Informed Search I

Review: Uniform Cost Search
Introduction to informed search
The A* search algorithm
Designing good admissible heuristics

(AIMA Chapter 3.5.1, 3.5.2, 3.6)
Review: “Uniform Cost” Search
Motivation: Romanian Map Problem

- All our search methods so far assume \( \text{step-cost} = 1 \)
- \textbf{This isn’t always true}
\( g(N) \): the path cost function

- If all moves equal in cost:
  - Cost = \# of nodes in path - 1
  - \( g(N) = \text{depth}(N) \)
  - Equivalent to what we’ve been assuming so far

- Assigning a (potentially) unique cost to each step
  - \( N_0, N_1, N^2, N_3 = \) nodes visited on path \( p \)
  - \( C(i,j) \): Cost of going from \( N_i \) to \( N_j \)
  - \( g(N_3) = C(0,1) + C(1,2) + C(2,3) \)
Uniform-cost search (UCS)

- Extension of BF-search:
  - Expand node with lowest path cost

- Implementation: \textit{frontier} = queue ordered by $g(n)$

- Differs from BF-search:
  - Tests if a node is a goal state when it is selected for expansion, not when it is added to the frontier.
  - Updates a node on the frontier if a better path to the same state is found.
  - So always enqueues nodes \textit{before checking whether they are goals}.
  - \textit{WHY}???

- (Dijkstra’s algorithm just UCS without goal)
Uniform Cost Search

Expand cheapest node first:

Frontier is a priority queue

No longer ply at a time, but follows cost contours

Must be optimal

Slide from CS 221, Stanford, (from slide by Dan Klein (UCB) and many others)
Outline – Informed Search

PART I
- Informed = use problem-specific knowledge
- Best-first search and its variants
- \( A^* \) - Optimal Search using Knowledge

- Proof of Optimality of \( A^* \)
- \( A^* \) for maneuvering AI agents in games
- Heuristic functions?
- How to invent them

PART II
- Local search and optimization
  - Hill climbing, local beam search, genetic algorithms,…
- Local search in continuous spaces
- Online search agents
Is Uniform Cost Search the best we can do?
Consider finding a route from Bucharest to Arad.
Is Uniform Cost Search the best we can do?
Consider finding a route from Bucharest to Arad.
A Better Idea…

- Node expansion based on some estimate of distance to the goal, extending current path.

- General approach of informed search:
  - *Best-first search*: node selected for expansion based on an evaluation function $f(n)$—$f(n)$ includes estimate of distance to goal.

- Implementation:
  - Sort *frontier* queue monotonically by $f(n)$.
  - Special cases: greedy search, A* search.
Romania with city-to-city distances & straight-line distances in km

<table>
<thead>
<tr>
<th>City</th>
<th>Distance (km)</th>
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<tbody>
<tr>
<td>Arad</td>
<td>366</td>
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<tr>
<td>Bucharest</td>
<td>0</td>
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<tr>
<td>Craiova</td>
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A heuristic function

- Let evaluation function $f(n) = h(n)$ (heuristic)
  - $h(n) = \text{estimated cost of the cheapest path from node } n \text{ to goal node.}$
  - If $n$ is goal then $h(n) = 0$

- Here: $h_{SLD}(n) = \text{straight-line distance from } n \text{ to Bucharest}$

[dictionary]“A rule of thumb, simplification, or educated guess that reduces or limits the search for solutions in domains that are difficult and poorly understood.”

Heuristic knowledge is useful, but not necessarily correct.

Heuristic algorithms use heuristic knowledge to solve a problem.

A heuristic function here takes a state and returns an estimate of the distance to the goal.

