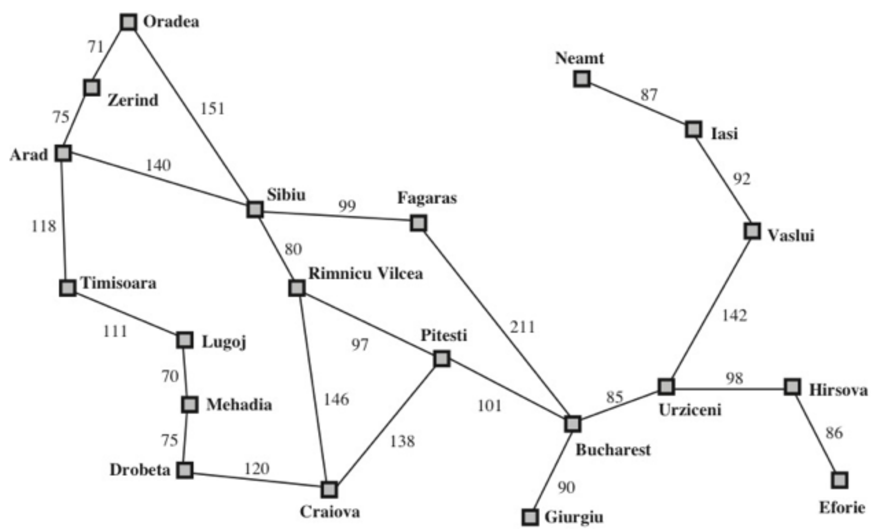
Informed Search

AI Class 4 (Ch. 3.5-3.7)



Based on slides by Dr. Marie desJardin. Some material also adapted from slides by Dr. Matuszek @ Villanova University, which are based on Hwee Tou Ng at Berkeley, which are based on Russell at Berkeley. Some diagrams are based on AIMA.

Bookkeeping

- HW 1 due 9/19, 11:59pm – **Monday night**
- Reminder: Office hours

TA (Koninika Patil)	Tues, Thurs 12-1	ITE 353H
Grader (Tejas Sathe)	Wednesday 3-4	ITE 353H
Professor (Dr. M)	Tues 3:30-4:30, Wednesday 9-10	ITE 331

Today's Class

- Heuristic search
- Best-first search
  - Greedy search
  - Beam search
  - A, A*
  - Examples
- Memory-conserving variations of A*
- Heuristic functions

"An informed search strategy—one that uses problem specific knowledge… can find solutions more efficiently then an uninformed strategy."

– *R&N pg. 92*

Weak vs. Strong Methods

- *Weak methods*:
  - Extremely *general*, not tailored to a specific situation
- Examples
  - **Means-ends analysis**: try to represent the current situation the goal, then look for ways to shrink the differences between the two
  - **Space splitting**: try to list the possible solutions to a problem, then try to rule out classes of these possibilities.
  - **Subgoaling**: split a large problem into several smaller ones that can be solved one at a time.
- Called "weak" methods because they do not take advantage of more powerful domain-specific heuristics

Heuristic

Free On-line Dictionary of Computing*

1. **A rule of thumb, simplification, or educated guess**
2. Reduces, limits, or guides search in particular domains
3. Does not guarantee feasible solutions; often used with no theoretical guarantee

WordNet (r) 1.6*

1. Commonsense rule (or set of rules) intended to increase the probability of solving some problem

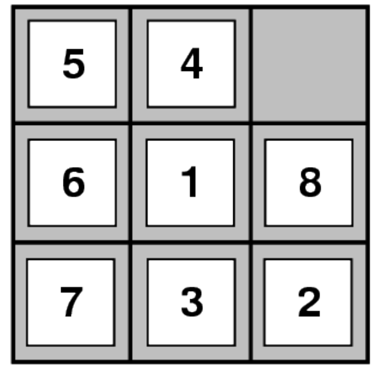
**Heavily edited for clarity*

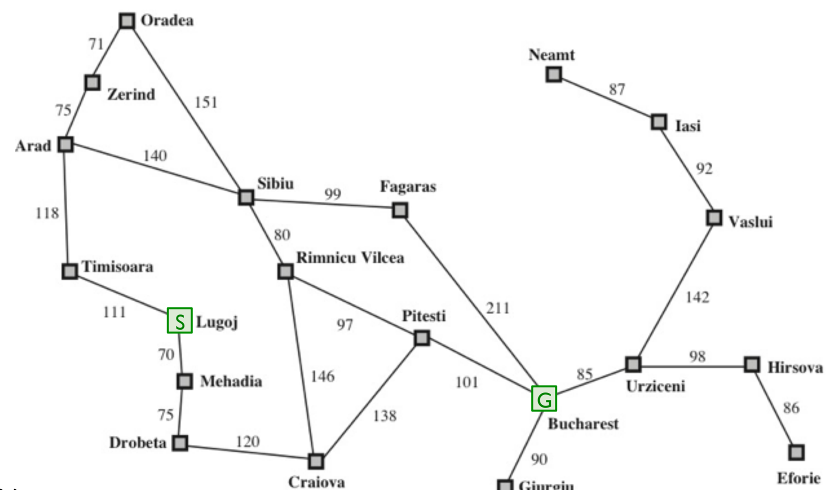
Heuristic Search

- Uninformed search is **generic**
  - Node selection depends only on shape of tree and node expansion trategy.
- Sometimes **domain knowledge** → Better decision
  - Knowledge about the specific problem
- Romania:
  - Eyeballing it → certain cities first
  - They "look closer" to where we are going
- Can domain knowledge can be captured in a heuristic?

Heuristics Examples

- 8-puzzle:
  - # of tiles in wrong place
- 8-puzzle (better):
  - Sum of distances from goal
  - Captures distance *and* number of nodes
- Romania:
  - Straight-line distance from start node to Bucharest
  - Captures “closer to Bucharest”





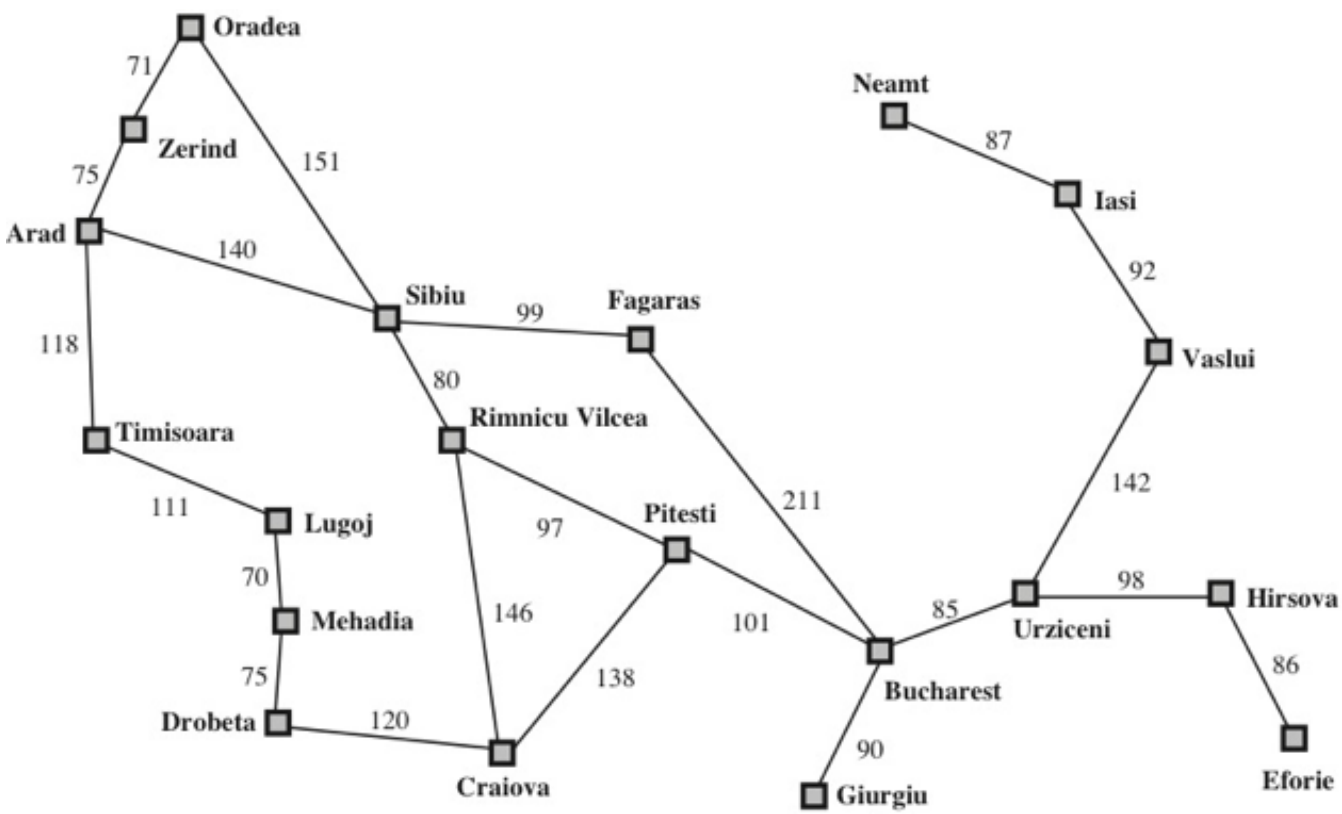
Heuristic Function

- **All** domain-specific knowledge is encoded in heuristic function h
- h is some estimate of how desirable a move is
  - How "close" (we think) it gets us to our goal
- Usually:
  - $h(n) \geq 0$: for all nodes n
  - $h(n) = 0$: n is a goal node
  - $h(n) = \infty$: n is a dead end (no goal can be reached from n)

