Solving problems by searching

Chapter 3
Outline

• Problem-solving agents
• Problem types
• Problem formulation
• Example problems
• Basic search algorithms
Example: Romania

- 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
Example: Romania
Problem-solving agent

Restricted form of general agent; solution executed “eyes closed“:

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

static: seq, an action sequence

state, some description of the current world state

goal, a goal

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)

action ← FIRST(seq)

seq ← REST(seq)

return action
Problem types

• **Deterministic, fully observable** $\rightarrow$ *single-state problem*
  - Agent knows exactly which state it will be in; solution is a sequence

• **Non-observable** $\rightarrow$ *sensor-less problem (conformant problem)*
  - Agent may have no idea where it is; solution is a sequence

• **Partially observable** $\rightarrow$ *contingency problem*
  - Perception provides *new* information about current state
  - Often *interleave* search, execution

• **Unknown state space** $\rightarrow$ *exploration problem*
  - When states and actions of the environment are unknown
Example: vacuum world

- Single-state, start in #5.
  Solution?
Example: vacuum world

- **Single-state**, start in #5.
  \[\text{Solution?} \ [\text{Right, Suck}]\]

- **Sensorless**, start in\n  \{1,2,3,4,5,6,7,8\} e.g.,
  \textit{Right} goes to \{2,4,6,8\}
  \[\text{Solution?}\]
Example: vacuum world

• **Sensorless**, start in \{1,2,3,4,5,6,7,8\} e.g.,
  \textit{Right} goes to \{2,4,6,8\}
  
  **Solution?**
  \textit{[Right,Suck,Left,Suck]}

• **Contingency**
  - Nondeterministic: \textit{Suck} may
    dirty a clean carpet
  - Partially observable: location, dirt at current location
  - Percept: \textit{[L, Clean]}, i.e., start in #5 or #7
    
    **Solution?**
Example: vacuum world

- **Sensorless**, start in \{1,2,3,4,5,6,7,8\} e.g., *Right* goes to \{2,4,6,8\}
  
  Solution?  
  \([Right, Suck, Left, Suck]\)

- **Contingency**
  
  - Nondeterministic: *Suck* may dirty a clean carpet
  
  - Partially observable: location, dirt at current location.
  
  - Percept: \([L, Clean]\), i.e., start in \#5 or \#7
    
    Solution?  
    \([Right, \text{if dirt then Suck}]\)
A problem is defined by four items:

1. **initial state**, e.g. "at Arad"
2. **actions or successor function** $S(x) =$ set of action–state pairs
   - e.g., $S(\text{Arad}) = \{<\text{Arad} \rightarrow \text{Zerind}, \text{Zerind}>, \ldots \}$
3. **goal test**, can be
   - **explicit**, e.g., $x =$ "at Bucharest"
   - **implicit**, e.g., $\text{Checkmate}(x)$
4. **path cost** (additive)
   - e.g., sum of distances, number of actions executed, etc.
   - $c(x,a,y)$ is the **step cost**, assumed to be $\geq 0$

- A **solution** is a sequence of actions leading from the initial state to a goal state
Selecting a state space

• Real world is absurdly complex
  → State space must be abstracted for problem solving
• (Abstract) state corresponds to set of real states
• (Abstract) action corr. to complex combination of real actions
  - E.g., "Arad → Zerind" represents a complex set of possible routes, detours, rest stops, etc.
• For guaranteed realizability, any real state "in Arad" must get to some real state "in Zerind"
• (Abstract) solution corresponds to
  - Set of real paths that are solutions in the real world
• Each abstract action should be "easier" than the original problem
Vacuum world state space graph

- States?
- Actions?
- Goal test?
- Path cost?
Vacuum world state space graph

- **States?** two locations, dirt, and robot location
- **Actions?** Left, Right, Suck
- **Goal test?** no dirt at all locations
- **Path cost?** 1 per action
Example: The 8-puzzle

- States?
- Actions?
- Goal test?
- Path cost?
Example: The 8-puzzle

- **States?** locations of tiles
- **Actions?** move blank left, right, up, down
- **Goal test?** = goal state (given)
- **Path cost?** 1 per move