*Heureka!* ---Archimedes
Breadth First for Games, Robots, …

- Pink: Starting Point
- Blue: Goal
- Teal: Scanned squares
  - Darker: Closer to starting point…

Graphics from
http://theory.stanford.edu/~amitp/GameProgramming/
(A great site for practical AI & game Programming)
An optimal *informed search* algorithm (A*)

- We add a *heuristic estimate* of distance to the goal
  - Yellow: examined nodes with *high estimated* distance
  - Blue: examined nodes with *low estimated* distance
Breadth first in a world with obstacles
Informed search (A*) in a world with obstacles
Greedy best-first search

- Informally: Expands the node that *is estimated* to be closest to goal
- Expands nodes based on $f(n) = h(n)$
  - (Again, $h(n)$): Some *heuristic* estimate of cost from $n$ to *goal*
- Ignores cost so far to get to that node ($g(n)$)
- Here, $h(n) = h_{SLD}(n) = \text{straight-line distance from } n \text{ to Bucharest}$
Greedy best-first search example

Initial State = Arad
Goal State = Bucharest

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Greedy best-first search example

Frontier queue:
- Sibiu 253
- Timisoara 329
- Zerind 374
Greedy best-first search example

Frontier queue:

Fagaras 176
Rimnicu Vilcea 193
Timisoara 329
Arad 366
Zerind 374
Oradea 380

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Greedy best-first search example

Frontier queue:
- Bucharest 0
- Rimnicu Vilcea 193
- Sibiu 253
- Timisoara 329
- Arad 366
- Zerind 374
- Oradea 380

Goal reached!!
Properties of greedy best-first search

- **Optimal?**
  - No!
  - Found: \textit{Arad} \rightarrow \textit{Sibiu} \rightarrow \textit{Fagaras} \rightarrow \textit{Bucharest} (450km)
  - Shorter: \textit{Arad} \rightarrow \textit{Sibiu} \rightarrow \textit{Rimnicu Vilcea} \rightarrow \textit{Pitesti} \rightarrow \textit{Bucharest} (418km)
Properties of greedy best-first search

- **Complete?**
  - No – can get stuck in loops,
  - e.g., Iasi $\rightarrow$ Neamt $\rightarrow$ Iasi $\rightarrow$ Neamt $\rightarrow$...
Properties of greedy best-first search

- **Complete?** No – can get stuck in loops,
  - e.g., Iasi → Neamt → Iasi → Neamt → …

- **Time?** $O(b^m)$ – worst case (like Depth First Search)
  - But a good heuristic can give dramatic improvement

- **Space?** $O(b^m)$ – priority queue, so worst case: keeps all nodes in memory

- **Optimal?** No
A* search

- Best-known form of best-first search.
- Key Idea: avoid expanding paths that are already expensive, but expand most promising first.
  - Simple idea: \( f(n) = g(n) + h(n) \)
    - \( g(n) \) the cost (so far) to reach the node
    - \( h(n) \) estimated cost to get from the node to the goal
    - \( f(n) \) estimated total cost of path through \( n \) to goal
- Implementation: Frontier queue as priority queue by increasing \( f(n) \) (as expected...)

CIS 391 - Intro to AI
Admissible heuristics

- A heuristic \( h(n) \) is **admissible** if it never overestimates the cost to reach the goal; i.e. it is **optimistic**
  - Formally: \( \forall n, n \) a node:
    1. \( h(n) \leq h^*(n) \) where \( h^*(n) \) is the true cost from \( n \)
    2. \( h(n) \geq 0 \) so \( h(G)=0 \) for any goal \( G \).

- **Example**: \( h_{SLD}(n) \) never overestimates the actual road distance

**Theorem**: If \( h(n) \) is **admissible**, A* using Tree Search is **optimal**
A* search example

Frontier queue:

Arad 366

366 = 0 + 366
A* search example

Frontier queue:
Sibiu 393
Timisoara 447
Zerind 449

We add the three nodes we found to the Frontier queue.
We sort them according to the $g() + h()$ calculation.
A* search example

Frontier queue:
- Rimricu Vicea 413
- Fagaras 415
- Timisoara 447
- Zerind 449
- Arad 646
- Oradea 671