Informed Methods Add Domain-Specific Information

- Goal: **select** the best path to continue searching
- Define ***h*(*n*)** to estimates the "goodness" of node *n*
  - *h*(*n*) = **estimated cost** (or distance) of minimal cost path from *n* **to a goal state**
- Heuristic function is:
  - An estimate of how close we are to a goal
  - Based on domain-specific information
  - Computable from the current state description

Straight Lines to Budapest (km)



$h_{SLD}(n)$	
Arad	366
Bucharest	0
Craiova	160
Drobeta	242
Eforie	161
Fagaras	176
Giurgiu	77
Hirsova	151
Iasi	226
Lugoj	244
Mehadia	241
Neamt	234
Oradea	380
Pitesti	100
Rimnicu Vilcea	193
Sibiu	253
Timisoara	329
Urziceni	80
Vaslui	199
Zerind	374

R&N pg. 68, 93

Admissible Heuristics

- Admissible heuristics never <u>over</u>estimate cost
  - They are *optimistic* – think goal is closer than it is
- $h(n) \leq h^*(n)$
  - where $h^*(n)$ is **true** cost to reach goal from n
- h_{LSD}(Lugoj) = 244
  - Can there be a shorter path?
- Using admissible heuristics guarantees that the first solution found will be optimal

Best-First Search

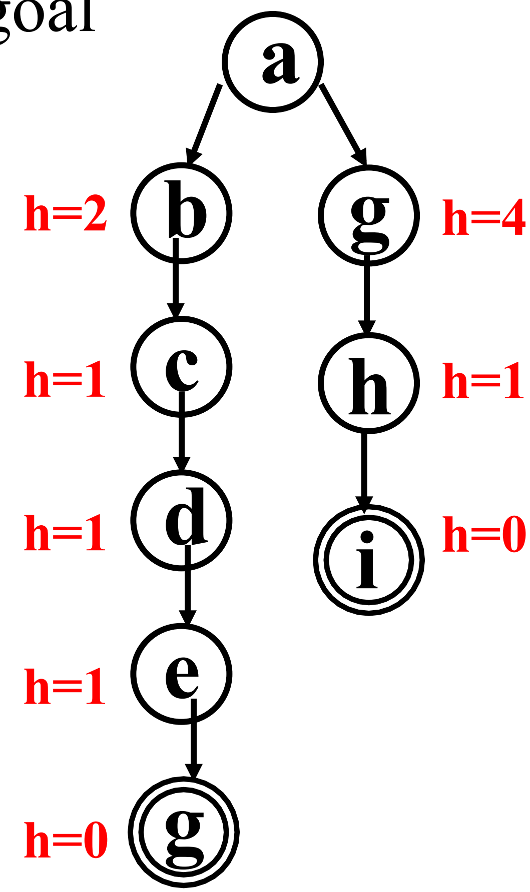
- Order nodes on the list by
  - Increasing value of an evaluation function ***f*(*n*)**
  - $f(n)$ incorporates domain-specific information
  - Different $f(n)$ → Different searches
- A generic way of referring to informed methods

Best-First Search (more)

- Use an **evaluation function** $f(n)$ for each node
  → estimate of "desirability"
- Expand most desirable unexpanded node
  - Implementation:
  - Order nodes in frontier in decreasing order of desirability
- Special cases:
  - Greedy best-first search
  - A* search

Greedy Best-First Search

- Idea: always choose "closest node" to goal
  - Most likely to lead to a solution quickly
- So, evaluate nodes based only on heuristic function
  - $f(n) = h(n)$
- Sort nodes by increasing values of f
- Select node believed to be **closest** to a goal node (hence "greedy")
  - That is, select node with smallest f value

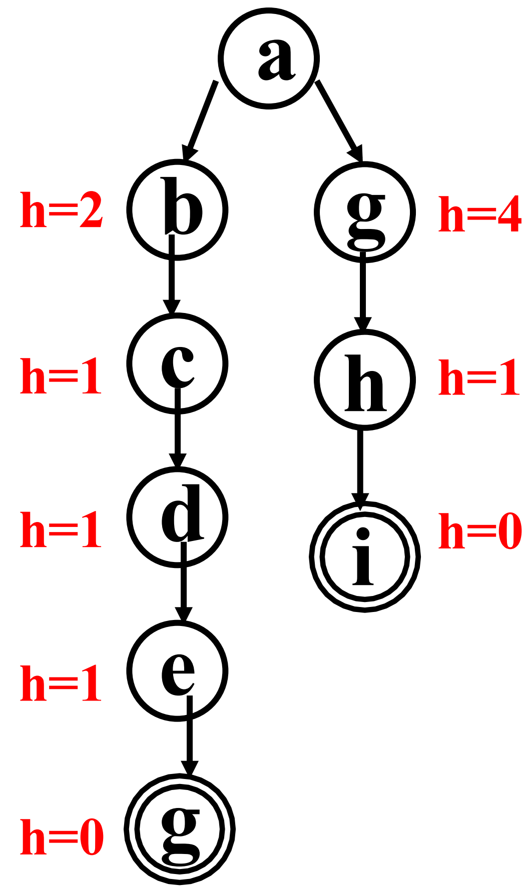


Greedy Best-First Search

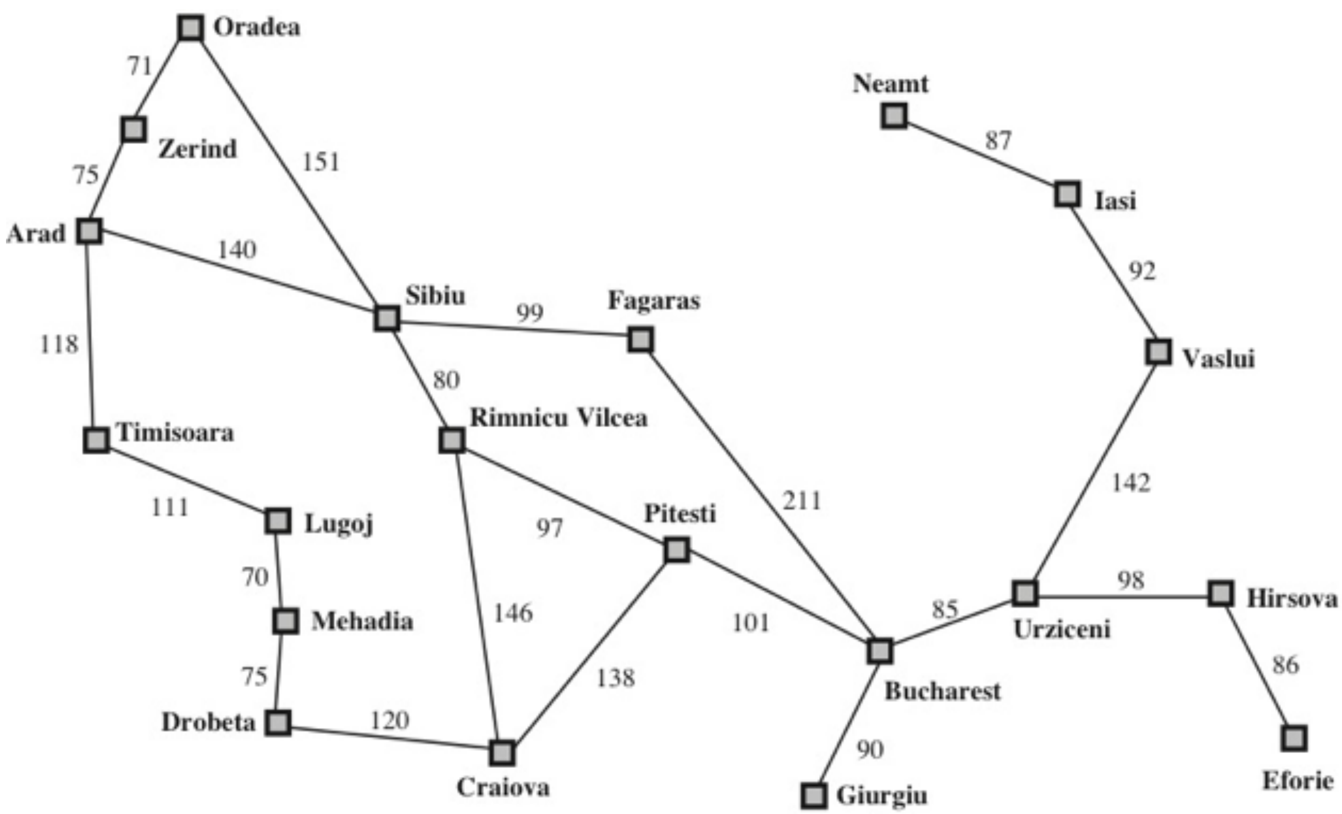
- Not admissible
- Example:
  - Greedy search will find:

