

Artificial Intelligence

INFORMED SEARCH STRATEGIES

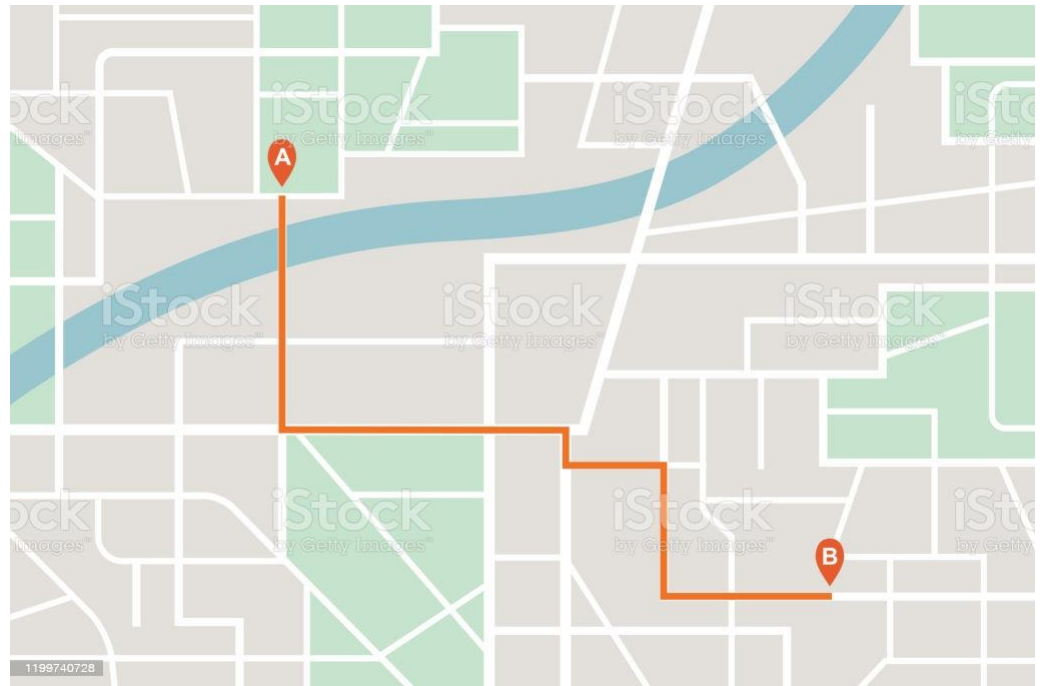
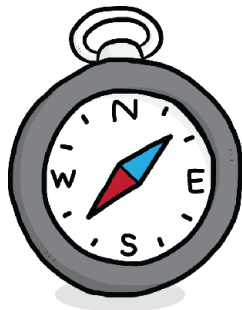
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Outline

- Informed (Heuristic) search strategies
- Best-first search
- Greedy best-first search
- A* search $UCS + A^*$
- Memory-bounded heuristic search
- Heuristic functions

Informed (Heuristic) search strategies

- Use **problem-specific knowledge** beyond the definition of the problem itself
- Find solutions **more efficiently**
- Provide **significant speed-up** in practice

