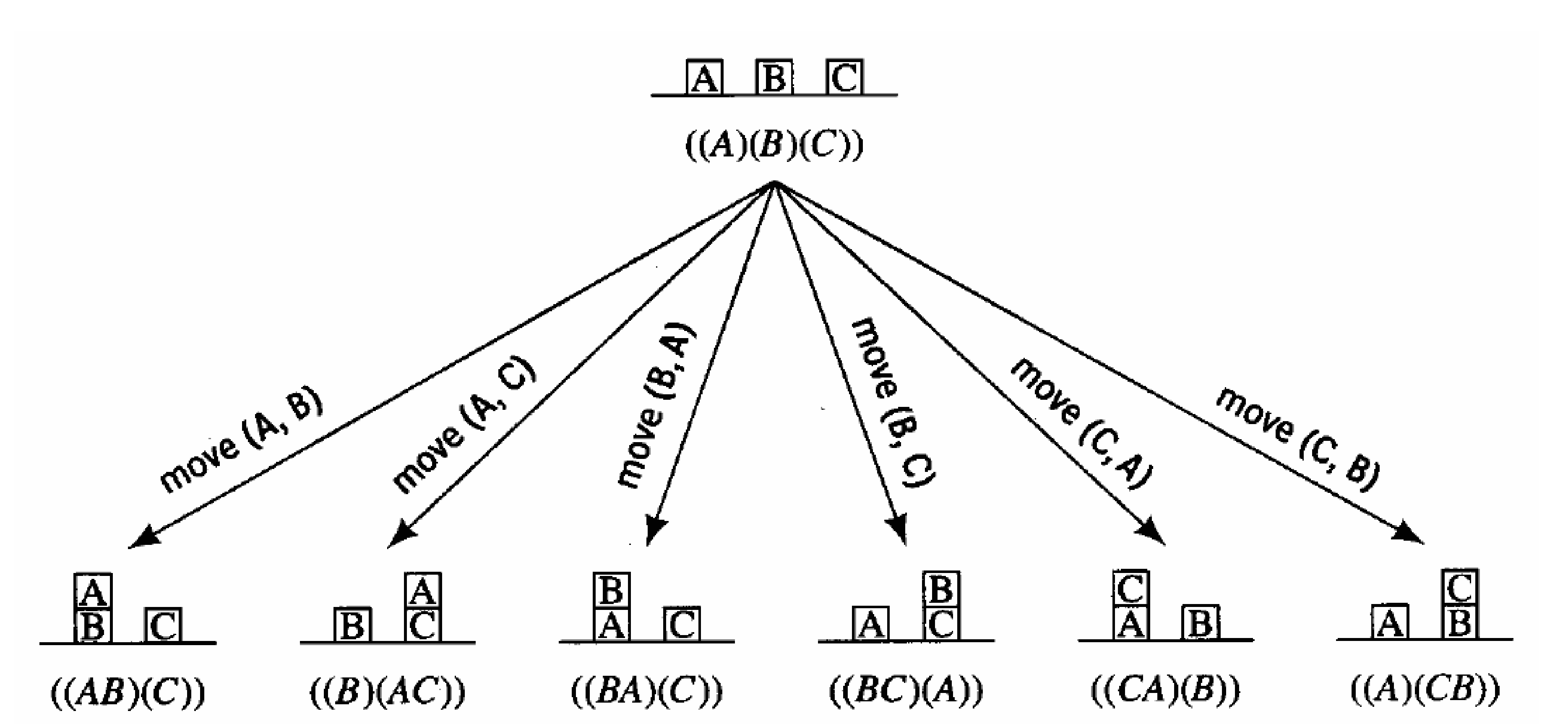
- State Space Defined by:
  - Initial State, Possible Actions, and Action Behaviors
- Abstraction required to create representation
  - Detail removed from state descriptions
  - Detail removed from action behaviors
- **Valid Abstraction:**
  - **Any abstract solution can be expanded into actual solution.**
- **Useful Abstraction:**
  - **Executing abstract solution is easier than original problem.**

# State Space: Robot Block World

- Given a set of blocks in a certain configuration,
- Move the blocks into a goal configuration
- Example:
  - (CBA) -> (BCA)

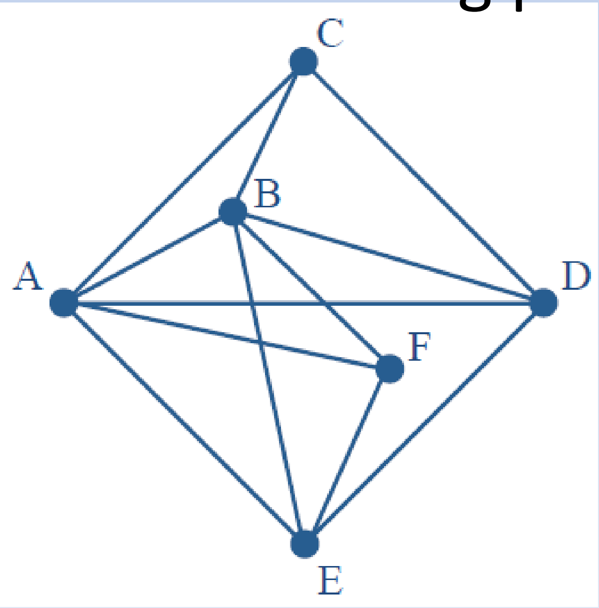


# Operator Description



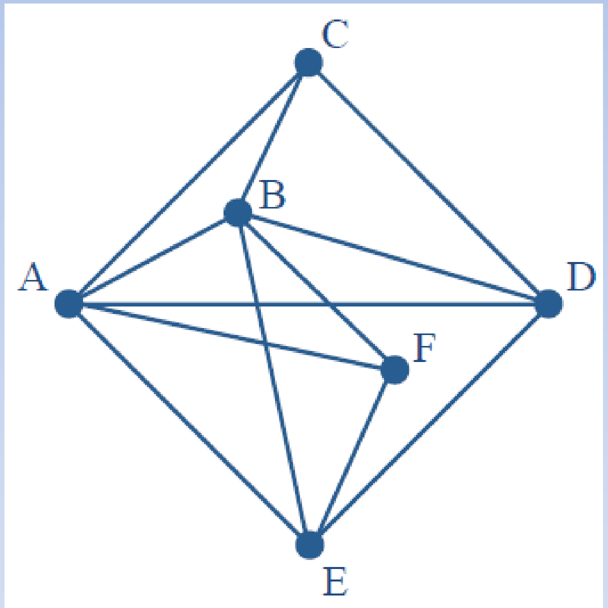
# Traveling Salesman Problem

- Our salesman needs to visit a bunch of cities.
  - He needs to visit each city only once.
  - He doesn't want to waste extra travel time.
- GOAL:
  - Find the shortest tour that visits all cities without visiting any city twice and return to starting point.
- STATE:
  - Sequence of Cities Visited.
- Start State:
  - First City (A)