    a→b→c→d→e→g ; cost = 5
  - Optimal solution:

    a→g→h→i ; cost = 3
- Not complete (why?)



Straight Lines to Budapest (km)

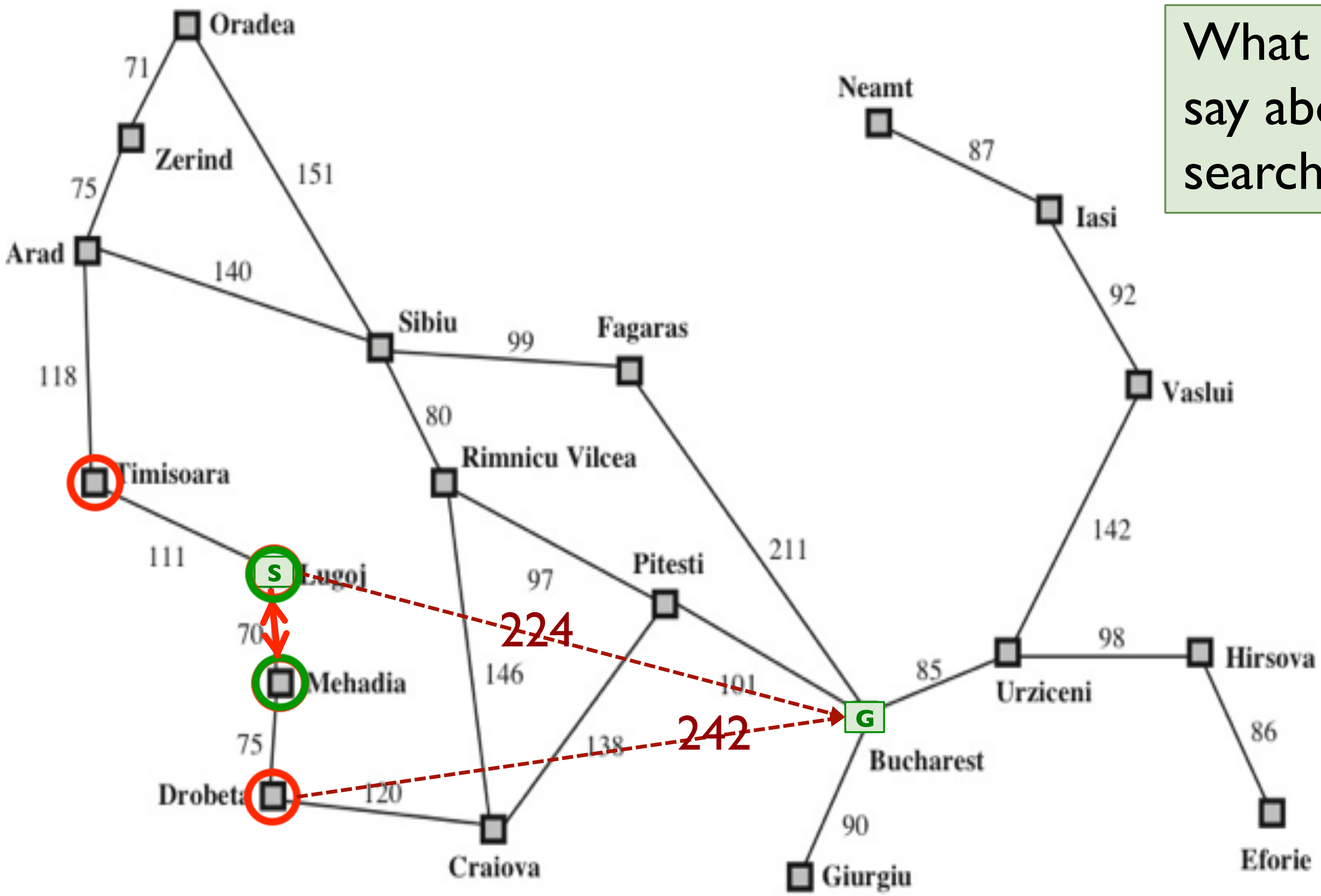


$h_{SLD}(n)$

Arad	366
Bucharest	0
Craiova	160
Drobeta	242
Eforie	161
Fagaras	176
Giurgiu	77
Hirsova	151
Iasi	226
Lugoj	244
Mehadia	241
Neamt	234
Oradea	380
Pitesti	100
Rimnicu Vilcea	193
Sibiu	253
Timisoara	329
Urziceni	80
Vaslui	199
Zerind	374

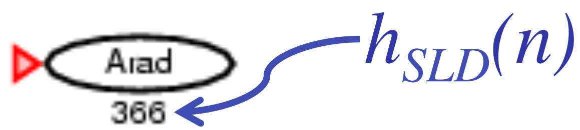
R&N pg. 68, 93

Greedy Best-First Search: Ex. 1



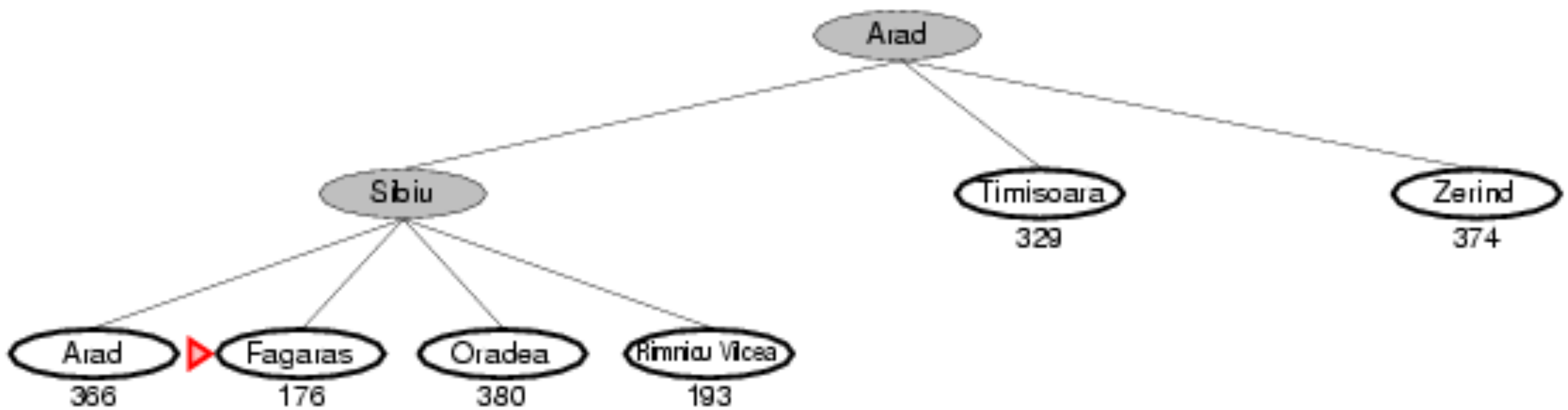
What can we say about the search space?