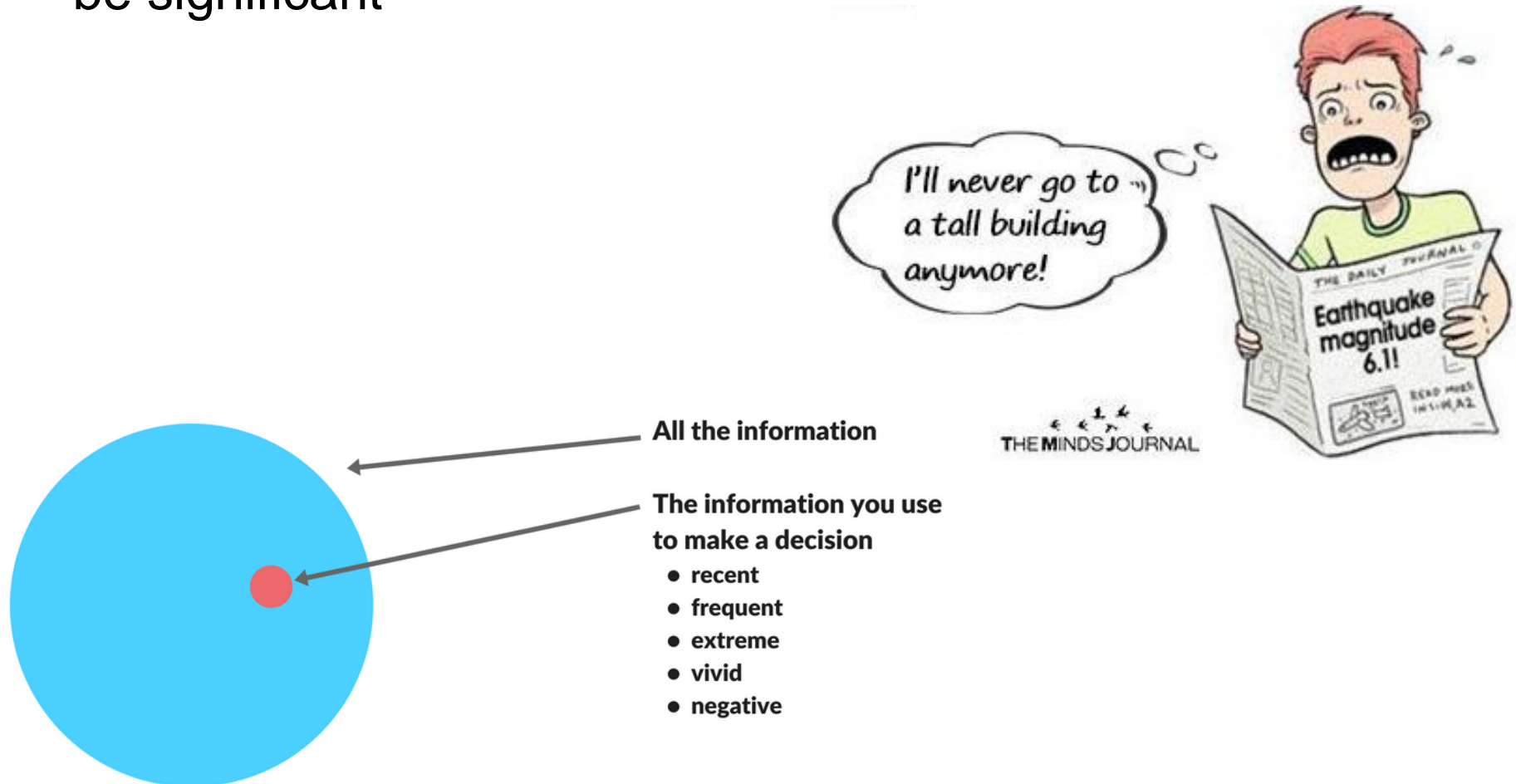


What are heuristics?

- **Additional knowledge** of the problem is imparted to the search algorithm using **heuristics**.
- A **heuristic** is any **practical approach** to problem solving sufficient for reaching an **immediate goal** where an optimal solution is usually impossible.
 - **Not guaranteed** to be **optimal, perfect, logical, or rational**
 - **Speed up the process of finding** a satisfactory solution
 - Ease the cognitive load of making a decision

Heuristics: An example

- **Availability heuristic:** what comes to mind quickly seems to be significant



Heuristics: An example

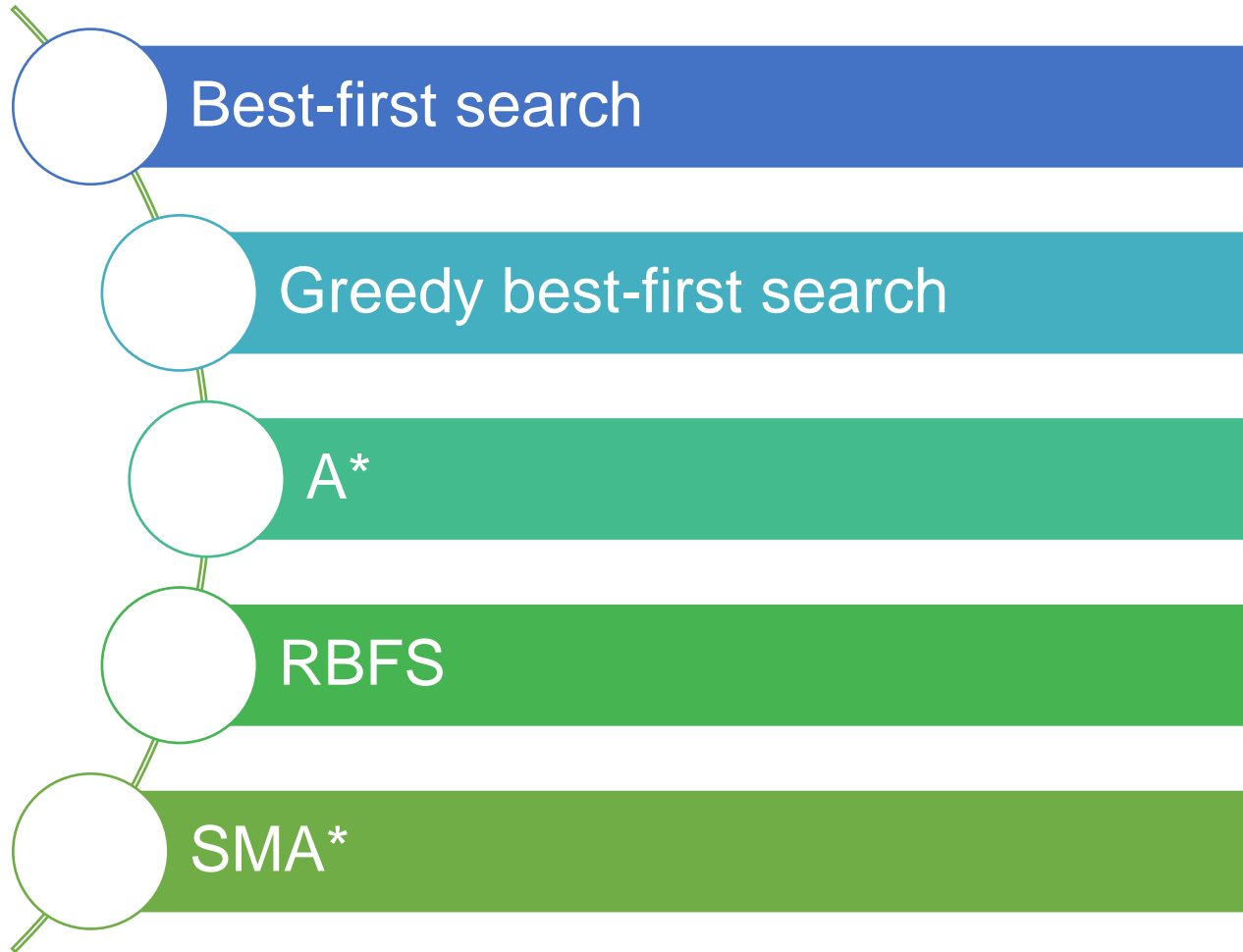
- **Representativeness heuristic:** estimate the likelihood of an event by comparing it to a prototype already exists in mind.



The portrait of an old woman
who is warm and caring
with a great love of children



Informed search strategies



Best-first search

- A best-first search algorithm can be either a TREE-SEARCH or GRAPH-SEARCH instance.
- A node is selected for expansion based on an **evaluation function, $f(n)$** .
 - Node with the **lowest $f(n)$** is expanded first
- The choice of f determines the search strategy.