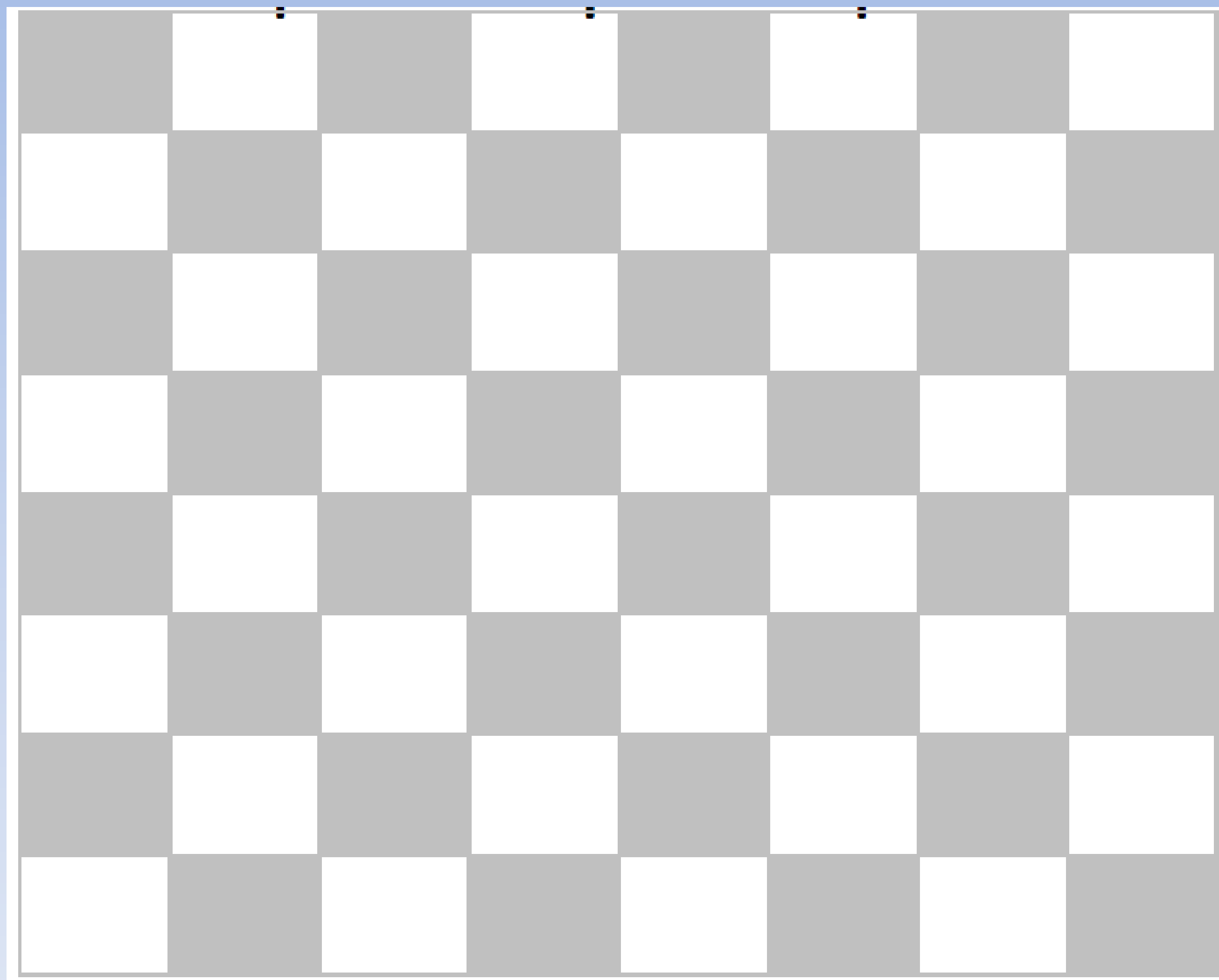


# Traveling Salesman Problem

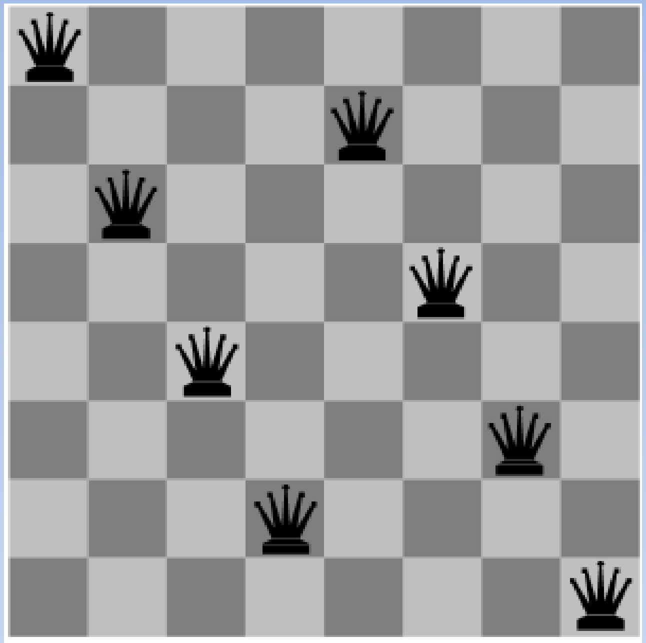
- GOAL:
  - Find the shortest tour that visits all cities without visiting any city twice and return to starting point.
- STATE:
  - Sequence of Cities Visited.
- Start State:
  - First City (A)
- Solution:
  - Complete Tour
- Transition Model:
  - {a, c, d} -> {a, c, d, X | X ∉ a, c, d}
  - don’t revisit state



