Informed search algorithms

This lecture topic
Chapter 3.5-3.7

Next lecture topic
Chapter 4.1-4.2

(Please read lecture topic material before and after each lecture on that topic)
Outline

- Review limitations of uninformed search methods
- **Informed (or heuristic) search** uses **problem-specific heuristics to improve efficiency**
  - Best-first, A* (and if needed for memory limits, RBFS, SMA*)
  - Techniques for generating heuristics
  - A* is optimal with admissible (tree)/consistent (graph) heuristics
  - A* is quick and easy to code, and often works *very* well

- **Heuristics**
  - A structured way to add “smarts” to your solution
  - Provide *significant* speed-ups in practice
  - Still have worst-case exponential time complexity
  - In AI, “NP-Complete” means “Formally interesting”
Limitations of uninformed search

- Search Space Size makes search tedious
  - **Combinatorial Explosion**
- For example, 8-puzzle
  - Avg. solution cost is about 22 steps
  - branching factor ~ 3
  - Exhaustive search to depth 22:
    - $3.1 \times 10^{10}$ states
  - E.g., $d=12$, IDS expands 3.6 million states on average

[24 puzzle has $10^{24}$ states (much worse)]
Recall tree search...
Recall tree search...

This “strategy” is what differentiates different search algorithms.

```plaintext
function TREE-SEARCH( problem, strategy ) returns a solution
  initialize the search tree using the initial state of problem
  loop do
    if there are no candidates for expansion then return failure
    choose a leaf node for expansion according to strategy
    if the node contains a goal state then return the corresponding solution
    else expand the node and add the resulting nodes to the search tree
```
Heuristic search

- Idea: use an evaluation function $f(n)$ for each node and a heuristic function $h(n)$ for each node
  - $g(n) =$ known path cost so far to node n.
  - $h(n) =$ estimate of (optimal) cost to goal from node n.
  - $f(n) =$ $g(n) + h(n) =$ estimate of total cost to goal through node n.
  - $f(n)$ provides an estimate for the total cost: Expand the node $n$ with smallest $f(n)$.

- Implementation:
  Order the nodes in frontier by increasing estimated cost.

- Evaluation function is an estimate of node quality
  - More accurate name for “best first” search would be “seemingly best-first search”

⇒ Search efficiency depends on heuristic quality!
⇒ The better your heuristic, the faster your search!
Heuristic function

- **Heuristic:**
  - Definition: a commonsense rule (or set of rules) intended to increase the probability of solving some problem
  - Same linguistic root as “Eureka” = “I have found it”
  - “using rules of thumb to find answers”

- **Heuristic function** $h(n)$
  - Estimate of (optimal) remaining cost from $n$ to $goal$
  - Defined using only the state of node $n$
  - $h(n) = 0$ if $n$ is a goal node
  - Example: straight line distance from $n$ to Bucharest
    - Note that this is not the true state-space distance
    - It is an estimate – actual state-space distance can be higher

- Provides problem-specific knowledge to the search algorithm
Heuristic functions for 8-puzzle

- 8-puzzle
  - Avg. solution cost is about 22 steps
  - branching factor ~ 3
  - Exhaustive search to depth 22:
    - $3.1 \times 10^{10}$ states.
  - A good heuristic function can reduce the search process.

- Two commonly used heuristics
  - $h_1 = \text{the number of misplaced tiles}$
    - $h_1(s) = 8$
  - $h_2 = \text{the sum of the distances of the tiles from their goal positions (Manhattan distance)}.$
    - $h_2(s) = 3 + 1 + 2 + 2 + 2 + 3 + 3 + 2 = 18$

![Start State 8-puzzle](image1)

![Goal State 8-puzzle](image2)
Romania with straight-line dist.
Relationship of Search Algorithms

- $g(n) = \text{known cost so far to reach } n$
- $h(n) = \text{estimated (optimal) cost from } n \text{ to goal}$
- $f(n) = g(n) + h(n) = \text{estimated (optimal) total cost of path through } n \text{ to goal}$

- Uniform Cost search sorts frontier by $g(n)$
- Greedy Best First search sorts frontier by $h(n)$
- A* search sorts frontier by $f(n)$
  - Optimal for admissible/consistent heuristics
  - Generally the preferred heuristic search
- Memory-efficient versions of A* are available
  - RBFS, SMA*
Greedy best-first search (often called just “best-first”)

- $h(n) = \text{estimate of cost from } n \text{ to } \text{goal}$
  - e.g., $h(n) = \text{straight-line distance from } n \text{ to Bucharest}$

- Greedy best-first search expands the node that \textbf{appears} to be closest to goal.
  - \textit{Priority queue sort function} = $h(n)$
Greedy best-first search example
Greedy best-first search example
Greedy best-first search example
Greedy best-first search example
Optimal Path
Properties of greedy best-first search

- **Complete?**
  - Tree version can get stuck in loops.
  - Graph version is complete in finite spaces.