Heuristic function

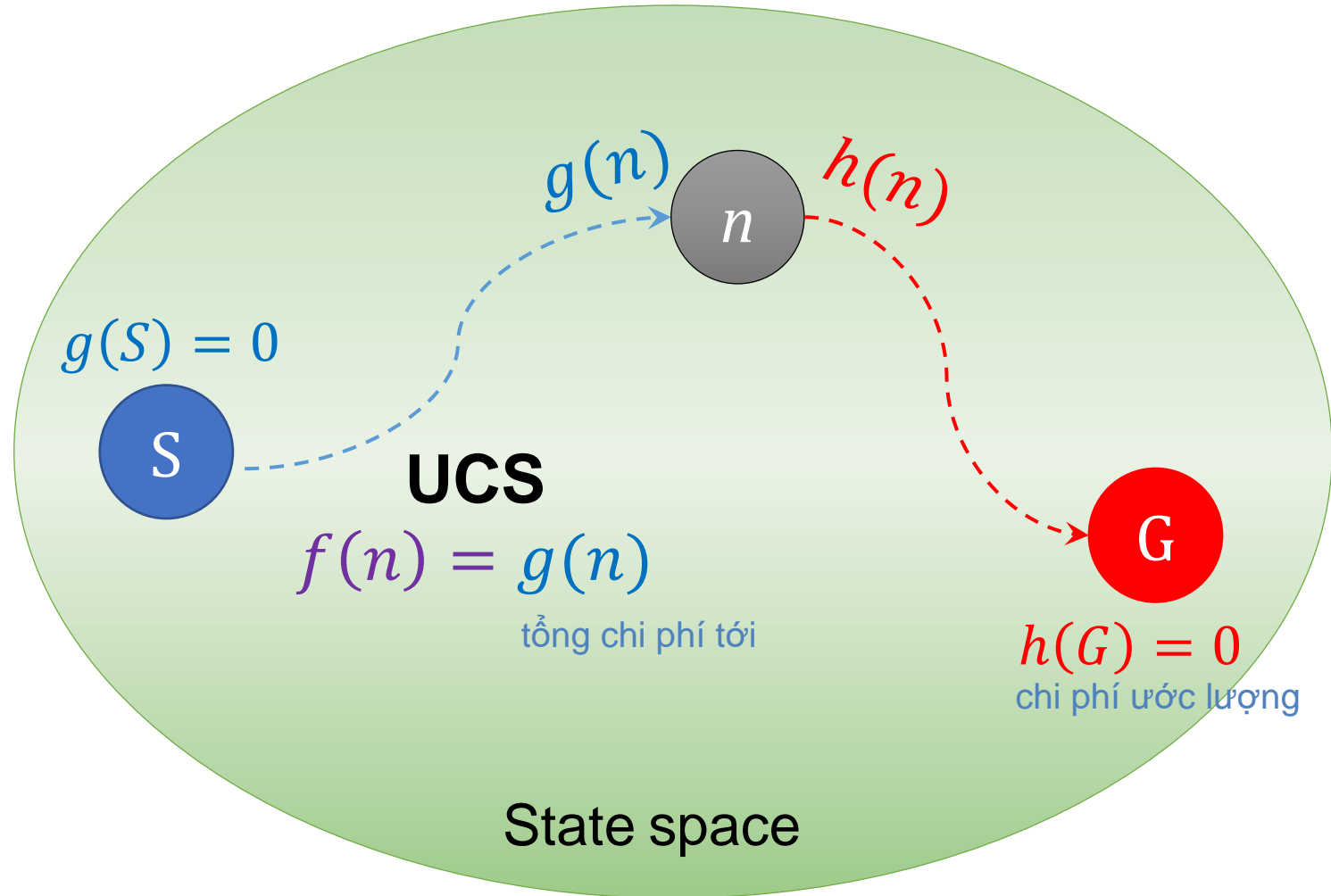
- Most best-first algorithms include a **heuristic function $h(n)$** as a component of f .

$h(n)$

estimated cost of the cheapest path
from the state at node n to a goal

- Unlike $g(n)$, $h(n)$ depends only on the state at that node
- Assumption of $h(n)$
 - Arbitrary, nonnegative, problem-specific functions
 - Constraint: if n is a goal node, then $h(n) = 0$