# 8-Queens Problem

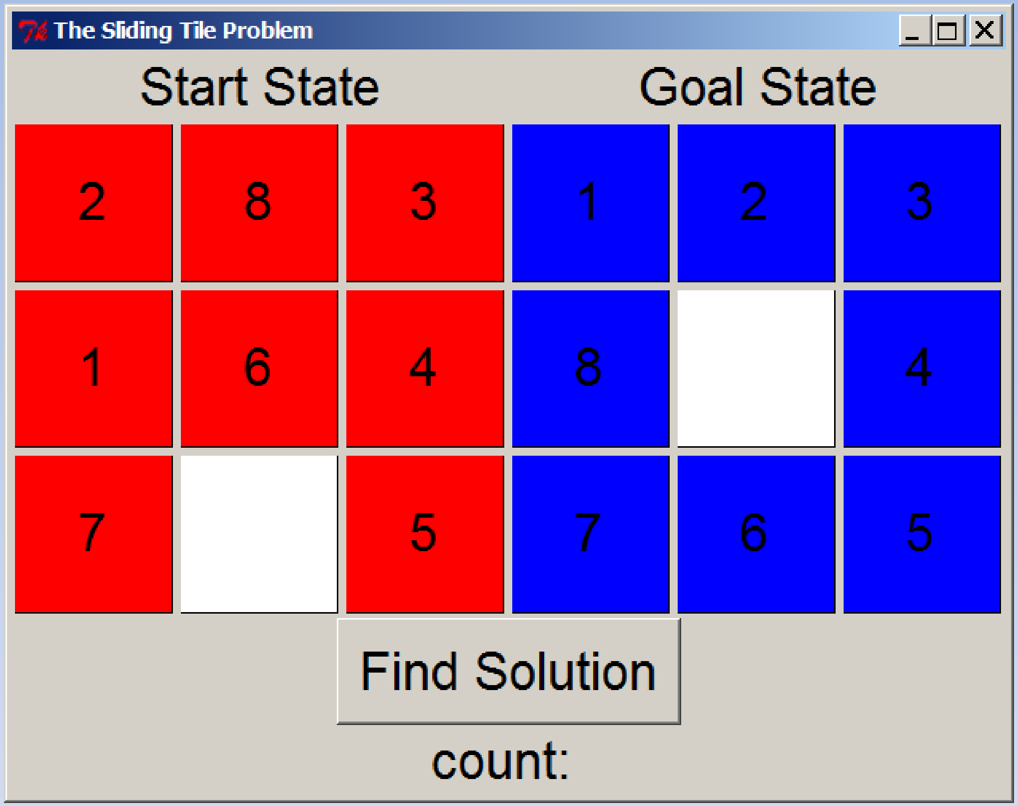


# 8-Queens



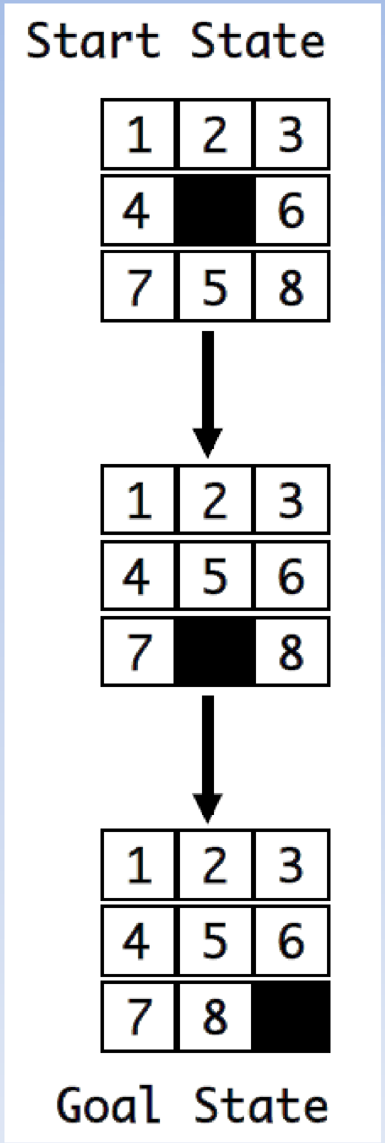
- States:
  - Any arrangement of n<=8 queens
  - OR: Arrangements of n<=8 queens:
    - In leftmost n columns, 1 per column,
    - such that no queen attacks any other.
- Initial State:
  - No Queens on board.
- Actions:
  - Add Queen to empty square.
  - OR: Add Queen to leftmost empty square such that it is not attacked by other Queens.
- Goal Test:
  - 8 Queens on board
  - None Attacked
- Path Cost: 1 per move

# The Sliding Tile Problem

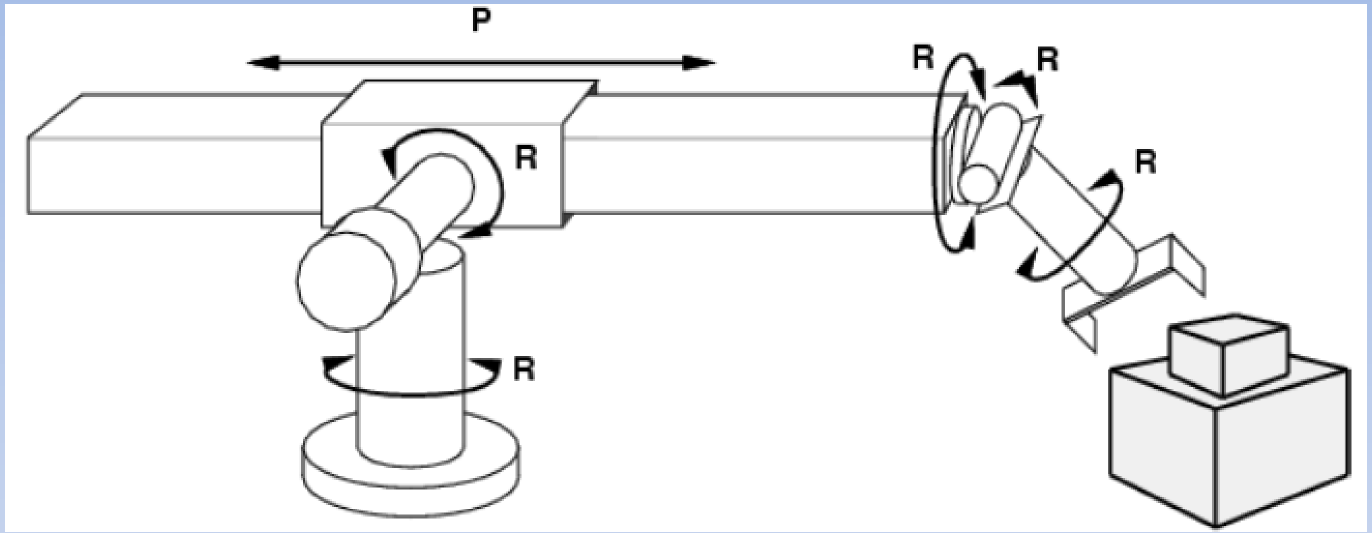



- Actions:
  - Up, Down, Left, Right
  - OR: move(x, loc_y, loc_z)

