Informed Search

• How can we make search smarter?
• Use problem-specific knowledge beyond the definition of the problem itself
• Specifically, incorporate knowledge of how good a non-goal state is
Best-First Search

• Node selected for expansion based on an evaluation function $f(n)$. i.e. expand the node that \textit{appears} to be the best
• Node with lowest evaluation is selected for expansion
• Uses a priority queue
• We’ll talk about Greedy Best-First Search and A* Search

Heuristic Function

• $h(n) = \text{estimated cost of the cheapest path from node } n \text{ to a goal node}$
• $h(\text{goal node}) = 0$
• Contains additional knowledge of the problem
Greedy Best-First Search

- Expands the node that is closest to the goal
- $f(n) = h(n)$

Greedy Best-First Search Example

Straight line distance (as the crow flies) to Wilsonville in miles

<table>
<thead>
<tr>
<th>City</th>
<th>Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corvallis</td>
<td>56</td>
</tr>
<tr>
<td>Albany</td>
<td>49</td>
</tr>
<tr>
<td>Salem</td>
<td>28</td>
</tr>
<tr>
<td>Portland</td>
<td>17</td>
</tr>
<tr>
<td>McMinnville</td>
<td>18</td>
</tr>
</tbody>
</table>
Greedy Best-First Search Example

Corvallis 56
Albany 49
Salem 28
Portland 17
McMinnville 18
Greedy Best-First Search Example

Corvallis → McMinnville → Wilsonville = 74 miles

Greedy Best-First Search Example

But the route below is much shorter than the route found by Greedy Best-First Search!

Corvallis → Albany → Salem → Wilsonville = 67 miles
Evaluating Greedy Best-First Search

<table>
<thead>
<tr>
<th>Complete?</th>
<th>No (could start down an infinite path)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimal?</td>
<td>No</td>
</tr>
<tr>
<td>Time Complexity</td>
<td>O(b^m)</td>
</tr>
<tr>
<td>Space Complexity</td>
<td>O(b^m)</td>
</tr>
</tbody>
</table>

Greedy Best-First search results in lots of dead ends which leads to unnecessary nodes being expanded

A* Search

- A much better alternative to greedy best-first search
- Evaluation function for A* is:
  \[ f(n) = g(n) + h(n) \]
  where \( g(n) = \) path cost from the start node to \( n \)
- If \( h(n) \) satisfies certain conditions, A* search is optimal and complete!
Admissible Heuristics

• A* is optimal if $h(n)$ is an admissible heuristic
• An admissible heuristic is one that never overestimates the cost to reach the goal
• Admissible heuristic = optimistic
• Straight line distance was an admissible heuristic

A* Search Example

56 = 0 + 56

$f(n) = g(n) + h(n)$
A* Search Example

Corvallis

McMinnville
46+18=64

Albany
11+49=60

Salem
37+28=65

Corvallis
22+56=78
A* Search Example

Note: Don’t stop when you put a goal state on the priority queue (otherwise you get a suboptimal solution)

Proper termination: Stop when you pop a goal state from the priority queue
Proof that A* using TREE-SEARCH is optimal if h(n) is admissible

- Suppose a suboptimal goal node $G_2$ appears on the fringe and let the cost of the optimal solution be $C^*$.
- Because $G_2$ is suboptimal:
  \[
  f(G_2) = g(G_2) + h(G_2) = g(G_2) > C^*
  \]
- Now consider a fringe node $n$ on an optimal solution path.
- If $h(n)$ is admissible then:
  \[
  f(n) = g(n) + h(n) \leq C^*
  \]
- We have shown that $f(n) \leq C^* < f(G_2)$, so $G_2$ will not get expanded and A* must return an optimal solution.

What about search graphs (more than one path to a node)?

- What if we expand a state we’ve already seen?
- Suppose we use the GRAPH-SEARCH solution and not expand repeated nodes.
- Could discard the optimal path if it’s not the first one generated.
- One simple solution: ensure optimal path to any repeated state is always the first one followed (like in Uniform-cost search).
- Requires an extra requirement on $h(n)$ called consistency (or monotonicity).
A heuristic is **consistent** if, for every node $n$ and every successor $n'$ of $n$ generated by any action $a$:

$$h(n) \leq c(n,a,n') + h(n')$$

- Step cost of going from $n$ to $n'$ by doing action $a$

- A form of the triangle inequality – each side of the triangle cannot be longer than the sum of the two sides

- Every consistent heuristic is also admissible

- A* using GRAPH-SEARCH is optimal if $h(n)$ is consistent

- Most admissible heuristics are also consistent
Consistency

• If \( h(n) \) is consistent, then the values of \( f(n) \) along any path are nondecreasing
• Proof: Suppose \( n' \) is a successor of \( n \). Then \( g(n') = g(n) + c(n,a,n') \) for some \( a \), and we have
  \[
  f(n') = g(n') + h(n')
  = g(n) + c(n,a,n') + h(n')
  \geq g(n) + h(n)
  = f(n)
  \]
  From defn of consistency: \( c(n,a,n') + h(n') \geq h(n) \)
• Thus, the sequence of nodes expanded by A* is in nondecreasing order of \( f(n) \)
• First goal selected for expansion must be an optimal solution since all later nodes will be at least as expensive

A* is Optimally Efficient

• Among optimal algorithms that expand search paths from the root, A* is optimally efficient for any given heuristic function
• Optimally efficient: no other optimal algorithm is guaranteed to expand fewer nodes than A*
  – Fine print: except A* might possibly expand more nodes with \( f(n) = C^* \) where \( C^* \) is the cost of the optimal path – tie-breaking issues
• Any algorithm that does not expand all nodes with \( f(n) < C^* \) runs the risk of missing the optimal solution
Evaluating A* Search

With a consistent heuristic, A* is complete, optimal and optimally efficient. Could this be the answer to our searching problems?