- **Time?** $O(b^m)$
  - A good heuristic can give **dramatic** improvement

- **Space?** $O(b^m)$
  - Keeps all nodes in memory

- **Optimal?** No

  e.g., Arad → Sibiu → Rimnicu Vilcea → Pitesti → Bucharest is shorter!
A* search

- Idea: avoid paths that are already expensive
  - Generally the preferred simple heuristic search
  - Optimal if heuristic is: admissible(tree)/consistent(graph)
- Evaluation function \( f(n) = g(n) + h(n) \)
  - \( g(n) \) = known path cost so far to node \( n \).
  - \( h(n) \) = estimate of (optimal) cost to goal from node \( n \).
  - \( f(n) = g(n) + h(n) \)
    = estimate of total cost to goal through node \( n \).
- Priority queue sort function = \( f(n) \)
Admissible heuristics

- A heuristic $h(n)$ is **admissible** if for every node $n$,
  $$h(n) \leq h^*(n),$$
  where $h^*(n)$ is the true cost to reach the goal state from $n$.

- An admissible heuristic **never overestimates** the cost to reach the goal, i.e., it is **optimistic** (or at least, **never pessimistic**)
  - Example: $h_{SLD}(n)$ (never overestimates actual road distance)

- **Theorem:**
  If $h(n)$ is admissible, $A^*$ using **TREE-SEARCH** is optimal
Admissible heuristics

E.g., for the 8-puzzle:

- \( h_1(n) = \) number of misplaced tiles
- \( h_2(n) = \) total Manhattan distance
  (i.e., no. of squares from desired location of each tile)

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

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

- \( h_1(S) = ? \)
- \( h_2(S) = ? \)
Admissible heuristics

E.g., for the 8-puzzle:

- $h_1(n) =$ number of misplaced tiles
- $h_2(n) =$ total Manhattan distance

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

$h_1(S) =$ ?

$h_2(S) =$ ? $3 + 1 + 2 + 2 + 2 + 3 + 3 + 2 = 18$

```
Start State
7  2  4
5  6
8  3  1

Goal State
3  4  5
6  7  8
1  2
```
Consistent heuristics
(consistent => admissible)

- A heuristic is **consistent** if for every node \( n \), every successor \( n' \) of \( n \) generated by any action \( a \),

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

- If \( h \) is consistent, we have

\[
f(n') = g(n') + h(n') \quad \text{(by def.)}
= g(n) + c(n,a,n') + h(n') \quad \text{(}g(n')=g(n)+c(n,a,n')\text{)}
\geq g(n) + h(n) = f(n) \quad \text{(consistency)}
\]

\[
f(n') \geq f(n)
\]

- i.e., \( f(n) \) is non-decreasing along any path.

- **Theorem:**
  - If \( h(n) \) is consistent, \( \text{A}* \) using \text{GRAPH-SEARCH} is optimal

It's the triangle inequality!
keeps all checked nodes in memory to avoid repeated states
Admissible (Tree Search) vs. Consistent (Graph Search)

- Why two different conditions?
  - In graph search you often find a long cheap path to a node after a short expensive one, so you might have to update all of its descendants to use the new cheaper path cost so far
  - A consistent heuristic avoids this problem (it can’t happen)
  - Consistent is slightly stronger than admissible
  - Almost all admissible heuristics are also consistent

- Could we do optimal graph search with an admissible heuristic?
  - Yes, but you would have to do additional work to update descendants when a cheaper path to a node is found
  - A consistent heuristic avoids this problem
A* search example
A* search example: Simulated queue. City/h/g/f

- Expanded:
- Next:
- Children:
- Frontier: Arad/366/0/366
A* search example, tree view: Simulated queue. City/h/g/f

Arad/366/0/366
A* search example, tree view: Simulated queue. City/h/g/f

Arad/
366/0/366
A* search example:
Simulated queue. City/h/g/f

- Expanded: Arad
- Next: Arad/366/0/366
- Children: Sibiu/253/140/393, Timisoara/329/118/447, Zerind/374/75/449
A* search example, tree view: Simulated queue. City/h/g/f
A* search example:
Simulated queue. City/h/g/f

