INFORMED SEARCH ALGORITHMS

CHAPTER 4, SECTIONS 1–2
Outline

♦ Best-first search
♦ A* search
♦ Heuristics
Review: Tree search

function $\text{Tree-Search}(\text{problem}, \text{fringe})$ returns a solution, or failure

$\text{fringe} \leftarrow \text{Insert}(\text{Make-Node}(\text{Initial-State}[\text{problem}]), \text{fringe})$

loop do
    if $\text{fringe}$ is empty then return failure
    $\text{node} \leftarrow \text{Remove-Front}(\text{fringe})$
    if $\text{Goal-Test}[\text{problem}]$ applied to $\text{State}(\text{node})$ succeeds return $\text{node}$
    $\text{fringe} \leftarrow \text{InsertAll}(\text{Expand}(\text{node}, \text{problem}), \text{fringe})$

A strategy is defined by picking the order of node expansion
Best-first search

Idea: use an evaluation function for each node
   – estimate of “desirability”

⇒ Expand most desirable unexpanded node

Implementation:
fringe is a queue sorted in decreasing order of desirability

Special cases:
  greedy search
  A* search
Romania with step costs in km

Straight-line distance to Bucharest

<table>
<thead>
<tr>
<th>City</th>
<th>Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arad</td>
<td>366</td>
</tr>
<tr>
<td>Bucharest</td>
<td>0</td>
</tr>
<tr>
<td>Craiova</td>
<td>160</td>
</tr>
<tr>
<td>Dobrota</td>
<td>242</td>
</tr>
<tr>
<td>Eforie</td>
<td>161</td>
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<tr>
<td>Fagaras</td>
<td>178</td>
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<tr>
<td>Giurgiu</td>
<td>77</td>
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<tr>
<td>Hirsova</td>
<td>151</td>
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<tr>
<td>Iasi</td>
<td>226</td>
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<tr>
<td>Lugoj</td>
<td>244</td>
</tr>
<tr>
<td>Mehadia</td>
<td>241</td>
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<tr>
<td>Neamt</td>
<td>234</td>
</tr>
<tr>
<td>Oradea</td>
<td>380</td>
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<tr>
<td>Pitesti</td>
<td>98</td>
</tr>
<tr>
<td>Rimnicu Vilcea</td>
<td>193</td>
</tr>
<tr>
<td>Sibiu</td>
<td>253</td>
</tr>
<tr>
<td>Timisoara</td>
<td>329</td>
</tr>
<tr>
<td>Urziceni</td>
<td>80</td>
</tr>
<tr>
<td>Vaslui</td>
<td>199</td>
</tr>
<tr>
<td>Zerind</td>
<td>374</td>
</tr>
</tbody>
</table>

Chapter 4, Sections 1–2
Greedy search

Evaluation function $h(n)$ (heuristic)

$= \text{estimate of cost from } n \text{ to the closest goal}$

E.g., $h_{SLD}(n) = \text{straight-line distance from } n \text{ to Bucharest}$

Greedy search expands the node that \textbf{appears} to be closest to goal
Greedy search example
Greedy search example

![Diagram showing cities connected by paths and distances: Arad to Sibiu (253), Arad to Timisoara (329), Arad to Zerind (374).]
Greedy search example

Chapter 4, Sections 1–2
Greedy search example
Properties of greedy search

Complete??
Properties of greedy search

Complete?? No—can get stuck in loops, e.g., with Oradea as goal,
    Iasi → Neamt → Iasi → Neamt →
Complete in finite space with repeated-state checking

Time??
Properties of greedy search

**Complete??** No–can get stuck in loops, e.g.,
  Iasi → Neamt → Iasi → Neamt →
Complete in finite space with repeated-state checking

**Time??** $O(b^m)$, but a good heuristic can give dramatic improvement

**Space??**
Properties of greedy search

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Iasi → Neamt → Iasi → Neamt →
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**Time**?? $O(b^m)$, but a good heuristic can give dramatic improvement

**Space**?? $O(b^m)$—keeps all nodes in memory

**Optimal**??
Properties of greedy search

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Iasi → Neamt → Iasi → Neamt →
Complete in finite space with repeated-state checking

**Time**? \(O(b^m)\), but a good heuristic can give dramatic improvement

**Space**? \(O(b^m)\)—keeps all nodes in memory

**Optimal**? No
A* search

Idea: avoid expanding paths that are already expensive

Evaluation function \( f(n) = g(n) + h(n) \)

- \( g(n) = \) cost so far to reach \( n \)
- \( h(n) = \) estimated cost to goal from \( n \)
- \( f(n) = \) estimated total cost of path through \( n \) to goal

A* search uses an admissible heuristic
i.e., \( h(n) \leq h^*(n) \) where \( h^*(n) \) is the true cost from \( n \).
(Also require \( h(n) \geq 0 \), so \( h(G) = 0 \) for any goal \( G \).)

E.g., \( h_{SLD}(n) \) never overestimates the actual road distance

Theorem: A* search is optimal
A* search example

Arad

366 = 0 + 366
A* search example

- Sibiu: 393 = 140 + 253
- Timisoara: 447 = 118 + 329
- Zerind: 449 = 75 + 374
A* search example

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A* search example

Arad

Sibiu

Timisoara
447 = 118 + 329

Zerind
449 = 75 + 374

Arad
464 = 280 + 366

Fagaras
415 = 239 + 176

Oradea
671 = 291 + 380

Rimnicu Vilcea

Craiova
526 = 366 + 160

Pitesti
417 = 317 + 100

Sibiu
553 = 300 + 253
A* search example

Chapter 4, Sections 1–2
A* search example
Suppose some suboptimal goal $G_2$ has been generated and is in the queue. Let $n$ be an unexpanded node on a shortest path to an optimal goal $G_1$.