[Note: optimal solution of $n$-Puzzle family is NP-hard]
Example: robotic assembly

- **States?** real-valued coordinates of robot joint angles and parts of the object to be assembled
- **Actions?** continuous motions of robot joints
- **Goal test?** complete assembly
- **Path cost?** time to execute
Example: 8-queens problem

- States?
- Actions?
- Goal test?
- Path cost?
Example: 8-queens problem

Incremental formulation vs. complete-state formulation

- **States?**
- **Actions?**
- **Goal test?**
- **Path cost?**
Example: 8-queens problem

Incremental formulation

- **States?** any arrangement of 0 to 8 queens on the board
- **Initial state?** no queens
- **Actions?** add queen in empty square
- **Goal test?** 8 queens on board and none attacked
- **Path cost?** none

\[64 \times 63 \times \ldots \times 57 \approx 1.8 \times 10^{14}\] possible sequences to investigate
Example: 8-queens problem

Incremental formulation (alternative)

• **States?** \( n (0 \leq n \leq 8) \) queens on the board, one per column in the \( n \) leftmost columns with no queen attacking another.

• **Actions?** Add queen in leftmost empty column such that is not attacking other queens
Basic search algorithms

How do we find the solutions of previous problems?

- Search the state space (remember complexity of space depends on state representation)

- Here: search through *explicit tree generation*
  - ROOT = initial state.
  - Nodes and leaves generated through successor function.

- In general search generates a graph (same state through multiple paths)
Simple tree search example

function TREE-SEARCH(problem, strategy) return a solution or failure

  Initialize search tree to the initial state of the problem
  do
    if no candidates for expansion then return failure
    choose leaf node for expansion according to strategy
    if node contains goal state then return solution
    else expand the node and add resulting nodes to the search tree
  enddo
**Simple tree search example**

**function** TREE-SEARCH(*problem*, *strategy*) **return** a solution or failure

  Initialize search tree to the *initial state* of the *problem*

  do
    if no candidates for expansion then return *failure*
    choose leaf node for expansion according to *strategy*
    if node contains goal state then return *solution*
    else expand the node and add resulting nodes to the search tree
  enddo
function TREE-SEARCH(problem, strategy) return a solution or failure

    Initialize search tree to the initial state of the problem
    do
        if no candidates for expansion then return failure
        choose leaf node for expansion according to strategy
        if node contains goal state then return solution
        else expand the node and add resulting nodes to the search tree
    enddo
State space vs. search tree

A *state* is a (representation of) a physical configuration

A *node* is a data structure belong to a search tree

- A node has a parent, children, … and includes path cost, depth, …
- Here *node* = *(state, parent-node, action, path-cost, depth)*
- *FRINGE* contains generated nodes which are not yet expanded
  - White nodes with black outline
function TREE-SEARCH\( (problem, fringe) \) return a solution or failure

\( fringe \leftarrow \text{INSERT(MAKE-NODE(INITIAL-STATE[problem]), fringe)} \)

loop do
  if EMPTY\((fringe)\) then return failure
  node \leftarrow \text{REMOVE-FIRST(fringe)}
  if GOAL-TEST\([problem]\) applied to STATE\([node]\) succeeds
    then return SOLUTION\((node)\)
  fringe \leftarrow \text{INSERT-ALL(EXPAND(node, problem), fringe)}
function EXPAND(node, problem) return a set of nodes

successors ← the empty set

for each <action, result> in SUCCESSOR-FN[problem](STATE[node]) do

    s ← a new NODE
    STATE[s] ← result
    PARENT-NODE[s] ← node
    ACTION[s] ← action
    PATH-COST[s] ← PATH-COST[node] + STEP-COST(node, action, s)
    DEPTH[s] ← DEPTH[node] + 1
    add s to successors

return successors
Search strategies

- A search strategy is defined by picking the order of node expansion.
- Strategies are evaluated along the following dimensions:
  - **completeness**: does it always find a solution if one exists?
  - **time complexity**: number of nodes generated
  - **space complexity**: maximum number of nodes in memory
  - **optimality**: does it always find a least-cost solution?
- Time and space complexity are measured in terms of:
  - $b$: maximum branching factor of the search tree
  - $d$: depth of the least-cost solution
  - $m$: maximum depth of the state space (may be $\infty$)
Uninformed search strategies use only the information available in the problem definition.