# The “8-Puzzle” Problem



# Robotic Assembly




- States: Real-valued coordinates of robot joint angles parts of the object to be assembled.
- Actions: Continuous motions of robot joints
- Goal Test: Complete Assembly
- Path Cost: Time to execute

# Formulating Problems; Another Angle

- Problem types
  - Satisficing: 8-queen
  - Optimizing: Traveling salesperson
- Object sought
  - Board configuration,
  - Sequence of moves
  - A strategy (contingency plan)
- Satisfying leads to optimizing since “small is quick”
- For traveling salsperson
  - Satisficing easy, optimizing hard
- Semi-optimizing
  - Find a good solution

# Searching the State Space

- States, operators, **control strategies**
- The search space graph is implicit
- The control strategy generates a small search tree.
- Systematic search
  - Do not leave any stone unturned
- Efficiency
  - Do not turn any stone more than once

# Question 3.9

- Missionaries and Cannibals Problem
  - 3 missionaries and 3 cannibals are on one side of a river, along with a boat that can hold one or two people.
  - Find a way to get everyone to the other side without ever leaving a group of missionaries in one place outnumbered by the cannibals in that place.
- This problem is famous in AI because it was the subject of the first paper that approached problem formulation from an analytical viewpoint (Amarel, 1968).
- Formulate the problem precisely, making only those distinctions necessary to ensure a valid solution.

# Question 3.9

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- Formulate the problem precisely, making only those distinctions necessary to ensure a valid solution.

# Question 3.9

- Here is one possible representation:
  - A state is a six-tuple of integers listing the number of missionaries, cannibals, and boats on the first side, and then the second side of the river.
  - The goal is a state with 3 missionaries and 3 cannibals on the second side.
  - The cost function is one per action, and the successors of a state are all the states that move 1 or 2 people and 1 boat from one side to another.

# Question 3.9

- Representation = (# of Missionaries on left, # of Cannibals on left, # of boats on left, # of Missionaries on right, # of Cannibals on right, # of boats on right
- Initial State = (3, 3, 1, 0, 0, 0)
- After MoveRight(1, 1):
  - (2, 2, 0, 1, 1, 1)