Greedy Best-First Search: Ex. 2

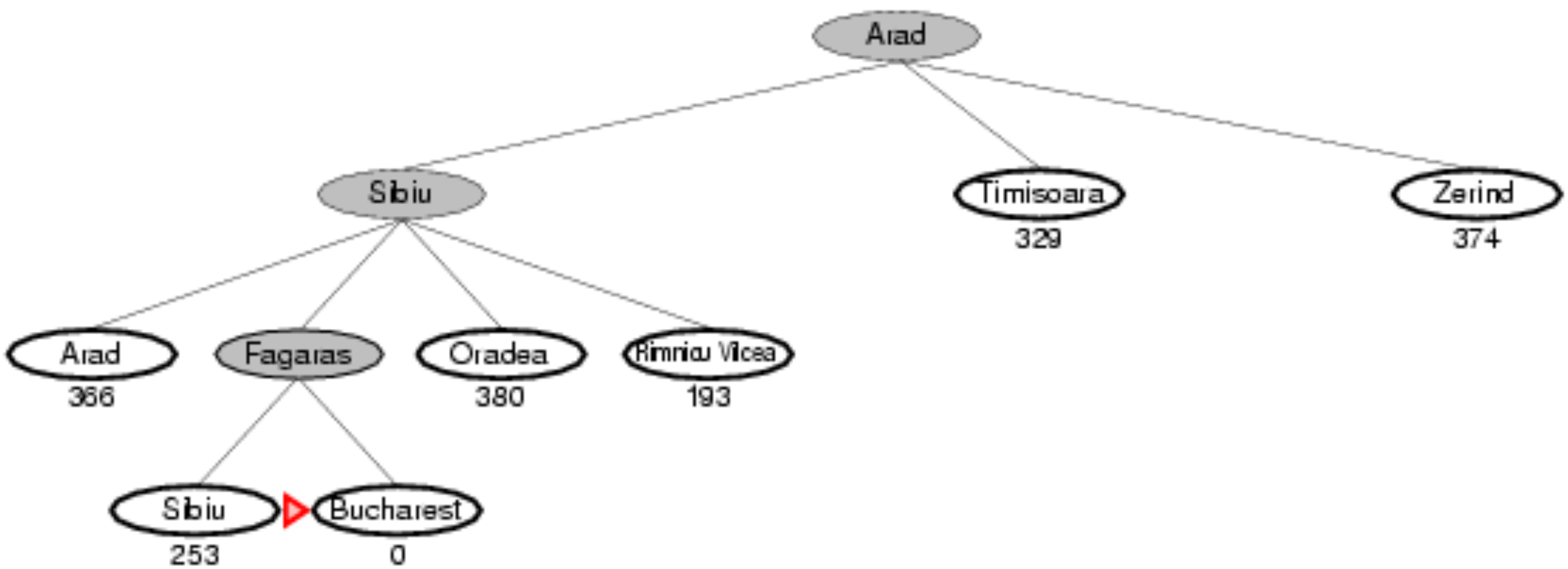


Greedy Best-First Search: Ex. 2

Greedy Best-First Search: Ex. 2



Greedy Best-First Search: Ex. 2

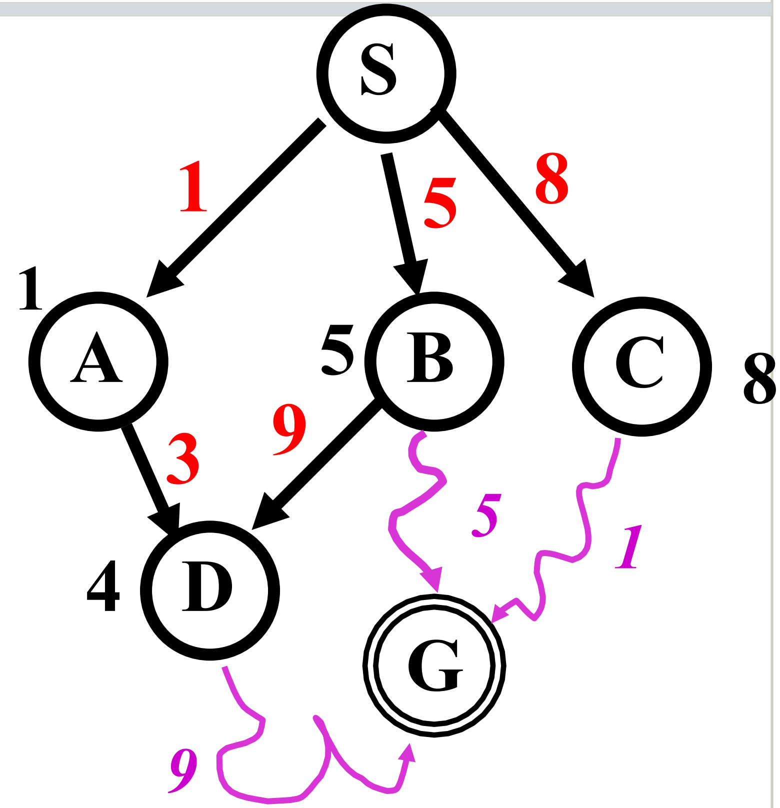


Beam Search

- Use an evaluation function $f(n) = h(n)$, but the maximum size of the nodes list is k, a fixed constant
- Only keeps k best nodes as candidates for expansion, and throws the rest away
- More space-efficient than greedy search, but may throw away a node that is on a solution path
- Not complete
- Not admissible

Algorithm A

- Use evaluation function
  $f(n) = g(n) + h(n)$
- $g(n)$ = minimal-cost path from any S to state n
- Ranks nodes on search frontier by *estimated* cost of solution
  - From start node, through given node, to goal
- Not complete if $h(n)$ can $= \infty$
- Not admissible



$g(d)=4$

$h(d)=9$

C is chosen next to expand

Algorithm A

1. Put the start node S on the nodes list, called OPEN
2. If OPEN is empty, exit with failure
3. Select node in OPEN with minimal $f(n)$ and place on CLOSED
4. If n is a goal node, collect path back to start and stop.
5. Expand n, generating all its successors and attach to them pointers back to n. For each successor n' of n
   1. If n' is not already on OPEN or CLOSED
      - put n' on OPEN
      - compute $h(n')$, $g(n') = g(n) + c(n,n')$, $f(n') = g(n') + h(n')$
   2. If n' is already on OPEN or CLOSED and if $g(n')$ is lower for the new version of n', then:
      - Redirect pointers backward from n' along path yielding lower $g(n')$.
      - Put n' on OPEN.

Some Observations on A

- **Perfect heuristic:** If $h(n) = h^*(n)$ for all n:
  - Only nodes on the optimal solution path will be expanded
  - No extra work will be performed
- **Null heuristic:** If $h(n) = 0$ for all n:
  - This is an admissible heuristic
  - A* acts like Uniform-Cost Search

The closer h is to h^*, the fewer extra nodes will be expanded

Some Observations on A

- **Better heuristic:**
  If $h_1(n) < h_2(n) \leq h^*(n)$ for all non-goal nodes, h_2 is a better heuristic than h_1
- If A_1* uses h_1, A_2* uses h_2,
  → every node expanded by A_2* is also expanded by A_1*
  - So A_1 expands at least as many nodes as A_2*

We say that A_2* is better informed than A_1*

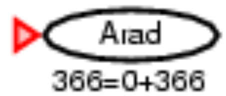
Quick Terminology Check

- What is $f(n)$?
  - An **evaluation function** that gives…
  - A cost estimate of...
  - The distance from n to G
- What is $h(n)$?
  - A **heuristic function** that…
  - Encodes domain knowledge about...
  - The search space
- What is $h^*(n)$?
  - A **heuristic function** that gives the…
  - **True** cost to reach goal from n
  - Why don't we just use that?
- What is $g(n)$?
  - The **path cost** of getting from S to n
  - describes the "spent" costs of the current search

A^* Search

- Idea: avoid expanding paths that are already expensive
  - Combines costs-so-far with expected-costs
- Evaluation function $f(n) = g(n) + h(n)$
  - $g(n)$ = cost so far to reach n
  - $h(n)$ = estimated cost from n to goal
  - $f(n)$ = estimated total cost of path through n to goal
- A* is **complete** iff
  - Branching factor is finite
  - Every operator has a fixed positive cost
- A* is **admissible** iff
  - $h(n)$ is admissible