When strategies can determine whether one non-goal state is better than another → informed search

- Breadth-first search
- Uniform-cost search
- Depth-first search
- Depth-limited search
- Iterative deepening search
- Bidirectional search
Breadth-first search

- Expand shallowest unexpanded node
- **Implementation:**
  - *fringe* is a FIFO queue, i.e., new successors go at end
Breadth-first search

- Expand shallowest unexpanded node
- Implementation:
  - *fringe* is a FIFO queue, i.e., new successors go at end
Breadth-first search

- Expand shallowest unexpanded node
- **Implementation:**
  - *fringe* is a FIFO queue, i.e., new successors go at end
Breadth-first search

• Expand shallowest unexpanded node

• Implementation:
  - *fringe* is a FIFO queue, i.e., new successors go at end
Properties of breadth-first search

- **Complete?** Yes (if \( b \) is finite)
- **Time?** \( 1+b+b^2+b^3+\ldots +b^d + b(b^d-1) = O(b^{d+1}) \)
- **Space?** \( O(b^{d+1}) \) (keeps every node in memory)
- **Optimal?** Yes (if cost = 1 per step)
- **Space** is the bigger problem (more than time)
BF-search; evaluation

b=10; 10,000 nodes/sec; 1000 bytes/node

<table>
<thead>
<tr>
<th>DEPTH</th>
<th>NODES</th>
<th>TIME</th>
<th>MEMORY</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1100</td>
<td>0.11 seconds</td>
<td>1 megabyte</td>
</tr>
<tr>
<td>4</td>
<td>1,111,100</td>
<td>11 seconds</td>
<td>106 megabytes</td>
</tr>
<tr>
<td>6</td>
<td>$10^7$</td>
<td>19 minutes</td>
<td>10 gigabytes</td>
</tr>
<tr>
<td>8</td>
<td>$10^9$</td>
<td>31 hours</td>
<td>1 terabyte</td>
</tr>
<tr>
<td>10</td>
<td>$10^{11}$</td>
<td>129 days</td>
<td>101 terabytes</td>
</tr>
<tr>
<td>12</td>
<td>$10^{13}$</td>
<td>35 years</td>
<td>10 petabytes</td>
</tr>
<tr>
<td>14</td>
<td>$10^{15}$</td>
<td>3523 years</td>
<td>1 exabyte</td>
</tr>
</tbody>
</table>

- Memory requirements are a bigger problem than its execution time
- Uniformed search only applicable for small instances
  -> Exploit knowledge about the problem
Uniform-cost search

- Expand least-cost unexpanded node
- **Implementation:**
  - fringe = queue ordered by path cost
- Equivalent to breadth-first if step costs all equal
- **Complete?** Yes, if step cost $\geq \epsilon$
- **Time?** # of nodes with $g \leq$ cost of optimal solution, $O(b^{1+\lfloor \log(C^*/\epsilon) \rfloor})$
  where $C^*$ is the cost of the optimal solution
- **Space?** # of nodes with $g \leq$ cost of optimal solution, $O(b^{1+\lfloor \log(C^*/\epsilon) \rfloor})$
- **Optimal?** Yes – nodes expanded in increasing order of path costs
Depth-first search

- Expand deepest unexpanded node
- **Implementation:**
  - *fringe* = LIFO queue, i.e., put successors at front
Depth-first search

- Expand deepest unexpanded node
- **Implementation:**
  - *fringe* = LIFO queue, i.e., put successors at front
Depth-first search

- Expand deepest unexpanded node
- **Implementation:**
  - fringe = LIFO queue, i.e., put successors at front
Depth-first search