The Dark Side of A*…

- Time complexity is exponential (although it can be reduced significantly with a good heuristic)
- The really bad news: space complexity is exponential (usually need to store all generated states). Typically runs out of space on large-scale problems.
### Summary of A* Search

<table>
<thead>
<tr>
<th>Complete?</th>
<th>Yes if h(n) is consistent, b is finite, and all step costs exceed some finite $\varepsilon$ (^1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimal?</td>
<td>Yes if h(n) is consistent and admissible</td>
</tr>
<tr>
<td>Time Complexity</td>
<td>O(b^d) (In the worst case but a good heuristic can reduce this significantly)</td>
</tr>
<tr>
<td>Space Complexity</td>
<td>O(b^d) – Needs O(number of states), will run out of memory for large search spaces</td>
</tr>
</tbody>
</table>

\(^1\) Since f(n) is nondecreasing, we must eventually hit an f(n) = cost of the path to a goal state

### Iterative Deepening A*

- Use iterative deepening trick to reduce memory requirements for A*
- Cutoff is the f-cost (g+h) rather than the depth
- At each iteration, the cutoff is the smallest f-cost that exceeded the cutoff in the previous iteration

Complete, Optimal but more costly than A* and can take a while to run with real-valued costs
Examples of heuristic functions

The 8-puzzle

Heuristic #1: \( h_1 \) = number of misplaced tiles eg. start state has 8 misplaced tiles. This is an admissible heuristic.

Heuristic #2: \( h_2 \) = total Manhattan distance (sum of horizontal and vertical moves, no diagonal moves). Start state is 3+1+2+2+3+2+2+3=18 moves away from the end state. This is also an admissible heuristic.
Which heuristic is better?

- $h_2$ dominates $h_1$. That is, for any node $n$, $h_2(n) \geq h_1(n)$.
- $h_2$ never expands more nodes than $A^*$ using $h_1$ (except possibly for some nodes with $f(n) = C^*$)
- Better to use $h_2$ provided it doesn’t overestimate and its computation time isn’t too expensive.
  (Remember that $h_2$ is also admissible)

Proof:
Every node with $f(n) < C^*$ will surely be expanded, meaning every node with $h(n) < C^* - g(n)$ will surely be expanded
Since $h_2$ is at least as big as $h_1$ for all nodes, every node expanded with $A^*$ using $h_2$ will also be expanded with $A^*$ using $h_1$. But $h_1$ might expand other nodes as well.

---

<table>
<thead>
<tr>
<th>Depth</th>
<th>IDS</th>
<th>$A^*(h_1)$</th>
<th>$A^*(h_2)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>10</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>4</td>
<td>112</td>
<td>13</td>
<td>12</td>
</tr>
<tr>
<td>6</td>
<td>680</td>
<td>20</td>
<td>18</td>
</tr>
<tr>
<td>8</td>
<td>6384</td>
<td>39</td>
<td>25</td>
</tr>
<tr>
<td>10</td>
<td>47127</td>
<td>93</td>
<td>39</td>
</tr>
<tr>
<td>12</td>
<td>3644035</td>
<td>227</td>
<td>73</td>
</tr>
<tr>
<td>14</td>
<td></td>
<td>539</td>
<td>113</td>
</tr>
<tr>
<td>16</td>
<td></td>
<td>1301</td>
<td>211</td>
</tr>
<tr>
<td>18</td>
<td></td>
<td>3056</td>
<td>363</td>
</tr>
<tr>
<td>20</td>
<td></td>
<td>7276</td>
<td>676</td>
</tr>
<tr>
<td>22</td>
<td></td>
<td>18094</td>
<td>1219</td>
</tr>
<tr>
<td>24</td>
<td></td>
<td>39135</td>
<td>1641</td>
</tr>
</tbody>
</table>

From Russell and Norvig Figure 4.8 (Results averaged over 100 instances of the 8-puzzle for depths 2-24).
Inventing Admissible Heuristics

• Relaxed problem: a problem with fewer restrictions on the actions
• The cost of an optimal solution to a relaxed problem is an admissible heuristic for the original problem
• If we relax the rules so that a square can move anywhere, we get heuristic $h_1$
• If we relax the rules to allow a square to move to any adjacent square, we get heuristic $h_2$

What you should know

• Be able to run A* by hand on a simple example
• Why it is important for a heuristic to be admissible and consistent
• Pros and cons of A*
• How do come up with heuristics
• What if means for a heuristic function to dominate another heuristic function