Cost function vs. Heuristic function



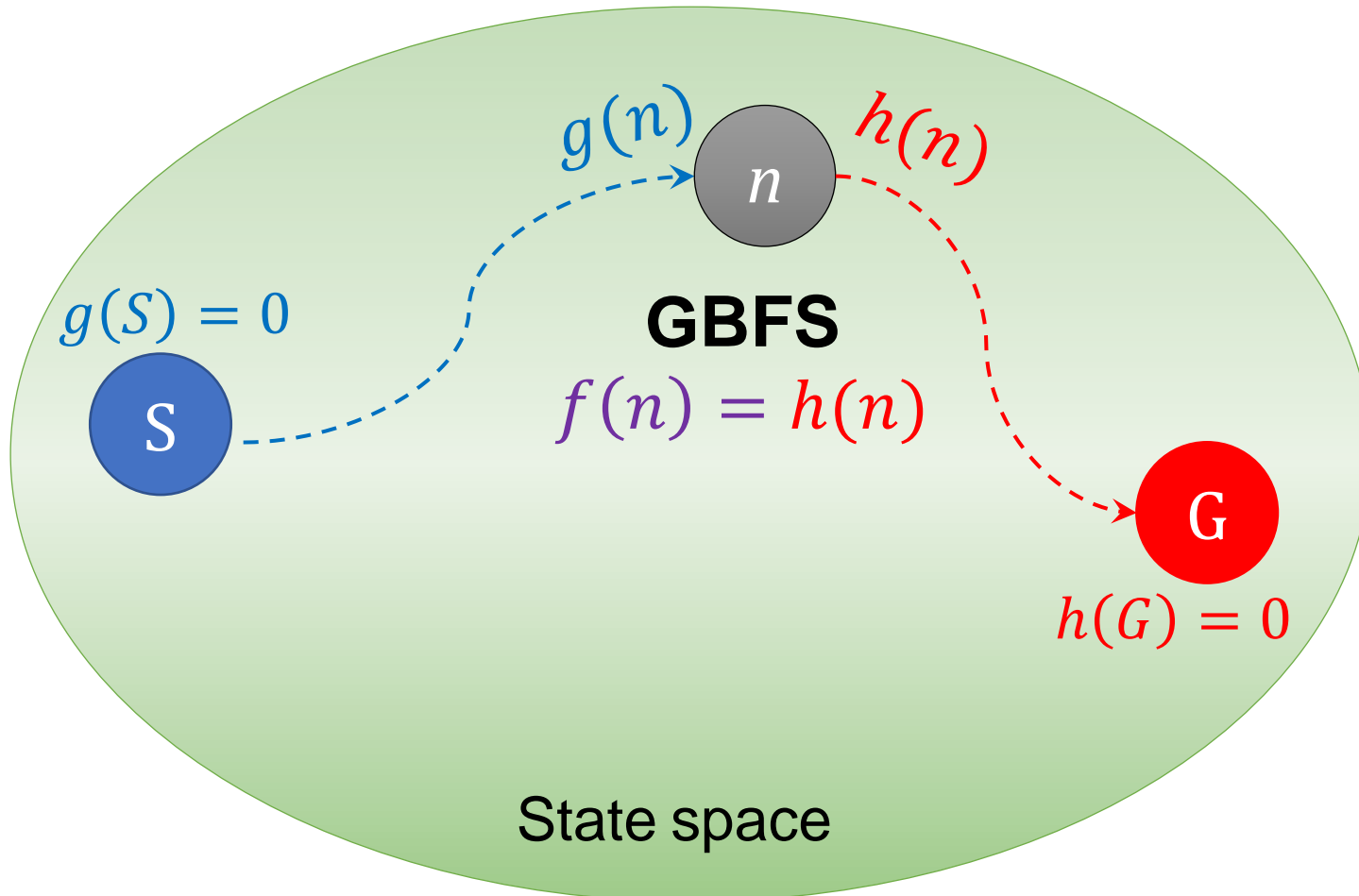
Greedy best-first search



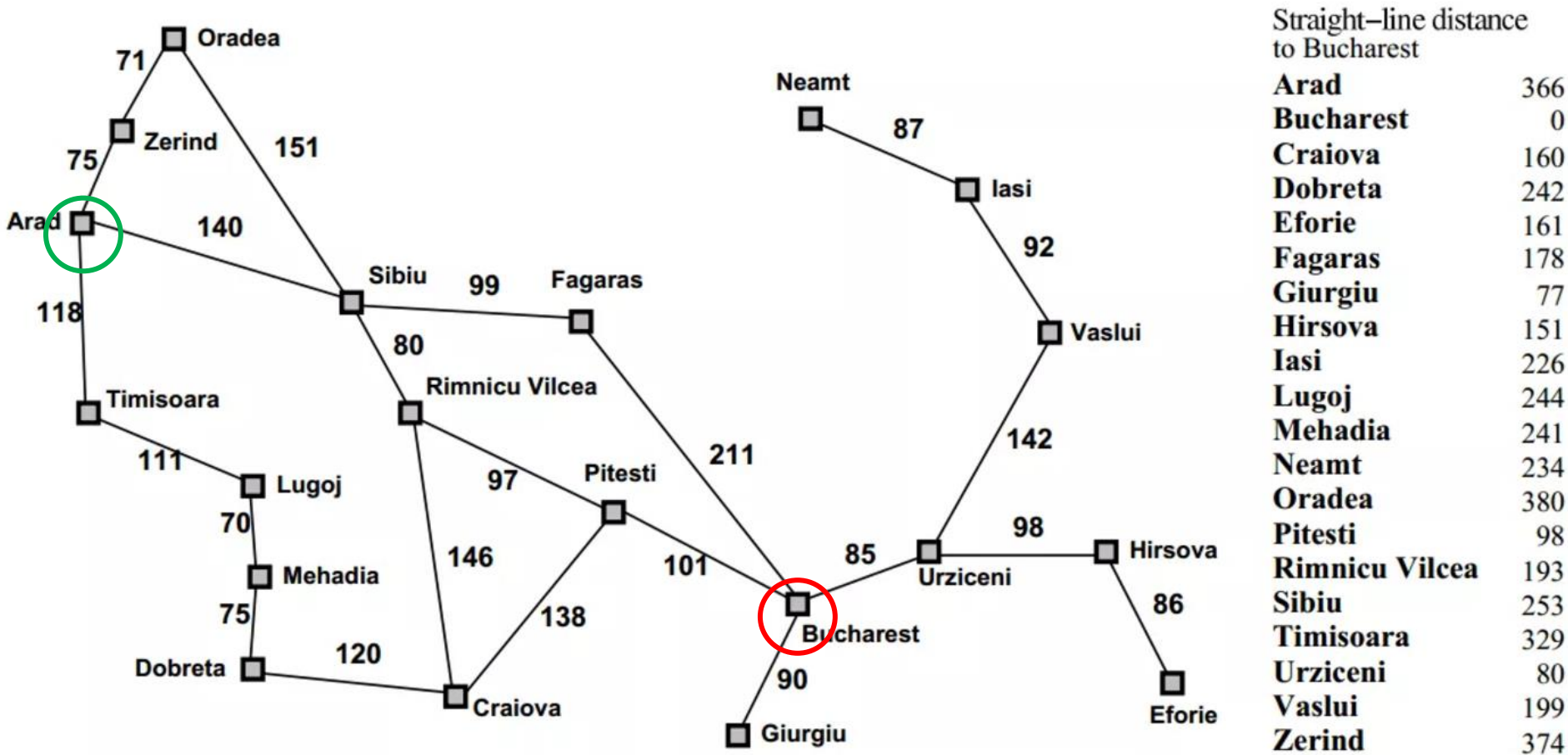
Greedy best-first search

- Expand the node that **appears** to be **closest to goal** using

$$f(n) = h(n)$$

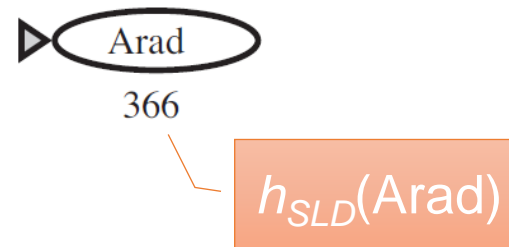