- Arad/366/0/366
- Sibiu/253/140/393
- Timisoara/329/118/447
- Zerind/374/75/449
A* search example
A* search example:
Simulated queue. City/h/g/f

- Expanded: Arad, Sibiu
- Next: Sibiu/253/140/393
A* search example, tree view: Simulated queue. City/h/g/f
A* search example, tree view: Simulated queue. City/h/g/f
A* search example
A* search example: Simulated queue.  City/h/g/f

- Expanded: Arad, Sibiu, RimnicuVilcea
- Next: RimnicuVilcea/193/220/413
- Children: Craiova/160/368/528, Pitesti/100/317/417, Sibiu/253/300/553
A* search example, tree view:
Simulated queue. City/h/g/f

- Arad/366/0/366
  - Sibiu/253/140/393
    - Arad/366/280/646
    - Fagaras/176/239/415
  - Timisoara/329/118/447
    - Oradea/380/291/671
    - RimnicuVilcea/193/220/413
      - Craiova/160/368/528
      - Pitesti/100/317/417
  - Zerind/374/75/449
    - Sibiu/253/300/553
A* search example, tree view: Simulated queue. City/h/g/f
A* search example
A* search example:
Simulated queue. City/h/g/f

- Expanded: Arad, Sibiu, RimnicuVilcea, Fagaras
- Next: Fagaras/176/239/415
- Children: Bucharest/0/579/579, Sibiu/253/338/591
A* search example
A* search example:
Simulated queue.  City/h/g/f

- Expanded: Arad, Sibiu, RimnicuVilcea, Fagaras, Pitesti
- Next: Pitesti/100/317/417
A* search example
A* search example:
Simulated queue. City/h/g/f

- Expanded: Arad, Sibiu, RimnicuVilcea, Fagaras, Pitesti, Bucharest
- Next: Bucharest/0/418/418
- Children: None; goal test succeeds.
A* search example, tree view: Simulated queue. City/h/g/f

- Arad/366/0/366
  - Sibiu/253/140/393
    - Arad/366/280/646
    - Fagaras/176/239/415
    - Timisoara/329/118/447
  - Timisoara/329/118/447
    - Oradea/380/291/671
    - RimnicuVilcea/193/220/413
  - Zerind/374/75/449
    - Craiova/160/368/528
    - Pitesti/100/317/417
    - Sibiu/253/300/553
    - Bucharest/0/418/418
A* search example, tree view: Simulated queue. City/h/g/f
Contours of A* Search

- 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 $f_i < f_{i+1}$
Properties of A*

- **Complete?** Yes
  (unless there are infinitely many nodes with $f \leq f(G)$; can’t happen if step-cost $\geq \varepsilon > 0$)

- **Time/Space?** Exponential $O(b^d)$
  except if: $|h(n) - h^*(n)| \leq O(\log h^*(n))$

- **Optimal?** Yes
  (with: Tree-Search, admissible heuristic; Graph-Search, consistent heuristic)

- **Optimally Efficient?** Yes
  (no optimal algorithm with same heuristic is guaranteed to expand fewer nodes)
Optimality of A* (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 $G$.

We want to prove:

$f(n) < f(G2)$

(then A* will prefer $n$ over $G2$)

- $f(G_2) = g(G_2)$ since $h(G_2) = 0$
- $f(G) = g(G)$ since $h(G) = 0$
- $g(G_2) > g(G)$ since $G_2$ is suboptimal
- $f(G_2) > f(G)$ from above
- $h(n) \leq h^*(n)$ since $h$ is admissible (under-estimate)
- $g(n) + h(n) \leq g(n) + h^*(n)$ from above
- $f(n) \leq f(G)$ since $g(n) + h(n) = f(n)$ & $g(n) + h^*(n) = f(G)$
- $f(n) < f(G2)$ from above
Memory Bounded Heuristic Search: Recursive Best First Search (RBFS)

- How can we solve the memory problem for A* search?

- Idea: Try something like depth first search, but let’s not forget everything about the branches we have partially explored.

- We remember the best f(n) value we have found so far in the branch we are deleting.
RBFS changes its mind very often in practice. This is because the \( f=g+h \) become more accurate (less optimistic) as we approach the goal. Hence, higher level nodes have smaller \( f \)-values and will be explored first.

Problem: We should keep in memory whatever we can.

i.e. do I want to back up?
Simple Memory Bounded A* (SMA*)

- This is like A*, but when memory is full we delete the worst node (largest f-value).
- Like RBFS, we remember the best descendent in the branch we delete.
- If there is a tie (equal f-values) we delete the oldest nodes first.
- simple-MBA* finds the optimal reachable solution given the memory constraint.
- Time can still be exponential.