When we expand Sibiu, we run into Arad again. Note that we’ve already expanded this node once; but we still add it to the Frontier queue again.
A* search example

Frontier queue:
Fagaras 415
Pitesti 417
Timisoara 447
Zerind 449
Craiova 526
Sibiu 553
Arad 646
Oradea 671

We expand Rimricu Vicea.
A* search example

Frontier queue:
- Pitesti 417
- Timisoara 447
- Zerind 449
- Bucharest 450
- Craiova 526
- Sibiu 553
- Sibiu 591
- Arad 646
- Oradea 671

When we expand Fagaras, we find Bucharest, but we’re not done. The algorithm doesn’t end until we “expand” the goal node – it has to be at the top of the Frontier queue.
**A* search example**

Frontier queue:
- Bucharest 418
- Timisoara 447
- Zerind 449
- Bucharest 450
- Craiova 526
- Sibiu 553
- Sibiu 591
- Rimricu Vicea 607
- Craiova 615
- Arad 646
- Oradea 671

Note that we just found a better value for Bucharest!

Now we expand this better value for Bucharest since it’s at the top of the queue.

We’re done and we know the value found is optimal!
Outline – Informed Search

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• Informed = use problem-specific knowledge
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• A* - Optimal Search using Knowledge
  • Proof of Optimality of A*
  • A* for maneuvering AI agents in games
  • Heuristic functions?
  • How to invent them

PART II
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**Optimality of A* (intuitive)**

- **Lemma**: A* expands nodes in order of increasing $f$ value
- Gradually adds "$f$-contours" of nodes
- Contour $i$ has all nodes with $f=f_i$, where $f_i < f_{i+1}$
- (After all, A* is just a variant of uniform-cost search….)

![Diagram of A* algorithm]
Optimality of A* using Tree-Search I (proof)

- Suppose some suboptimal goal $G_2$ has been generated and is in the frontier. Let $n$ be an arbitrary unexpanded node in the frontier such that $n$ is on a shortest path to an optimal goal $G$.

To prove: $f(G_2) > f(n)$

Why? Because if $f(n) < f(G_2)$, then $G_2$ will never get to the front of the priority queue.

(Note that $G$ is itself one of the $n$.)

1. $g(G_2) > g(G)$ since $G_2$ is suboptimal
2. $f(G_2) = g(G_2)$ since $h(G_2) = 0$
3. $f(G) = g(G)$ since $h(G) = 0$
4. $f(G_2) > f(G)$ from 1,2,3 - So $G_2$ is in a further out “f-contour” than $G$
Optimality of A* using Tree-Search II (proof)

- Suppose some suboptimal goal $G_2$ has been generated and is in the frontier. Let $n$ be an unexpanded node in the frontier such that $n$ is on a shortest path to an optimal goal $G$.

4. $f(G_2) > f(G)$ repeated
5. $h^*(n) \geq h(n)$ since $h$ is admissible, and therefore optimistic
6. $g(n) + h^*(n) \geq g(n) + h(n)$ from 5
7. $g(n) + h^*(n) \geq f(n)$ substituting definition of $f$
8. $f(G) \geq f(n)$ from definitions of $f$ and $h^*$ (think about it!)
9. $f(G_2) > f(n)$ from 4 & 8

So $A^*$ will never select $G_2$ for expansion
A* search, evaluation

- Completeness: YES
  - Since bands of increasing $f$ are added
  - As long as $b$ is finite
    - (guaranteeing that there aren’t infinitely many nodes $n$ with $f(n) < f(G)$)
A* search, evaluation

- Completeness: YES
- Time complexity:
  - Number of nodes expanded is still exponential in the length of the solution.
A* search, evaluation

- Completeness: YES
- Time complexity: (exponential with path length)
- Space complexity:
  - It keeps all generated nodes in memory
  - Hence space is the major problem not time
A* search, evaluation