- Expand deepest unexpanded node

**Implementation:**
  - *fringe* = LIFO queue, i.e., put successors at front
Depth-first search

- Expand deepest unexpanded node
- Implementation:
  - fringe = LIFO queue, i.e., put successors at front
Depth-first search

- Expand deepest unexpanded node
- **Implementation:**
  - *fringe* = LIFO queue, i.e., put successors at front
Depth-first search

- Expand deepest unexpanded node
- Implementation:
  - fringe = LIFO queue, i.e., put successors at front
Depth-first search

- Expand deepest unexpanded node
- **Implementation:**
  - *fringe* = LIFO queue, i.e., put successors at front
Depth-first search

- Expand deepest unexpanded node
- **Implementation:**
  - *fringe* = LIFO queue, i.e., put successors at front
Depth-first search

- Expand deepest unexpanded node
- Implementation:
  - *fringe* = LIFO queue, i.e., put successors at front
Depth-first search

- Expand deepest unexpanded node
- Implementation:
  - fringe = LIFO queue, i.e., put successors at front
Depth-first search

- Expand deepest unexpanded node

**Implementation:**
- \textit{fringe} = LIFO queue, i.e., put successors at front
Properties of depth-first search

- **Complete?** No: fails in infinite-depth spaces, spaces with loops
  - Modify to avoid repeated states along path
    - complete in finite spaces

- **Time?** $O(b^m)$: terrible if $m$ is much larger than $d$
  (remember: $m$ ... maximum depth of search space)
  - but if solutions are dense, may be much faster than breadth-first

- **Space?** $O(bm)$, i.e., linear space!

- **Optimal?** No
Depth-limited search

Is DF-search with depth limit $l$.
- i.e. nodes at depth $l$ have no successors
- Problem knowledge can be used

Solves the infinite-path problem, but
If $l < d$ then incompleteness results
If $l > d$ then not optimal

Time complexity: $O(b^l)$

Space complexity: $O(bl)$
**Depth-limited algorithm**

```plaintext
function DEPTH-LIMITED-SEARCH(problem, limit) return a solution or failure/cutoff
return RECURSIVE-DLS(MAKE-NODE(INITIAL-STATE[problem]), problem, limit)

function RECURSIVE-DLS(node, problem, limit) return a solution or failure/cutoff
cutoff_occurred? ← false
if GOAL-TEST[problem](STATE[node]) then return SOLUTION(node)
else if DEPTH[node] == limit then return cutoff
else for each successor in EXPAND(node, problem) do
    result ← RECURSIVE-DLS(successor, problem, limit)
    if result == cutoff then cutoff_occurred? ← true
    else if result ≠ failure then return result
if cutoff_occurred? then return cutoff else return failure
```
What?
- A general strategy to find best depth limit $l$
  - Solution is found at depth $d$, the depth of the shallowest solution-node
- Often used in combination with DF-search

Combines benefits of DF- and BF-search
Iterative deepening search

function ITERATIVE_DEEPENING_SEARCH(problem)
    return a solution or failure

inputs: problem

for depth ← 0 to \( \infty \) do
    result ← DEPTH-LIMITED_SEARCH(problem, depth)
    if result \neq \text{cutoff} then return result
Iterative deepening search / = 0

Limit = 0
Iterative deepening search / = 1

Limit = 1

Diagram showing iterative deepening search with a limit of 1.
Iterative deepening search \( l = 2 \)
Iterative deepening search \( l = 3 \)
Iterative deepening search

- Number of nodes generated in a depth-limited search to depth \( d \) with branching factor \( b \):
  \[
  N_{DLS} = b^0 + b^1 + b^2 + \ldots + b^{d-2} + b^{d-1} + b^d
  \]

- Number of nodes generated in an iterative deepening search to depth \( d \) with branching factor \( b \):
  \[
  N_{IDS} = (d+1)b^0 + d b^1 + (d-1)b^2 + \ldots + 3b^{d-2} + 2b^{d-1} + 1b^d
  \]

- For \( b = 10 \), \( d = 5 \),
  - \( N_{DLS} = 1 + 10 + 100 + 1,000 + 10,000 + 100,000 = 111,111 \)
  - \( N_{IDS} = 6 + 50 + 400 + 3,000 + 20,000 + 100,000 = 123,456 \)