Since $f(G_2) = g(G_2)$ since $h(G_2) = 0$

$> g(G_1)$ since $G_2$ is suboptimal

$\geq f(n)$ since $h$ is admissible

Since $f(G_2) > f(n)$, $A^*$ will never select $G_2$ for expansion
Lemma: $A^*$ expands nodes in order of increasing $f$ value.

Gradually adds “$f$-contours” of nodes (cf. breadth-first adds layers)
Contour $i$ has all nodes with $f = f_i$, where $f_i < f_{i+1}$
Properties of $A^*$

Complete??
Properties of A∗

Complete?? Yes, unless there are infinitely many nodes with $f \leq f(G)$

Time??
Properties of A*

**Complete**?? Yes, unless there are infinitely many nodes with $f \leq f(G)$

**Time**?? Exponential in [relative error in $h \times$ length of soln.]

**Space**??
Properties of $A^*$

**Complete**? Yes, unless there are infinitely many nodes with $f \leq f(G)$

**Time**? Exponential in [relative error in $h \times$ length of soln.]

**Space**? Keeps all nodes in memory

**Optimal**?
Properties of A*

**Complete**?? Yes, unless there are infinitely many nodes with \( f \leq f(G) \)

**Time**?? Exponential in [relative error in \( h \times \) length of soln.]

**Space**?? Keeps all nodes in memory

**Optimal**?? Yes—cannot expand \( f_{i+1} \) until \( f_i \) is finished

A* expands all nodes with \( f(n) < C^* \)
A* expands some nodes with \( f(n) = C^* \)
A* expands no nodes with \( f(n) > C^* \)
Proof of lemma: Consistency

A heuristic is \textbf{consistent} if

\[ h(n) \leq c(n, a, n') + h(n') \]

If \( h \) is consistent, we have

\[
\begin{align*}
  f(n') &= g(n') + h(n') \\
  &= g(n) + c(n, a, n') + h(n') \\
  &\geq g(n) + h(n) \\
  &= f(n)
\end{align*}
\]

i.e., \( f(n) \) is nondecreasing along any path.
Admissible heuristics

E.g., for the 8-puzzle:

\[ h_1(n) = \text{number of misplaced tiles} \]
\[ h_2(n) = \text{total Manhattan distance} \]

(i.e., no. of squares from desired location of each tile)

\[
\begin{array}{c}
7 & 2 & 4 \\
5 & 6 \\
8 & 3 & 1
\end{array}
\]

\[
\begin{array}{c}
1 & 2 & 3 \\
4 & 5 & 6 \\
7 & 8
\end{array}
\]

Start State  Goal State

\[ h_1(S) = \ldots \]
\[ h_2(S) = \ldots \]
Admissible heuristics

E.g., for the 8-puzzle:

\[ h_1(n) = \text{number of misplaced tiles} \]
\[ h_2(n) = \text{total Manhattan distance} \]

(i.e., no. of squares from desired location of each tile)

Start State

\[
\begin{array}{|c|c|c|}
\hline
7 & 2 & 4 \\
\hline
5 & 6 & \text{\underline{3}} \\
\hline
8 & 1 & \text{\underline{5}} \\
\hline
\end{array}
\]

Goal State

\[
\begin{array}{|c|c|c|}
\hline
1 & 2 & 3 \\
\hline
4 & 5 & 6 \\
\hline
7 & 8 & \text{\underline{5}} \\
\hline
\end{array}
\]

\[ h_1(S) = 6 \]

\[ h_2(S) = 4 + 0 + 3 + 3 + 1 + 0 + 2 + 1 = 14 \]
Dominance

If $h_2(n) \geq h_1(n)$ for all $n$ (both admissible) then $h_2$ dominates $h_1$ and is better for search

Typical search costs:

$d = 14 \quad \text{IDS} = 3,473,941 \text{ nodes}$

$A^*(h_1) = 539 \text{ nodes}$

$A^*(h_2) = 113 \text{ nodes}$

$d = 24 \quad \text{IDS} \approx 54,000,000,000 \text{ nodes}$

$A^*(h_1) = 39,135 \text{ nodes}$

$A^*(h_2) = 1,641 \text{ nodes}$

Given any admissible heuristics $h_a, h_b,$

$$h(n) = \max(h_a(n), h_b(n))$$

is also admissible and dominates $h_a, h_b$
Admissible heuristics can be derived from the exact solution cost of a relaxed version of the problem

If the rules of the 8-puzzle are relaxed so that a tile can move anywhere, then $h_1(n)$ gives the shortest solution

If the rules are relaxed so that a tile can move to any adjacent square, then $h_2(n)$ gives the shortest solution

Key point: the optimal solution cost of a relaxed problem is no greater than the optimal solution cost of the real problem
Relaxed problems contd.

Well-known example: travelling salesperson problem (TSP)
Find the shortest tour visiting all cities exactly once

Minimum spanning tree can be computed in $O(n^2)$
and is a lower bound on the shortest (open) tour
Summary

Heuristic functions estimate costs of shortest paths

Good heuristics can dramatically reduce search cost

Greedy best-first search expands lowest $h$
  – incomplete and not always optimal

A* search expands lowest $g + h$
  – complete and optimal
  – also optimally efficient (up to tie-breaks, for forward search)

Admissible heuristics can be derived from exact solution of relaxed problems