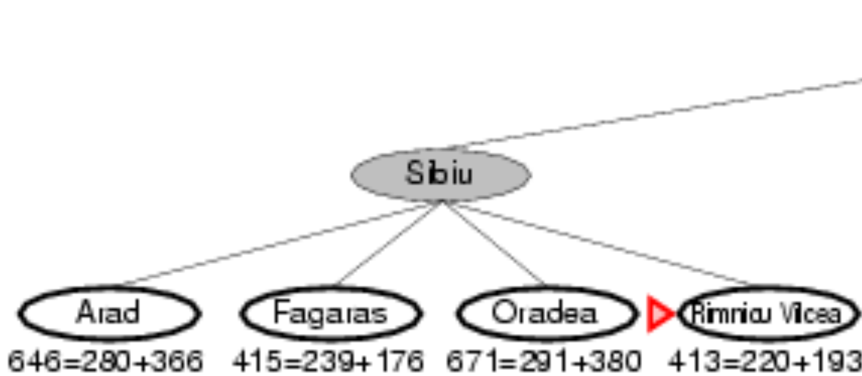
A* Example 1



A* Example 1

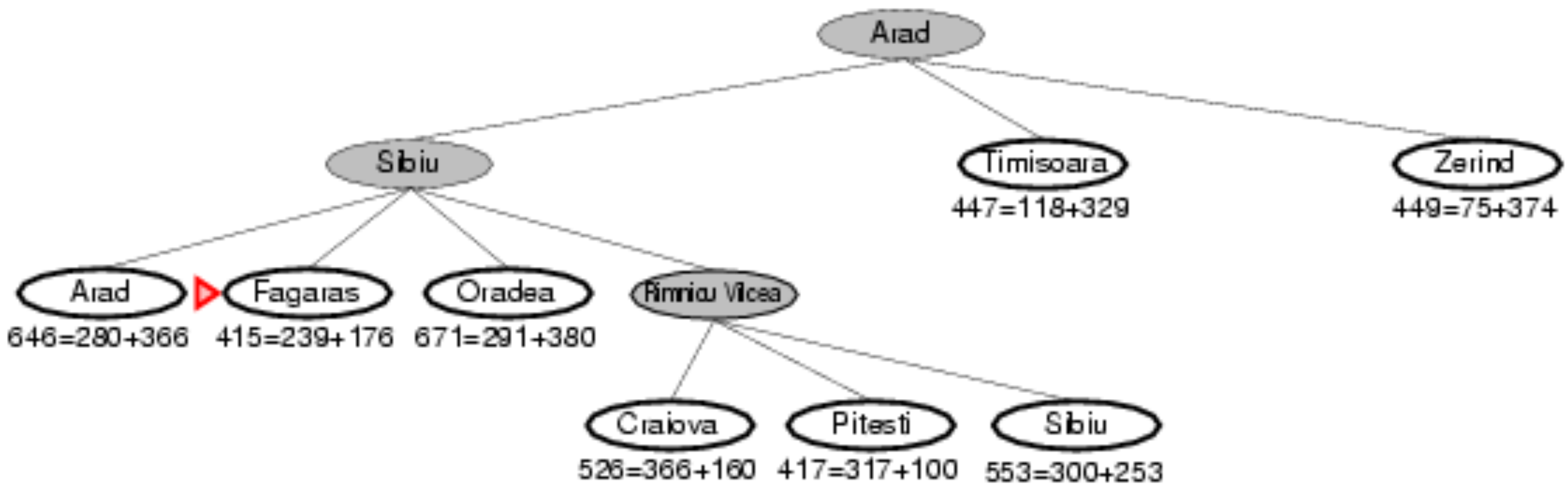

Arad
Sibiu
393=140+253
Timisoara
447=118+329
Zerind
449=75+374

A* Example 1



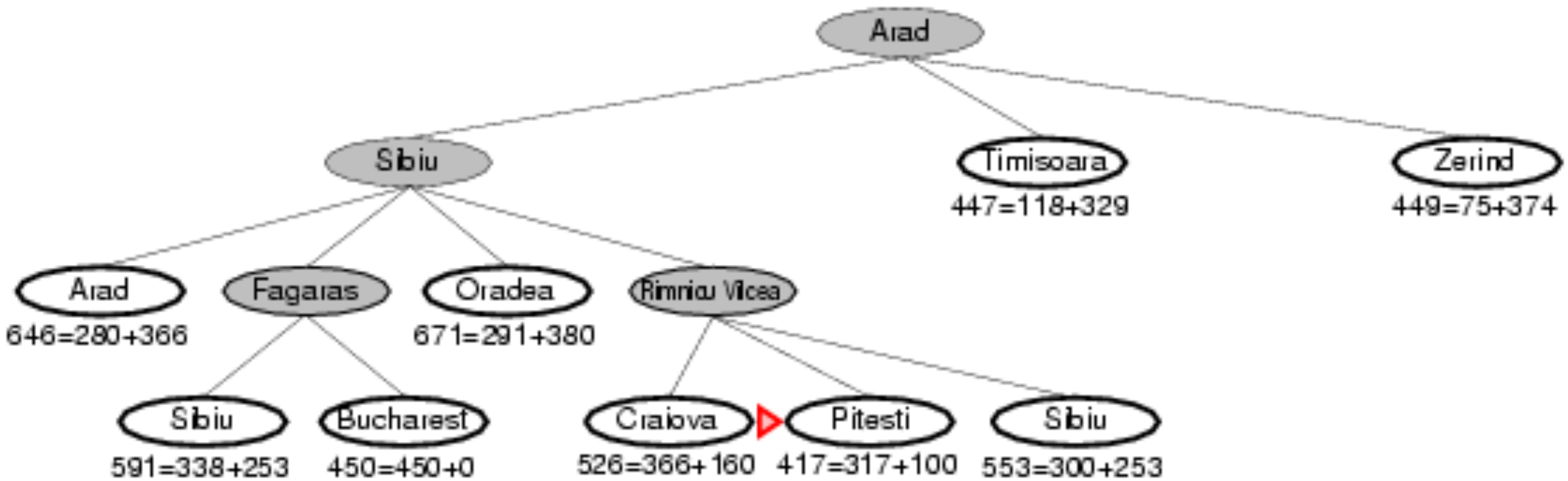
Arad
Sibiu
Timisoara
447=118+329
Zerind
449=75+374
Arad
646=280+366
Fagaras
415=239+176
Oradea
671=291+380
Rimnicu Vilcea
413=220+193

A* Example 1

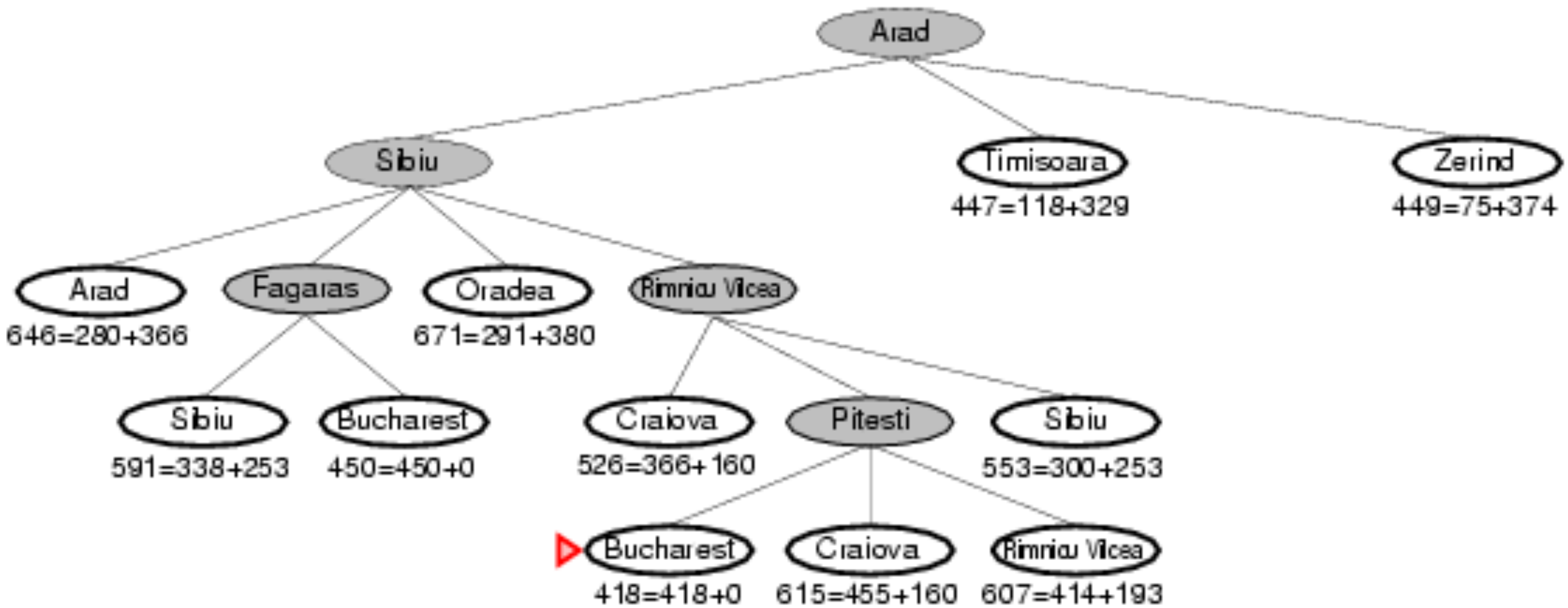


Arad
Sibiu
Timisoara
447=118+329
Zerind
449=75+374
Arad
646=280+366
Fagaras
415=239+176
Oradea
671=291+380
Rimnicu Vilcea
Craiova
526=366+160
Pitesti
417=317+100
Sibiu
553=300+253