A Solution is not reachable if a single path from root to goal does not fit into memory.
function SMA*(problem) returns a solution sequence
inputs: problem, a problem
static: Queue, a queue of nodes ordered by f-cost

Queue \leftarrow \text{MAKE-QUEUE}(\{\text{MAKE-NODE(INITIAL-STATE[problem])}\})
loop do
  if Queue is empty then return failure
  \( n \leftarrow \text{deepest least-f-cost node in Queue} \)
  if GOAL-TEST(\( n \)) then return success
  \( s \leftarrow \text{NEXT-SUCCESSOR}(n) \)
  if \( s \) is not a goal and is at maximum depth then
    \( f(s) \leftarrow \infty \)
  else
    \( f(s) \leftarrow \text{MAX}(f(n), g(s) + h(s)) \)
  if all of \( n \)'s successors have been generated then
    update \( n \)'s f-cost and those of its ancestors if necessary
  if SUCCESSORS(\( n \)) all in memory then remove \( n \) from Queue
  if memory is full then
    delete shallowest, highest-f-cost node in Queue
    remove it from its parent’s successor list
    insert its parent on Queue if necessary
  end
end
Simple Memory-bounded A* (SMA*)

(Example with 3-node memory)

Progress of SMA*. Each node is labeled with its current \( f \)-cost. Values in parentheses show the value of the best forgotten descendant.

\[ g + h = f \]

\[ \square = \text{goal} \]

Search space

\[ 20 + 5 = 25 \]

\[ 30 + 5 = 35 \]

Algorithm can tell you when best solution found within memory constraint is optimal or not.
Memory Bounded A* Search

- The Memory Bounded A* Search is the best of the search algorithms we have seen so far. It uses all its memory to avoid double work and uses smart heuristics to first descend into promising branches of the search-tree.

- If memory not a problem, then plain A* search is easy to code and performs well.
Heuristic functions

8-puzzle
- Avg. solution cost is about 22 steps
- Branching factor ~ 3
- Exhaustive search to depth 22:
  - $3.1 \times 10^{10}$ states.
- A good heuristic function can reduce the search process.

Two commonly used heuristics
- $h_1 = \text{the number of misplaced tiles}$
  - $h_1(s) = 8$
- $h_2 = \text{the sum of the axis-parallel distances of the tiles from their goal positions (manhattan distance)}$.
  - $h_2(s) = 3 + 1 + 2 + 2 + 2 + 3 + 3 + 2 = 18$
Dominance

- IF $h_2(n) \geq h_1(n)$ for all $n$
- THEN $h_2$ dominates $h_1$
  - $h_2$ is always better for search than $h_1$
  - $h_2$ guarantees to expand no more nodes than does $h_1$
  - $h_2$ almost always expands fewer nodes than does $h_1$
  - Not useful unless both $h_1$ & $h_2$ are admissible/consistent

- Typical 8-puzzle search costs
  (average number of nodes expanded):
  - $d=12$
    - IDS = 3,644,035 nodes
    - $A^*(h_1) = 227$ nodes
    - $A^*(h_2) = 73$ nodes
  - $d=24$
    - IDS = too many nodes
    - $A^*(h_1) = 39,135$ nodes
    - $A^*(h_2) = 1,641$ nodes
Heuristic for “Go to Bucharest” that dominates SLD

- Array \( A[i,j] \) = straight-line distance (SLD) from city \( i \) to city \( j \); \( B = \text{Bucharest} \);
- \( s(n) \) = successors of \( n \);
- \( c(m,n) = \{ \text{if } (n \in s(m)) \text{ then one-step road distance } m \text{ to } n \text{ else } +\infty \} \);
- \( s_k(n) = \text{all descendants of } n \text{ accessible from } n \text{ in exactly } k \text{ steps} \);
- \( S_k(n) = \text{all descendants of } n \text{ accessible from } n \text{ in } k \text{ steps or less} \);
- \( C_k(m,n) = \{ \text{if } (n \in S_k(m)) \text{ then shortest road distance } m \text{ to } n \text{ in } k \text{ steps or less} \text{ else } +\infty \} \);
- \( s, c, \) are computable in \( O(b) \); \( s_k, S_k, C_k, \) are computable in \( O(b^k) \).