- Completeness: YES
- Time complexity: (exponential with path length)
- Space complexity: (all nodes are stored)
- Optimality: YES
  - Cannot expand $f_{i+1}$ until $f_i$ is finished.
  - A* expands all nodes with $f(n) < f(G)$
  - A* expands one node with $f(n) = f(G)$
  - A* expands no nodes with $f(n) > f(G)$

Also *optimally efficient* (not including ties)
Proof of Lemma: Consistency

- A heuristic is **consistent** if
  \[ h(n) \leq c(n, a, n') + h(n') \]
- Lemma: If h is consistent,
  \[ f(n') = g(n') + h(n') \]
  \[ = g(n) + c(n, a, n') + h(n') \]
  \[ \geq g(n) + h(n) \]
  \[ \geq f(n) \]

  i.e. f(n) is **nondecreasing** along any path.

Theorem: if h(n) is consistent, \( A^* \) using Graph-Search is **optimal**
Creating Good Heuristic Functions

AIMA 3.6
Heuristic functions

- For the 8-puzzle
  - Avg. solution cost is about 22 steps
    — (branching factor \( \leq 3 \))
  - Exhaustive search to depth 22: \( 3.1 \times 10^{10} \) states
  - A good heuristic function can reduce the search process
Admissible heuristics

E.g., for the 8-puzzle:

- \( h_{ooop}(n) \) = number of out of place tiles

- \( h_{md}(n) \) = total Manhattan distance (i.e., # of moves from desired location of each tile)

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

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

\( h_{ooop}(S) = ? \)

\( h_{md}(S) = ? \)
Admissible heuristics

E.g., for the 8-puzzle:

- $h_{oop}(n) =$ number of out of place tiles

- $h_{md}(n) =$ total Manhattan distance (i.e., # of moves from desired location of each tile)

- $h_{oop}(S) =$ ? 8
- $h_{md}(S) =$ ? $3+1+2+2+2+3+3+2 = 18$
Relaxed problems

- A problem with fewer restrictions on the actions than the original is called a *relaxed problem*

- **The cost of an optimal solution to a relaxed problem is an admissible heuristic for the original problem**

- If the rules of the 8-puzzle are relaxed so that a tile can move *anywhere*, then $h_{oop}(n)$ gives the shortest solution.

- If the rules are relaxed so that a tile can move to *any adjacent square*, then $h_{md}(n)$ gives the shortest solution.
Defining Heuristics: $h(n)$

- Cost of an exact solution to a *relaxed* problem (fewer restrictions on operator)

- **Constraints on Full Problem:**
  A tile can move from square A to square B *if* A is adjacent to B *and* B is blank.

- **Constraints on relaxed problems:**
  - A tile can move from square A to square B *if* A is adjacent to B. ($h_{md}$)
  - A tile can move from square A to square B *if* B is blank.
  - A tile can move from square A to square B. ($h_{oop}$)
Dominance

- If $h_2(n) \geq h_1(n)$ for all $n$ (both admissible)
  - then $h_2$ dominates $h_1$
- So $h_2$ is optimistic, but more accurate than $h_1$
  - $h_2$ is therefore better for search
  - Notice: $h_{md}$ dominates $h_{oop}$

- Typical search costs (average number of nodes expanded):
  - $d=12$  
    - Iterative Deepening Search = 3,644,035 nodes
    - $A^*(h_{oop}) = 227$ nodes
    - $A^*(h_{md}) = 73$ nodes
  - $d=24$
    - IDS = too many nodes
    - $A^*(h_{oop}) = 39,135$ nodes
    - $A^*(h_{md}) = 1,641$ nodes
Iterative Deepening A* and beyond

Beyond our scope:

- Iterative Deepening A*
- Recursive best first search (incorporates A* idea, despite name)
- Memory Bounded A*
- Simplified Memory Bounded A* - R&N say the best algorithm to use in practice, but not described here at all.
  - (If interested, follow reference to Russell article on Wikipedia article for SMA*)

*(see 3.5.3 if you’re interested in these topics)*