A^* Example 1


Arad
Sibiu
Timisoara
447=118+329
Zerind
449=75+374
Arad
646=280+366
Fagaras
Oradea
671=291+380
Rimnicu Vilcea
Sibiu
591=338+253
Bucharest
450=450+0
Craiova
526=366+160
Pitesti
417=317+100
Sibiu
553=300+253

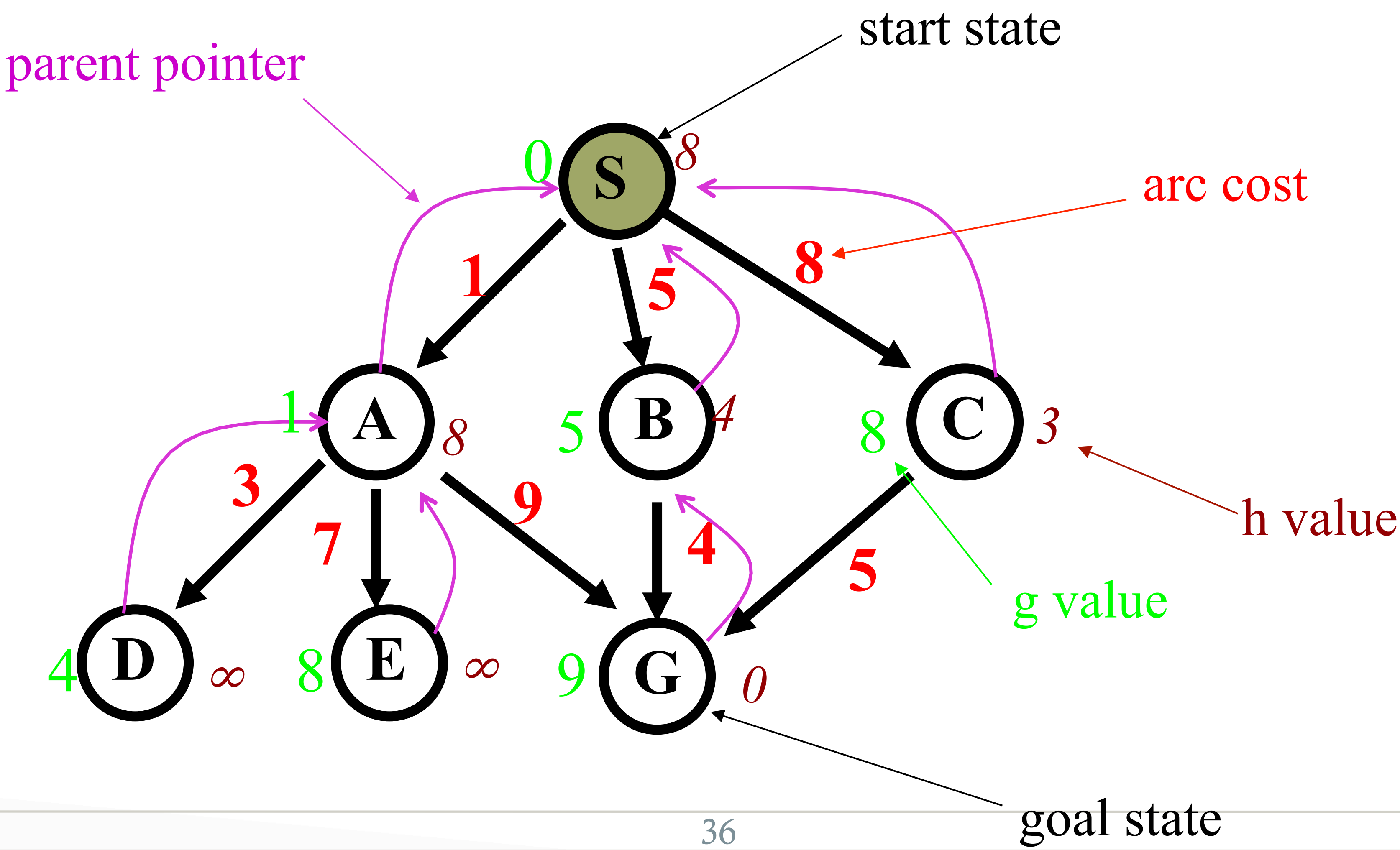
A* Example 1


Arad
Sibiu
Timisoara
447=118+329
Zerind
449=75+374
Arad
646=280+366
Fagaras
Oradea
671=291+380
Rimnicu Vilcea
Sibiu
591=338+253
Bucharest
450=450+0
Craiova
526=366+160
Pitesti
Sibiu
553=300+253
Bucharest
418=418+0
Craiova
615=455+160
Rimnicu Vilcea
607=414+193

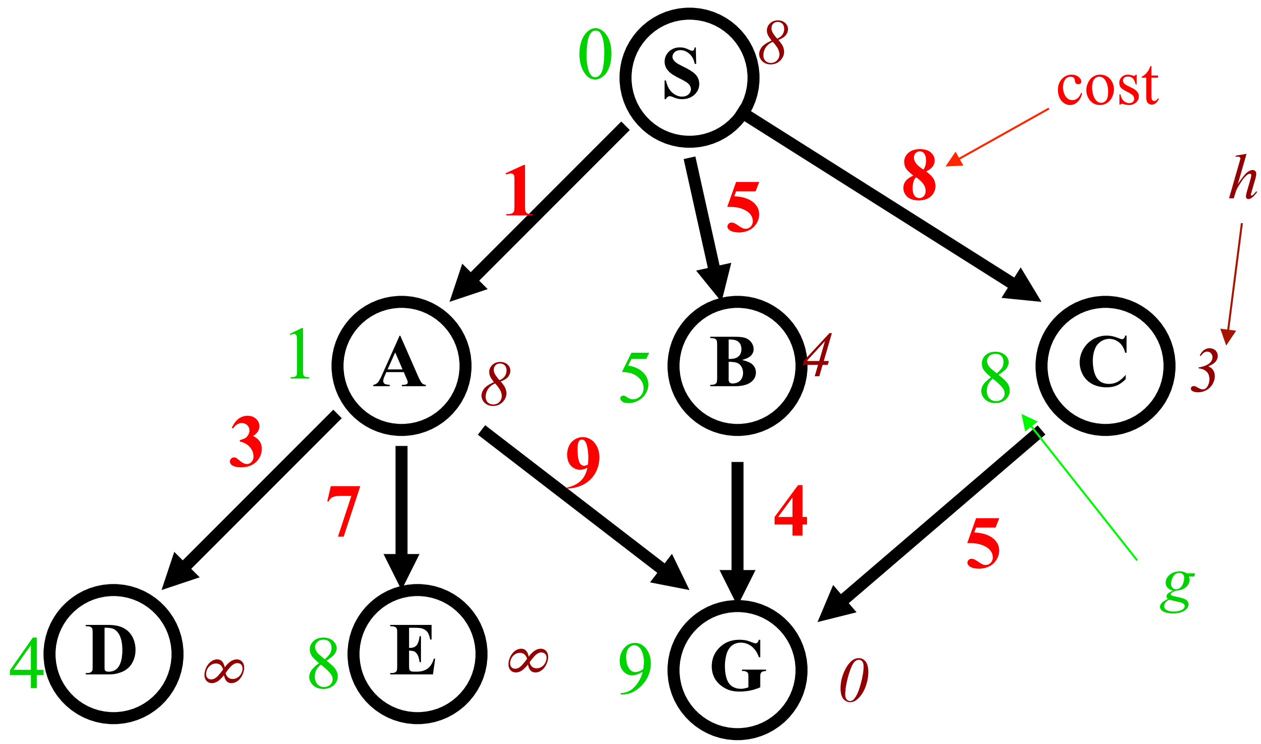
Algorithm A*

- Algorithm A with constraint that $h(n) \leq h^*(n)$
  - ***h*(n)*** = true cost of the minimal cost path from n to a goal.
- Therefore, ***h(n)*** is an **underestimate** of the distance to the goal
- $h()$ is **admissible** when $h(n) \leq h^*(n)$
  - Guarantees optimality
- A* is **complete** whenever the branching factor is finite, and every operator has a fixed positive cost
- A* is **admissible**