Straight-line distance heuristic h_{SLD}



Greedy best-first search: An example

(a) The initial state



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

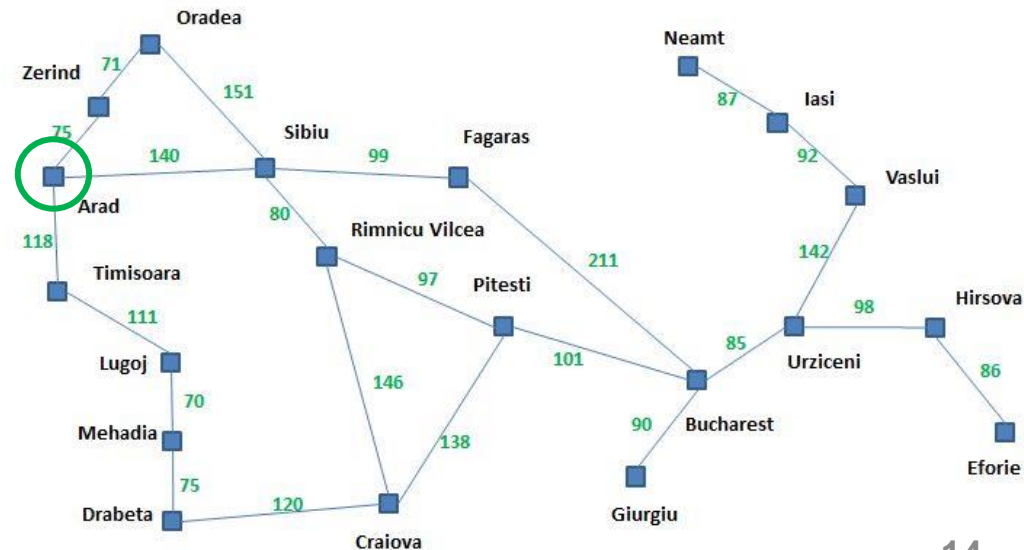
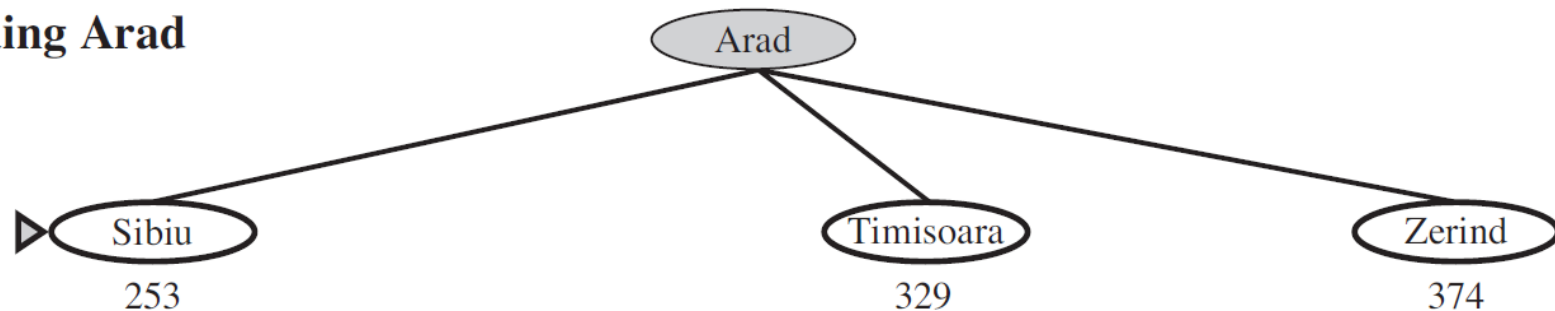


Figure A simplified road map of part of Romania.