- Overhead = \( (123,456 - 111,111)/111,111 = 11\% \)
Properties of iterative deepening search

- **Complete?** Yes
- **Time?** \((d+1)b^0 + d b^1 + (d-1)b^2 + \ldots + b^d = O(b^d)\)
- **Space?** \(O(bd)\)
- **Optimal?** Yes, if step cost = 1

Num. comparison for \(b=10\) and \(d=5\) solution at far right

\[ N_{\text{IDS}} = 6 + 50 + 400 + 3,000 + 20,000 + 100,000 = 123,456 \]
\[ N_{\text{BFS}} = 1 + 10 + 100 + 1,000 + 10,000 + 100,000 + 999,990 = 1,111,101 \]

- IDS does better because nodes at depth \(d\) are not further expanded
- BFS can be modified to apply goal test when a node is generated
Bidirectional search

Two simultaneous searches from start an goal

- Motivation: \[ b^{d/2} + b^{d/2} \neq b^d \]

Check whether the node belongs to the other fringe before expansion
Complete and optimal if both searches are BF
Space complexity is the most significant weakness
How to search backwards?

The predecessor of each node should be efficiently computable
- When actions are easily reversible

Number of goal states does not explode
### Summary of algorithms

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Breadth-First</th>
<th>Uniform-cost</th>
<th>Depth-First</th>
<th>Depth-limited</th>
<th>Iterative deepening</th>
<th>Bidirectional search</th>
</tr>
</thead>
<tbody>
<tr>
<td>Complete?</td>
<td>YES(a)</td>
<td>YES(a,b)</td>
<td>NO</td>
<td>YES, if (l \geq d)</td>
<td>YES(a)</td>
<td>YES(a,d)</td>
</tr>
<tr>
<td>Time</td>
<td>(b^{d+1})</td>
<td>(b^{1+\text{floor}(C/e)})</td>
<td>(b^m)</td>
<td>(b^l)</td>
<td>(b^d)</td>
<td>(b^{d/2})</td>
</tr>
<tr>
<td>Space</td>
<td>(b^{d+1})</td>
<td>(b^{1+\text{floor}(C/e)})</td>
<td>(b^m)</td>
<td>(b^l)</td>
<td>(b^d)</td>
<td>(b^{d/2})</td>
</tr>
<tr>
<td>Optimal?</td>
<td>YES(c)</td>
<td>YES</td>
<td>NO</td>
<td>NO</td>
<td>YES(c)</td>
<td>YES(c,d)</td>
</tr>
</tbody>
</table>

\(a\) … if \(d\) is finite  
\(b\) … if step costs \(\geq e\)  
\(c\) … if step costs are equal  
\(d\) … if both directions use BFS
Repeated states

- Failure to detect repeated states can turn a linear problem into an exponential one!
function GRAPH-SEARCH(problem, fringe) return a solution or failure

closed ← an empty set

fringe ← INSERT(MAKE-NODE(INITIAL-STATE[problem]), fringe)

loop do

if EMPTY?(fringe) then return failure

node ← REMOVE-FIRST(fringe)

if GOAL-TEST[problem] applied to STATE[node] succeeds

then return SOLUTION(node)

if STATE[node] is not in closed then

add STATE[node] to closed

fringe ← INSERT-ALL(EXPAND(node, problem), fringe)
Graph search, evaluation

Optimality:
- GRAPH-SEARCH discard newly discovered paths
  - This may result in a sub-optimal solution
  - YET: when uniform-cost search or BF-search with constant step cost

Time and space complexity,
- proportional to the size of the state space
  (may be much smaller than $O(b^d)$)
- DF- and ID-search with closed list no longer has linear space requirements since all nodes are stored in closed list!!
Summary

- Problem formulation usually requires abstracting away real-world details to define a state space that can feasibly be explored

- Variety of uninformed search strategies

- Iterative deepening search uses only linear space and not much more time than other uninformed algorithms