Example Search Space Revisited

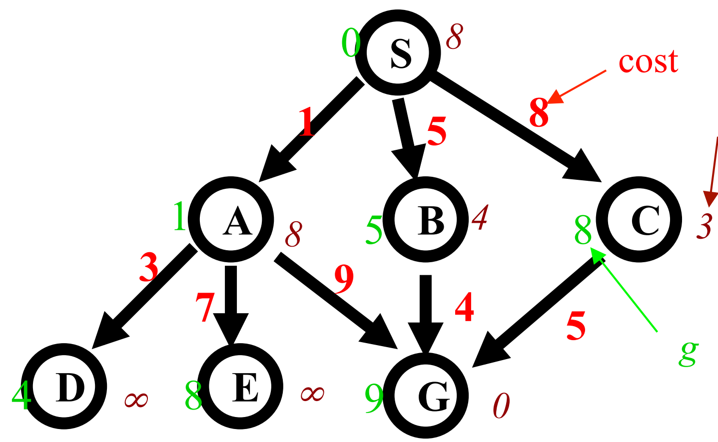


Example Search Space Revisited



Example

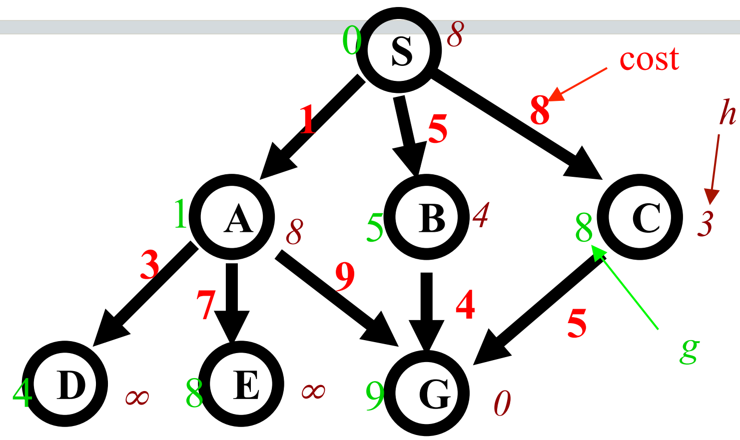
n	***g*(*n*)**	***h*(*n*)**	***f*(*n*)**	***h*(*n*)***
S	0	8	8	9
A	1	8	9	9
B	5	4	9	4
C	8	3	11	5
D	4	∞	∞	∞
E	8	∞	∞	∞
G	9	0	9	0



- $h^*(n)$ is the (hypothetical) perfect heuristic.
- Since $h(n) \leq h^*(n)$ for all n, h is admissible
- Optimal path = S B G with cost 9.

Greedy Search

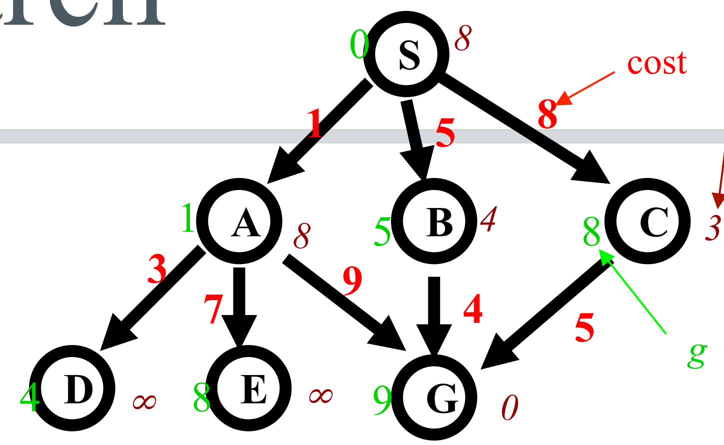
$f(n) = h(n)$



Node expanded	**Node list**
	{ S(8) }
S	{ C(3) B(4) A(8) }
C	{ G(0) B(4) A(8) }
G	{ B(4) A(8) }

- Solution path found is S C G, 3 nodes expanded.
- Fast!! But NOT optimal.

A* Search



$f(n) = g(n) + h(n)$

node exp.	nodes list
	{ S(8) }
S	{ A(9) B(9) C(11) }
A	{ B(9) G(10) C(11) D(∞) E(∞) }
B	{ G(9) G(10) C(11) D(inf) E(∞) }
G	{ C(11) D(∞) E(∞) }

- Solution path found is S B G, 4 nodes expanded..
- Still pretty fast, *and* optimal

Proof of the Optimality of A*

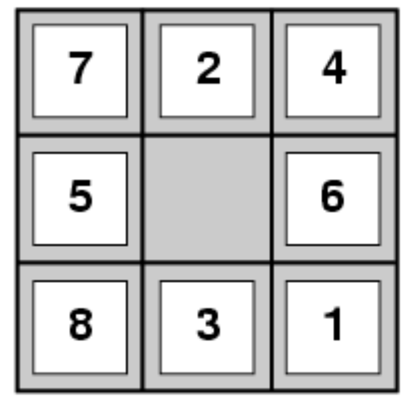
- Assume that A* has selected G_2, a goal state with a suboptimal solution ($g(G_2) > f^*$).
- We show that this is impossible.
  - Choose a node n on the optimal path to G.
  - Because $h(n)$ is admissible, $f(n) \leq f^*$.
  - If we choose G_2 instead of n for expansion, $\mathrm{f}(G_2) \leq \mathrm{f(n)}$.
  - This implies $f(G_2) \leq f^*$.
  - G_2 is a goal state: $h(G_2) = 0, f(G_2) = g(G_2)$.
  - Therefore $g(G_2) \leq f^*$
  - Contradiction.

Admissible heuristics

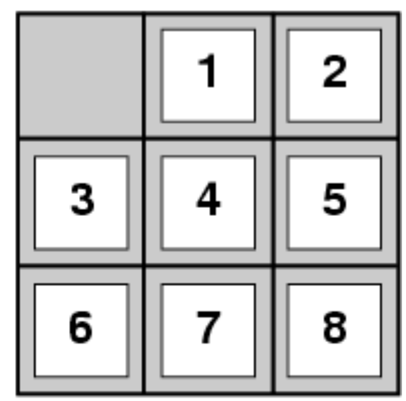
E.g., for the 8-puzzle:

$h_1(n)$ = number of misplaced tiles

$h_2(n)$ = total Manhattan distance
(i.e., # of squares each tile is from desired location)



Start



Goal

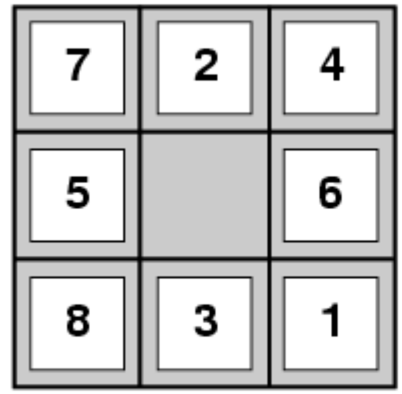
- $h_1(S)$ = ?
- $h_2(S)$ = ?

Admissible heuristics

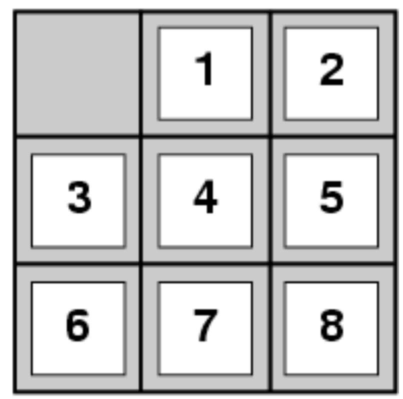
E.g., for the 8-puzzle:

$h_1(n)$ = number of misplaced tiles

$h_2(n)$ = total Manhattan distance
(i.e., # of squares each tile is from desired location)



Start



Goal

- $h_1(S) = 8$
- $h_2(S) = 3+1+2+2+2+3+3+2 = 18$

Dealing with Hard Problems

- For large problems, A* often requires too much space.
- Two variations conserve memory: IDA* and SMA*
- IDA* – iterative deepening A*
  - uses successive iteration with growing limits on f. For example,
    - A* but don't consider any node n where $f(n) > 10$
    - A* but don't consider any node n where $f(n) > 20$
    - A* but don't consider any node n where $f(n) > 30$, ...
- SMA* – Simplified Memory-Bounded A*
  - uses a queue of restricted size to limit memory use.
  - throws away the "oldest" worst solution.

What's a Good Heuristic?

- If $h_1(n) < h_2(n) \leq h^*(n)$ for all n, then:
  - Both are admissible
  - h_2 is strictly better than (**dominates**) h_1.
- How do we find one?