Greedy best-first search: An example

(b) After expanding Arad



Arad	366	Mehadia	241
Bucharest	0	Neamt	234
Craiova	160	Oradea	380
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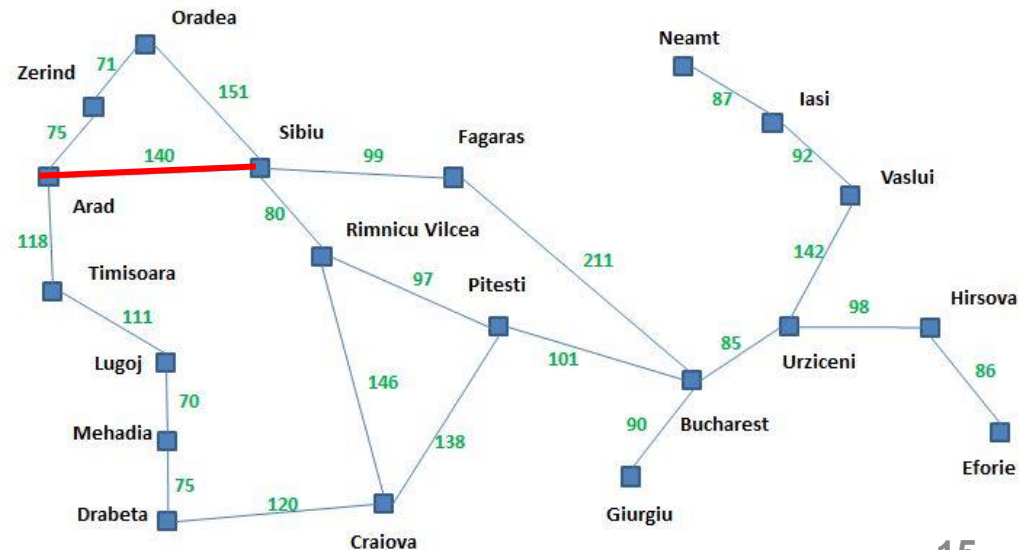
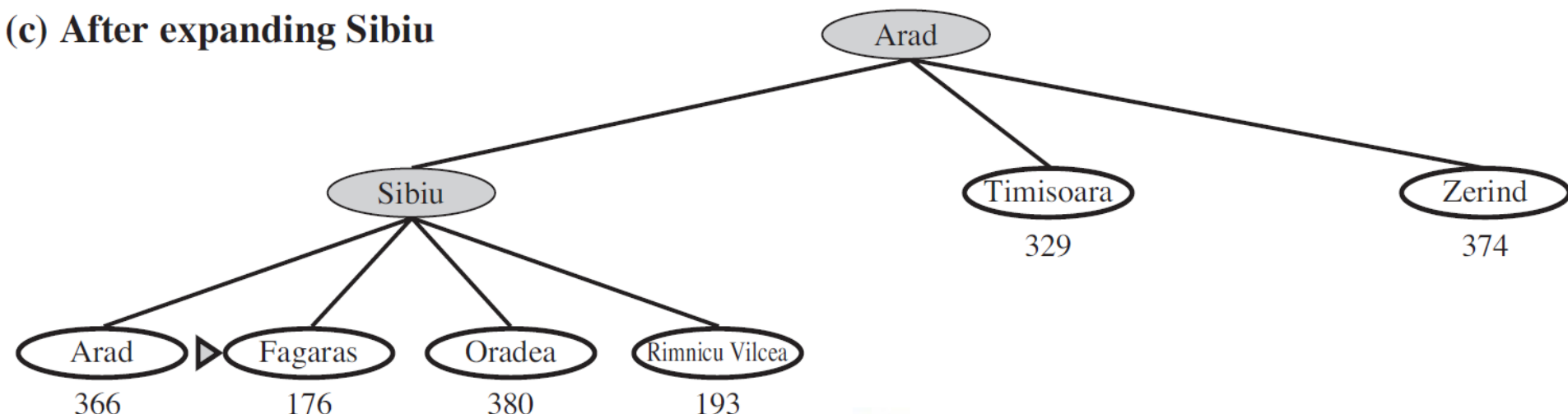


Figure A simplified road map of part of Romania.

Greedy best-first search: An example

(c) After expanding Sibiu



Arad	366	Mehadia	241
Bucharest	0	Neamt	234
Craiova	160	Oradea	380
Drobeta	242	Pitesti	100
Eforie	161	Rimnicu Vilcea	193
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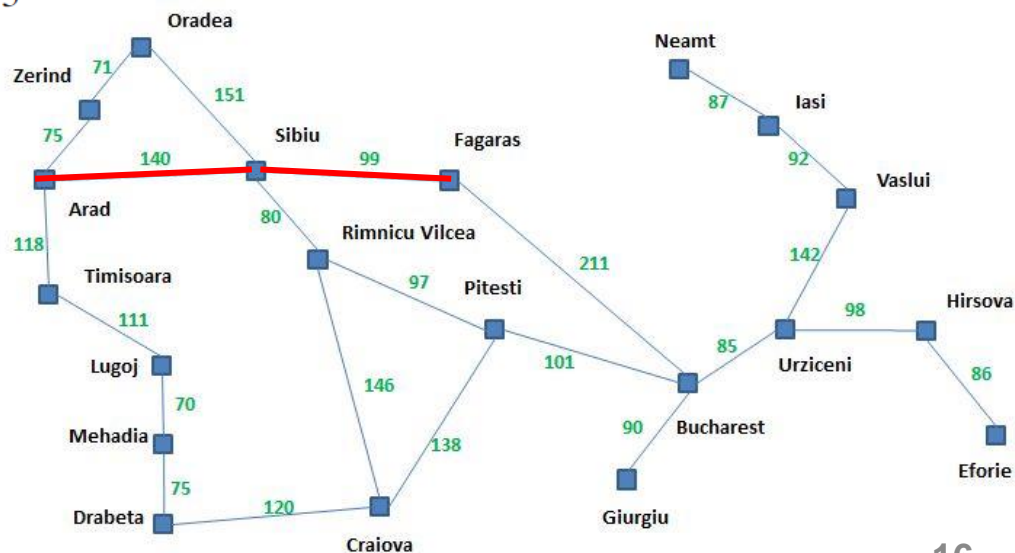
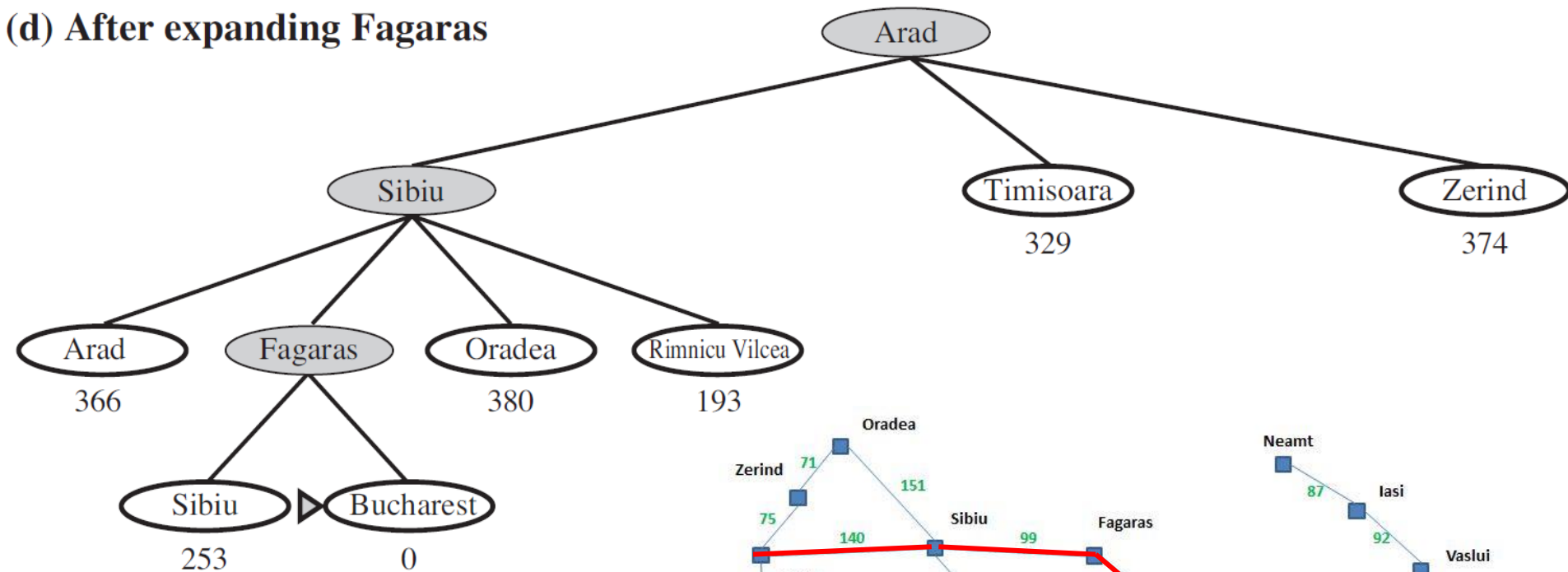