# Question 3.9

- The search space is small, so any optimal algorithm works.
  - It suffices to eliminate moves that circle back to the state just visited.
  - From all but the first and last states, there is only one other choice.
- Why do you think people have a hard time solving this puzzle, given that the state space is so simple?
  - It is not obvious that almost all moves are either illegal or revert to the previous state.
  - There is a feeling of a large branching factor, and no clear way to proceed.

```
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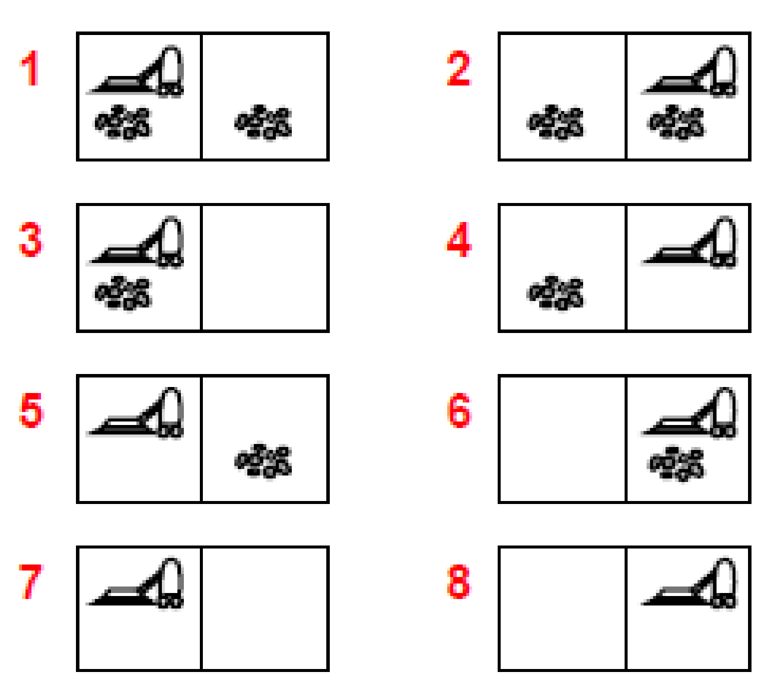
**Figure 3.1** A simple problem-solving agent. It first formulates a goal and a problem, searches for a sequence of actions that would solve the problem, and then executes the actions one at a time. When this is complete, it formulates another goal and starts over.

- Offline Problem Solving
  - Solution Executed EYES-CLOSED.
- Online problem solving involves acting without complete knowledge.

# Problem Types

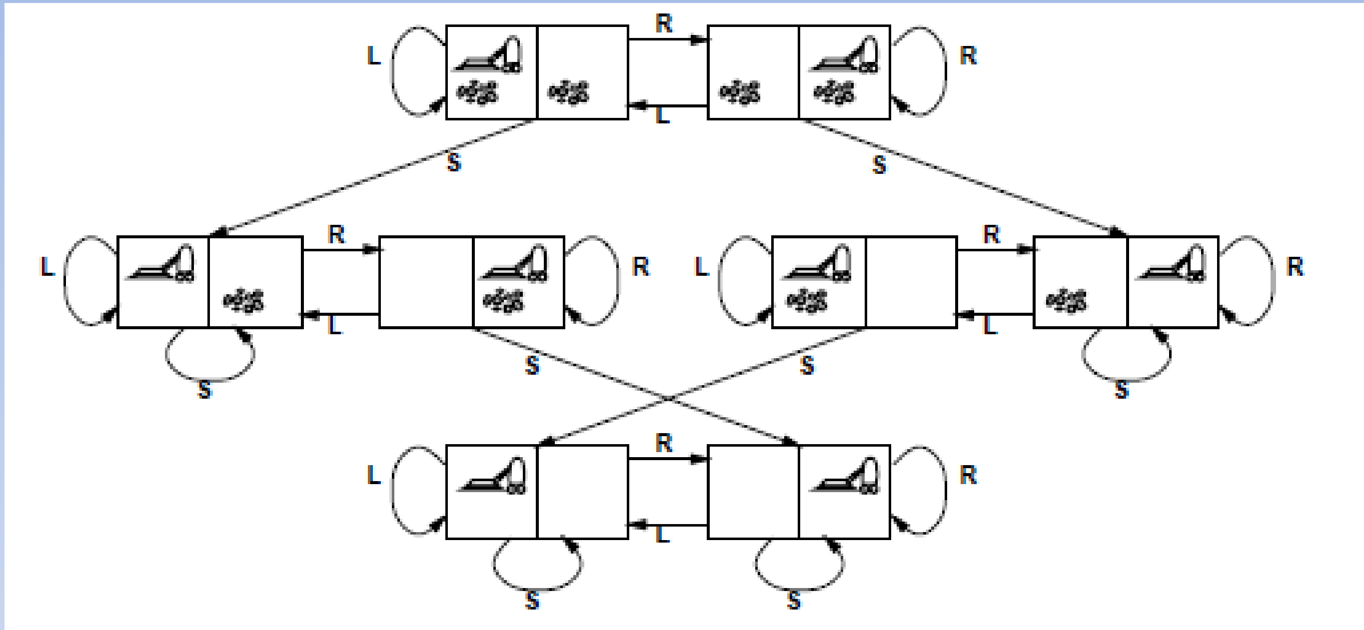
- Deterministic & Fully Observable