1. **Relaxing the problem:**
   - Remove constraints to create a (much) easier problem
   - Use the solution cost for this problem as the heuristic function
2. **Combining heuristics:**
   - Take the max of several admissible heuristics
   - Still have an admissible heuristic, and it's better!

What's a Good Heuristic? (2)

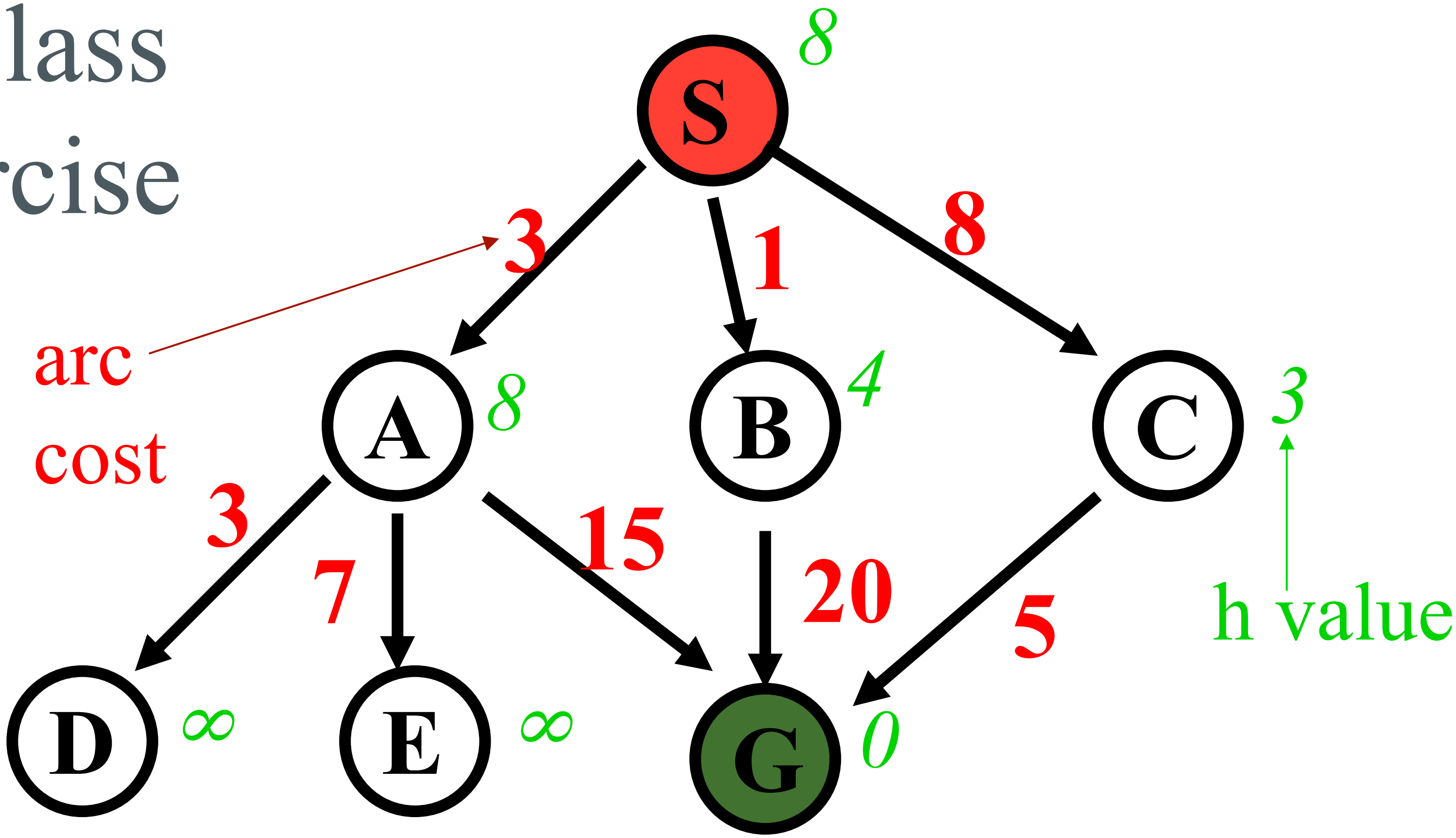
3. Use statistical estimates to compute *h*
   - May lose admissibility
4. Identify good features, then use a learning algorithm to find a heuristic function
   - Also may lose admissibility

- Why are these a good idea, then?
  - Machine learning can give you answers you don't "think of"
  - Can be applied to new puzzles without human intervention
  - Often work

Some Examples of Heuristics?

- 8-puzzle? Manhattan distance
- Driving directions? Straight line distance
- Crossword puzzle?
- Making a medical diagnosis?

In-Class Exercise

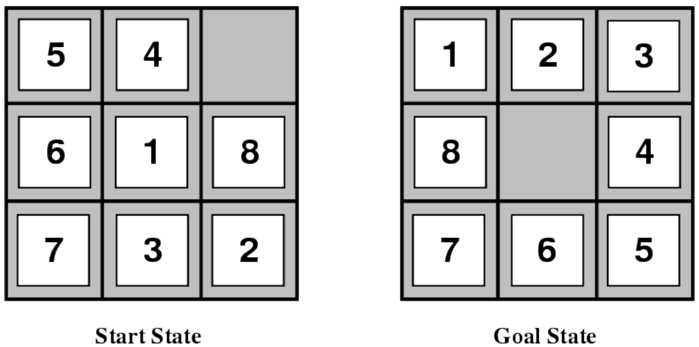


Apply the following to search this space. At each search step, show: the current node being expanded, $g(n)$ (path cost so far), $h(n)$ (heuristic estimate), $f(n)$ (evaluation function), and $h^*(n)$ (true goal distance).

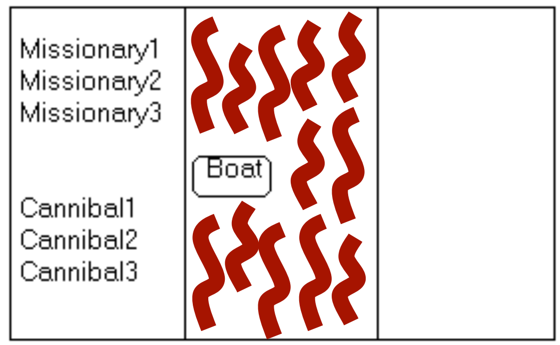
Depth-first search
Uniform-cost search
Breadth-first search
Greedy search
A* search

In-class Exercise: Creating Heuristics

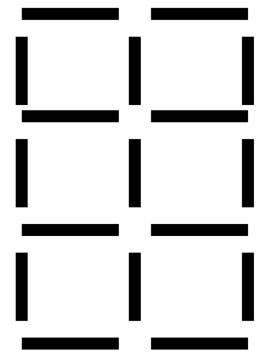
8-Puzzle



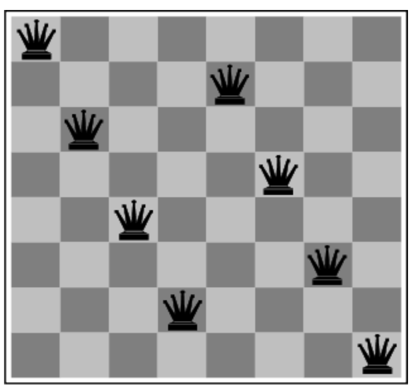
Missionaries and Cannibals



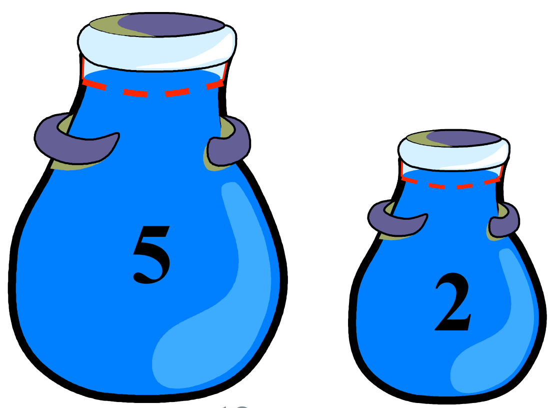
Remove 5 Sticks



N-Queens



Water Jug Problem



Route Planning

Summary: Informed Search

- **Best-first search:** general search where the *minimum-cost nodes* (according to some measure) are expanded first.
- **Greedy search:** uses *minimal estimated cost* $h(n)$ to the goal state as measure. Reduces search time but, is neither complete nor optimal.
- **A* search:** combines UCS and greedy search
  - $f(n) = g(n) + h(n)$
  - A* is complete and optimal, but space complexity is high.
  - Time complexity depends on the quality of the heuristic function.
- IDA* and SMA* reduce the memory requirements of A*.