Figure A simplified road map of part of Romania.

Greedy best-first search: An example

(d) After expanding Fagaras



Arad	366	Mehadia	241
Bucharest	0	Neamt	234
Craiova	160	Oradea	380
Drobeta	242	Pitesti	100
Eforie	161	Rimnicu Vilcea	193
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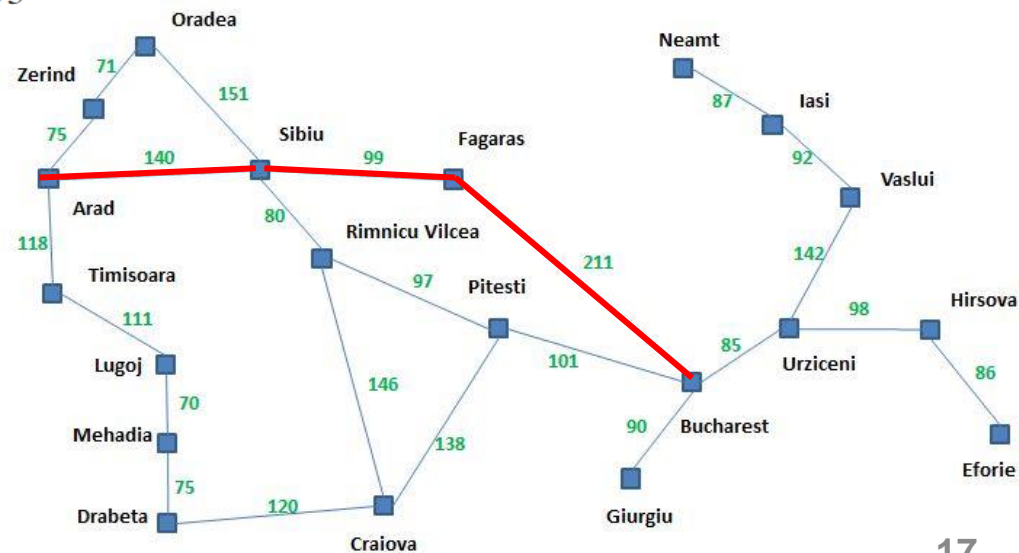


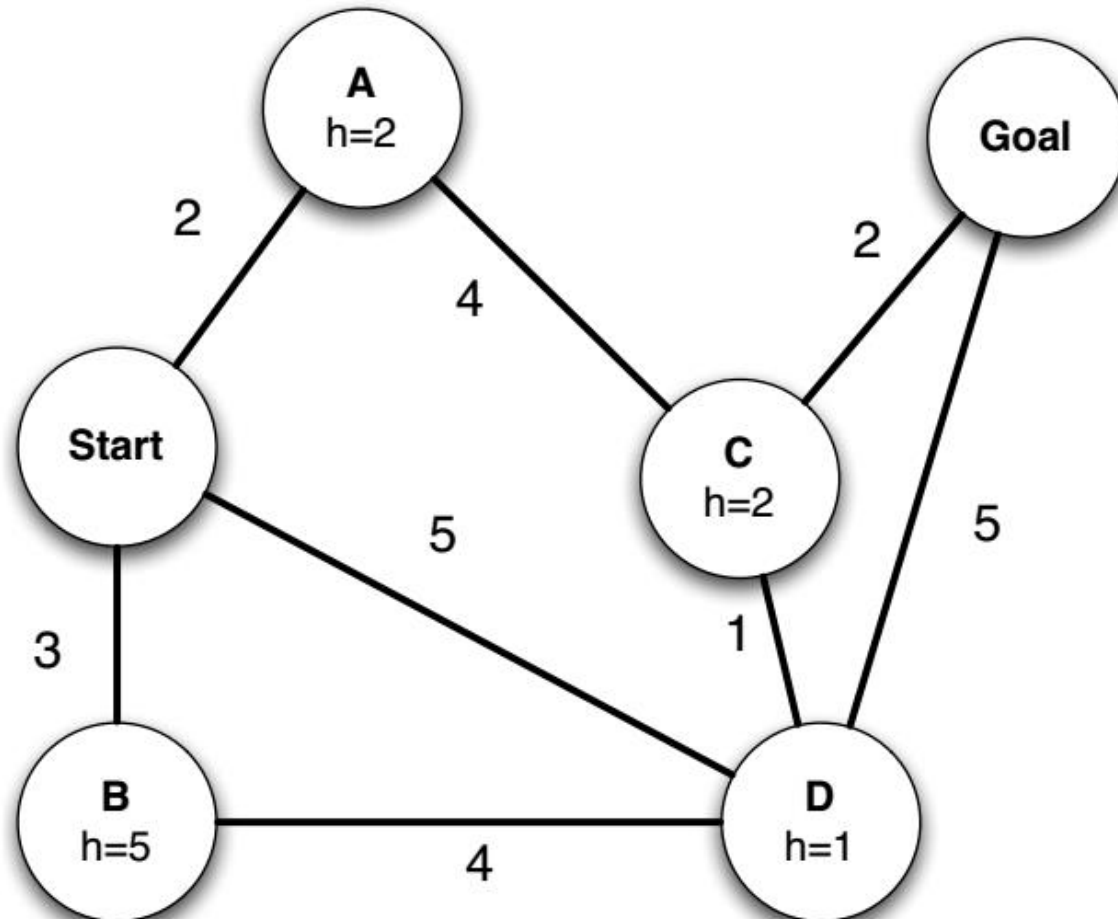
Figure A simplified road map of part of Romania.