  - Single-State Problem
  - Action Sequence Solution
- Non-observable
  - Conformant Problem
  - Agent may have no idea where it is
  - Solution (if any) is a sequence
- Nondeterministic and/or partially observable
  - Contingency Problem
  - Percepts provide new information about current state
  - Solution is a contingent plan or a policy
  - Often interleave search and execution
- Unknown State Space: Exploration Problem (“online”)

# Vacuum World




- Single-state:
  - Start in #5
  - Solution=[Right, Suck]
- Conformant:
  - Start={1,2,3,4,5,6,7,8}
  - Right goes to {2,4,6,8}
  - Solution=[Right, Suck, Left, Suck]
- Contingency: Start = #5
  - Murphy’s Law: ‘Suck’ can dirty clean carpet
  - Local sensing: dirt, location only
  - Solution =[Right, if Dirt then Suck]

# Vacuum World State Space Graph




- States: integer dirt and robot locations (ignore dirt amount, etc.)
- Actions: Left, Right, Suck, NoOp
- Goal Test: no dirt
- Path Cost: 1 per action (0 for NoOp)

# Tree Search Algorithms

- Basic Idea:
  - Offline, Simulation exploration of state space by generating successors of already-explored states (a.k.a. expanding states)

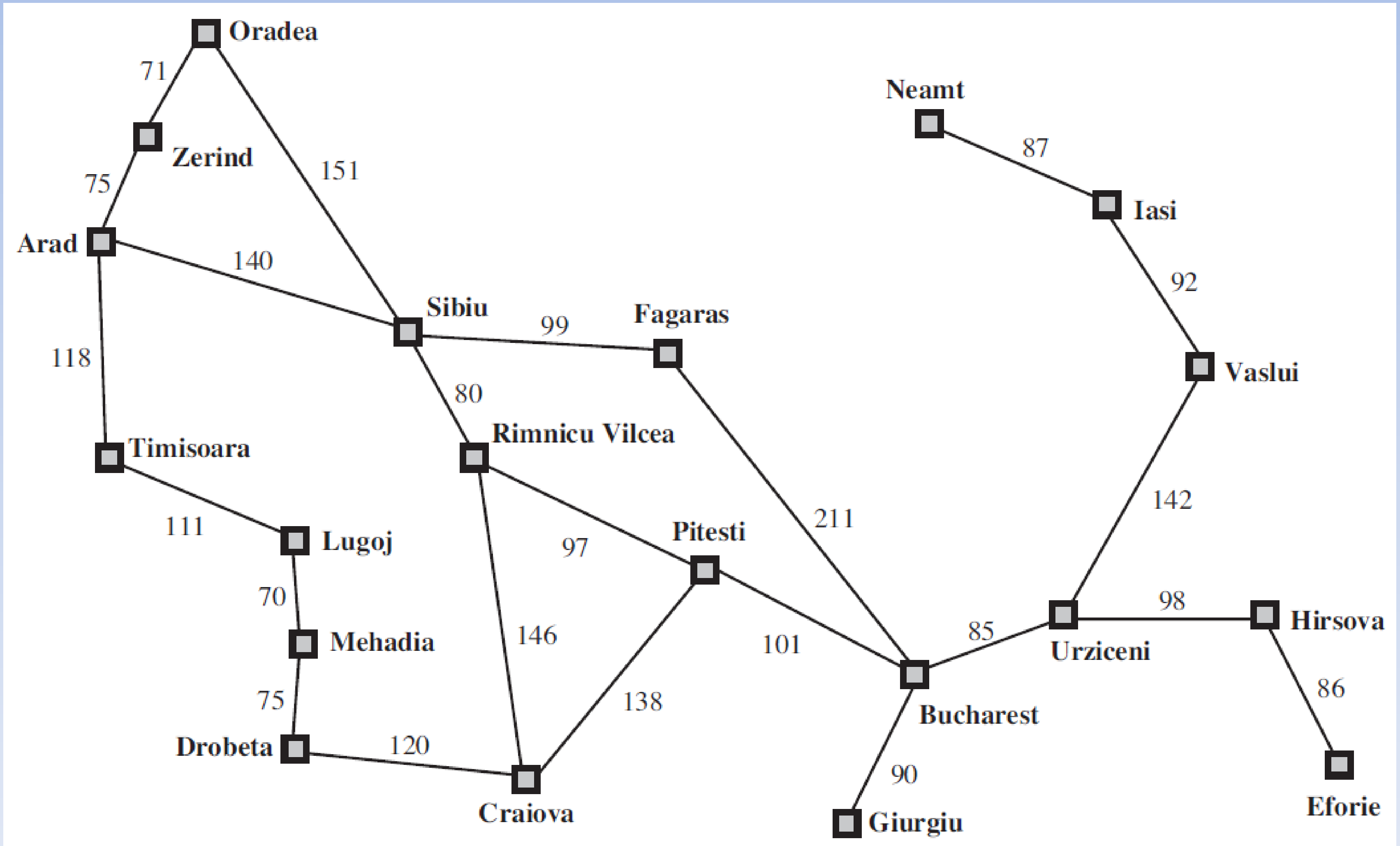
# Tree Search Algorithms (Fig 3.7)

**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

---

**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***

# Map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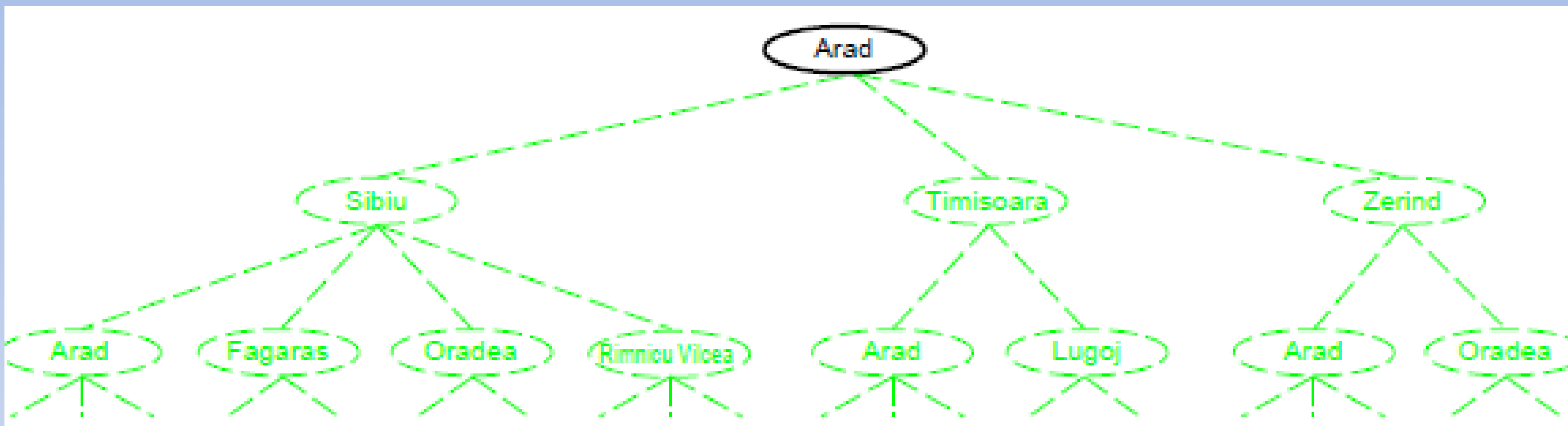
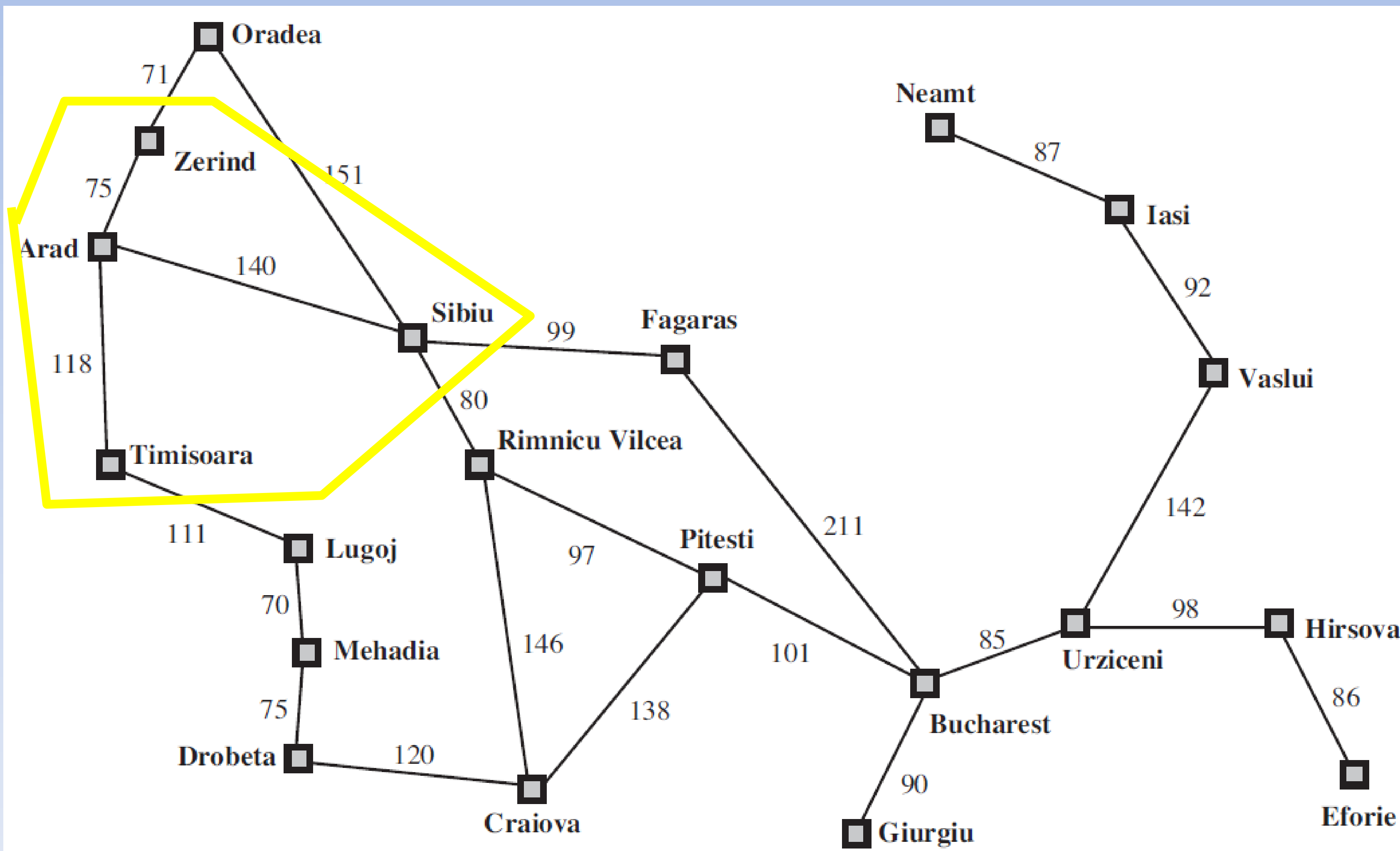
# Tree Search Example



# Map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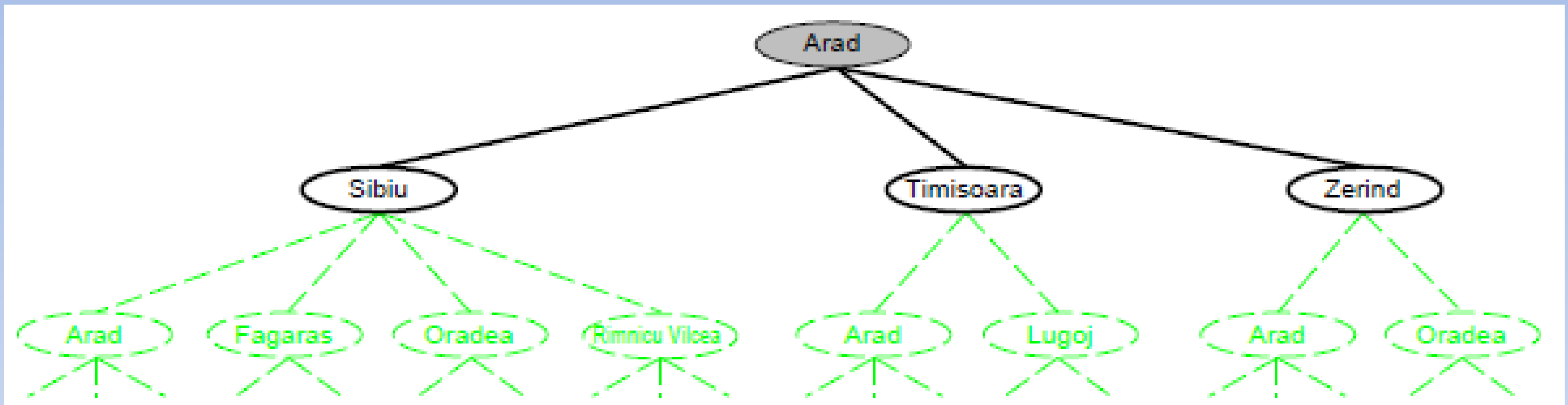
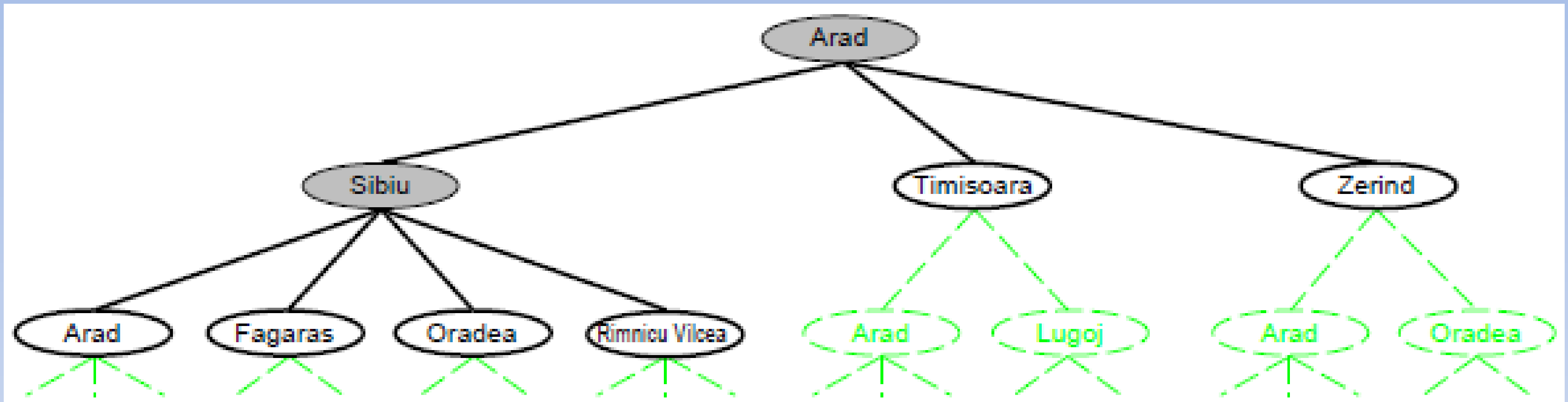
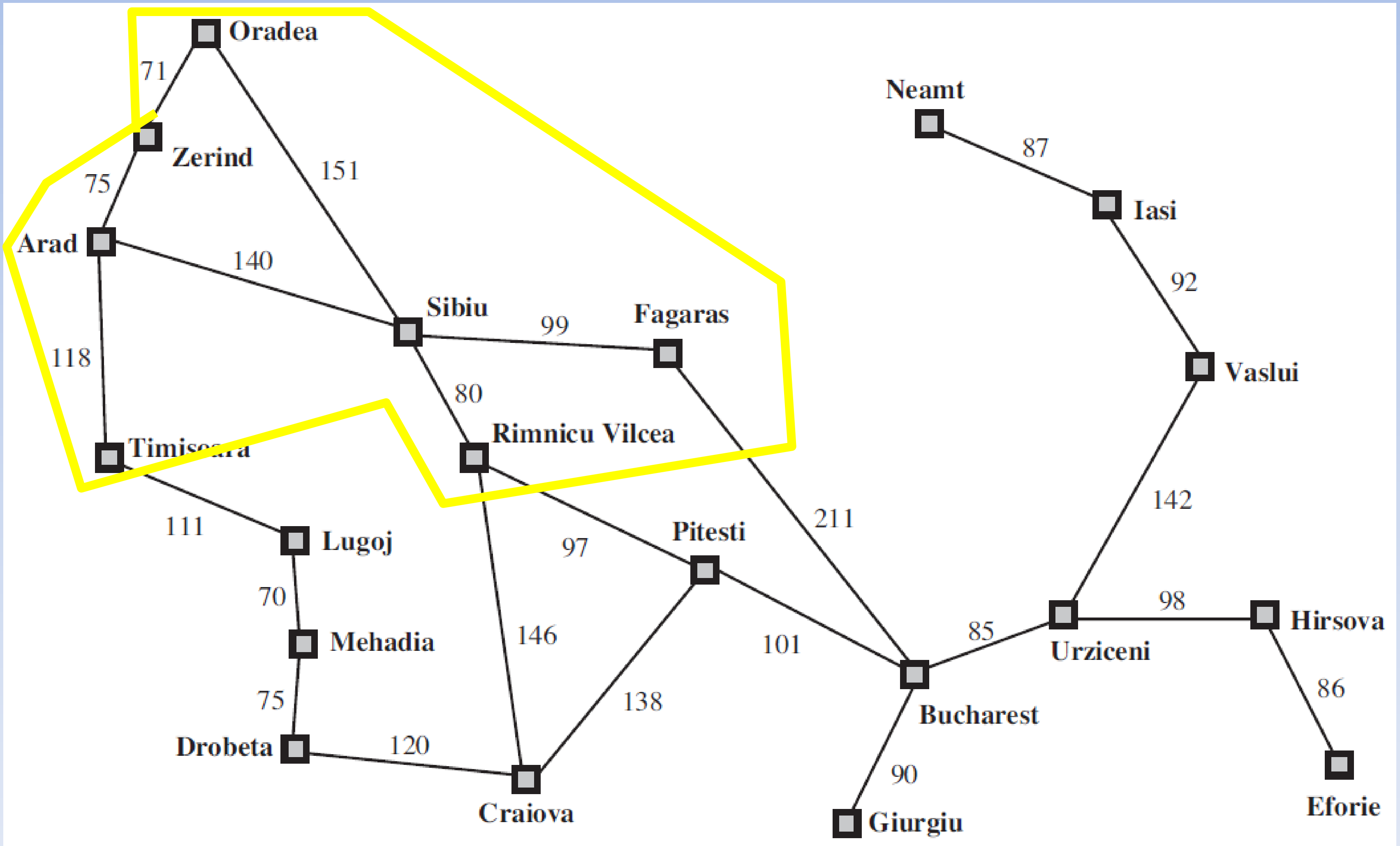
# Tree Search Example



# Tree Search Example



# Map



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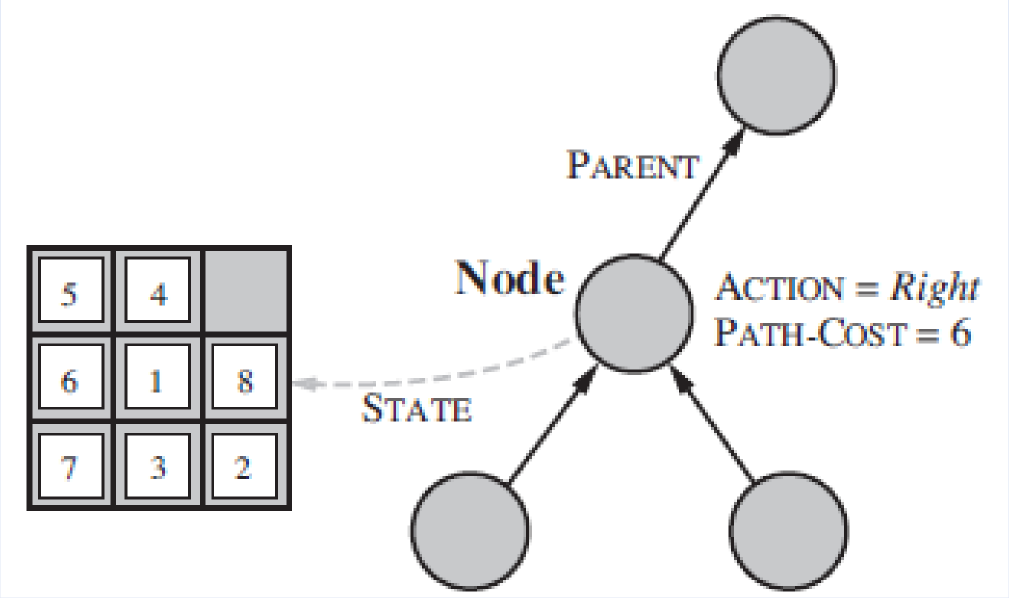
# Searching State Space

- Search Space Graph is Implicit

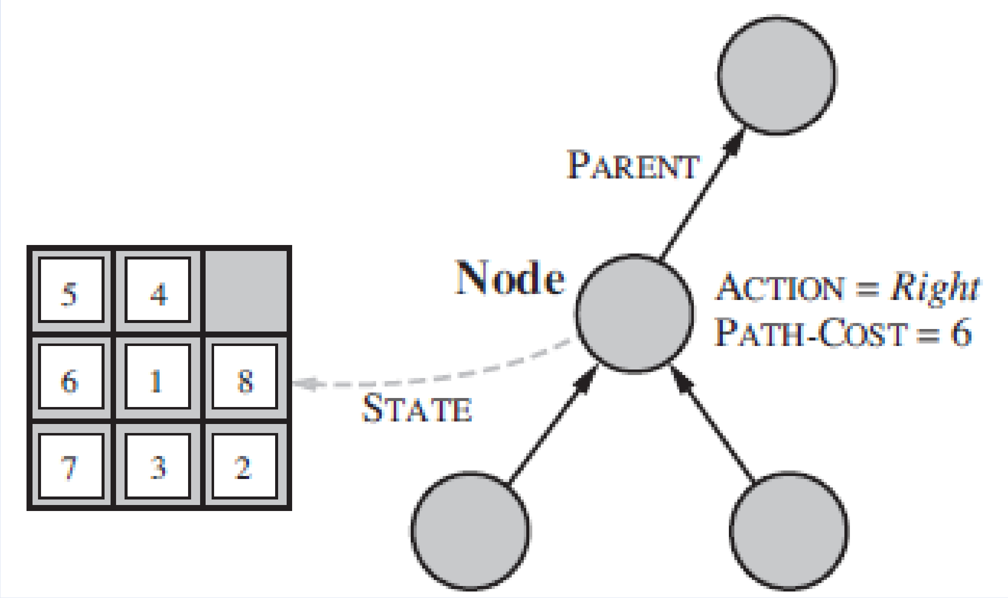
# States Versus Nodes

- State: Representation of a physical configuration.
- Node: Data structure constituting part of a search tree, including:
  - Parent, Children, Depth, or Path Cost (g).
- States do not have parents, children, depth or path cost.



# States Versus Nodes

**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*)



# Search Strategies

- Strategies are defined by picking the Order of Node Expansion
- Strategies are evaluated by:
  - Completeness: does it always find a solution if one exists?
  - Time Complexity: number of nodes generated/expanded.
  - Space Complexity: maximum nodes of nodes in memory.
  - Optimality: Does it always find a least-cost solution.
- Time and Space Complexity are measured by:
  - b: maximum branching factor of search tree.
  - d: depth of least-cost solution
  - m: maximum depth of the state space (may be $\infty$)

# Uninformed Search Strategies

- Uninformed Strategies: use only the information available to the problem definition.
  - Breadth-first Search
  - Depth-first Search
  - Uniform-Cost Search
  - Depth-Limited Search
  - Iterative Deepening Search

# Remembering Graphs

- Lets look more formally at graphs
- Graph G=(V, E)
  - V: Set of vertices
  - E: Set of edges
- Two representations
  - Adjacency Lists
  - Adjacency Matrix