- These heuristics both dominate SLD, and \( h_2 \) dominates \( h_1 \):
  - \( h_1(n) = \min_{x \in \text{Romania}} (A[n,x] + A[x,B]) \)
  - \( h_2(n) = \min_{x \in s(n)} (c(n,x) + A[x,B]) \)
- This family of heuristics all dominate SLD, and \( i > j \Rightarrow h_i \) dominates \( h_j \):
  - \( h_k(n) = \min( (\min_{x \in (S_k(n) \cap S_k(B))} C_k(n,x)+C_k(x,B)), (\min_{x \in s_k(n), y \in s_k(B)} (C_k(n,x) + A[x,y] + C_k(y,B))) ) \)
- \( h_{\text{final}}(n) = \text{same as bidirectional search}; \Rightarrow \text{exponential cost} \)
Effective branching factor: \( b^* \)

- Let A* generate \( N \) nodes to find a goal at depth \( d \)
  - \( b^* \) is the branching factor that a uniform tree of depth \( d \) would have in order to contain \( N+1 \) nodes.

\[ N + 1 = 1 + b^* + (b^*)^2 + \ldots + (b^*)^d \]
\[ N + 1 = \frac{((b^*)^{d+1} - 1)}{(b^* - 1)} \]
\[ N \approx (b^*)^d \Rightarrow b^* \approx \sqrt[d]{N} \]

- For sufficiently hard problems, the measure \( b^* \) usually is fairly constant across different problem instances.

- A good guide to the heuristic’s overall usefulness.
- A good way to compare different heuristics.
Effective Branching Factor

Pseudo-code (Binary search)

- PROCEDURE EFFBRANCH (START, END, N, D, DELTA)
  COMMENT DELTA IS A SMALL POSITIVE NUMBER FOR ACCURACY OF RESULT.
  MID := (START + END) / 2.
  IF (END - START < DELTA)
    THEN RETURN (MID).
  TEST := EFFPOLY (MID, D).
  IF (TEST < N+1)
    THEN RETURN (EFFBRANCH (MID, END, N, D, DELTA) )
  ELSE RETURN (EFFBRANCH (START, MID, N, D, DELTA) ).
END EFFBRANCH.

- PROCEDURE EFFPOLY (B, D)
  ANSWER = 1.
  TEMP = 1.
  FOR I FROM 1 TO (D-1) DO
    TEMP := TEMP * B.
    ANSWER := ANSWER + TEMP.
  ENDDO.
  RETURN (ANSWER).
END EFFPOLY.

For binary search please see: http://en.wikipedia.org/wiki/Binary_search_algorithm
An attractive alternative is to use Newton’s Method (next lecture) to solve for the root (i.e., f(b)=0) of
f(b) = 1 + b + ... + b^d - (N+1)
Effectiveness of different heuristics

- Results averaged over random instances of the 8-puzzle

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<th>IDS</th>
<th>$A^*(h_1)$</th>
<th>$A^*(h_2)$</th>
<th>IDS</th>
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Inventing heuristics via “relaxed problems”

- A problem with fewer restrictions on the actions 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 $h_1(n)$ 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.

- Can be a useful way to generate heuristics.
  - E.g., ABSOLVER (Prieditis, 1993) discovered the first useful heuristic for the Rubik’s cube puzzle.
More on heuristics

- \( h(n) = \max\{ h_1(n), h_2(n), \ldots, h_k(n) \} \)
  - Assume all \( h \) functions are admissible
  - E.g., \( h_1(n) = \# \) of misplaced tiles
  - E.g., \( h_2(n) = \) manhattan distance, etc.
  - \( \max \) chooses least optimistic heuristic (most accurate) at each node

- \( h(n) = w_1 h_1(n) + w_2 h_2(n) + \ldots + w_k h_k(n) \)
  - A convex combination of features
    - Weighted sum of \( h(n) \)'s, where weights sum to 1
  - Weights learned via repeated puzzle-solving
  - Try to identify which features are predictive of path cost
Summary

- Uninformed search methods have uses, also severe limitations
- Heuristics are a structured way to add “smarts” to your search

- Informed (or heuristic) search uses problem-specific heuristics to improve efficiency
  - Best-first, A* (and if needed for memory limits, RBFS, SMA*)
  - Techniques for generating heuristics
  - A* is optimal with admissible (tree)/consistent (graph) heuristics

- Can provide significant speed-ups in practice
  - E.g., on 8-puzzle, speed-up is dramatic
  - Still have worst-case exponential time complexity
  - In AI, “NP-Complete” means “Formally interesting”

- Next lecture topic: local search techniques
  - Hill-climbing, genetic algorithms, simulated annealing, etc.
  - Read Chapter 4 in advance of lecture, and again after lecture