An evaluation of GBFS (graph-search)

- Completeness
 - YES – if it is a graph-search instance in finite state spaces
- Time complexity
 - $O(b^m)$ → reduced substantially with a good heuristic
- Space complexity
 - $O(b^m)$ – keeps all nodes in memory
- Optimality
 - NO

Quiz 01: Greedy best-first search

- Work out the order in which states are expanded, as well as the path returned by graph search. Assume ties resolve in such a way that states with earlier alphabetical order are expanded first.



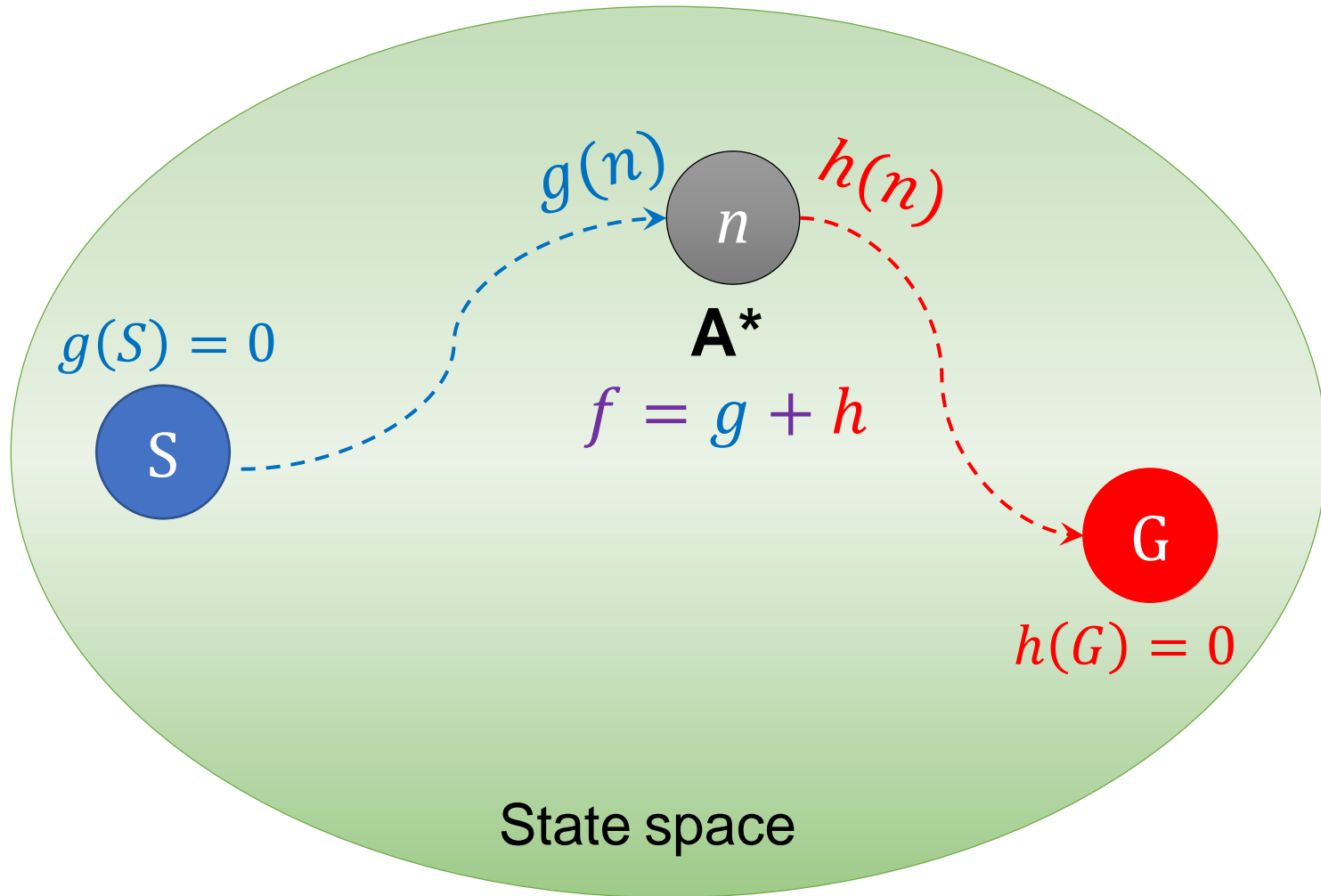
A* Search



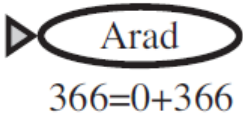
A* search

- The most widely known form of best-first search
- Use heuristic to guide search, but not only
- Avoid expanding paths that are already expensive
- Ensure to compute a path with minimum cost
- Evaluate nodes by $f(n) = g(n) + h(n)$
 - where $g(n)$ is the cost to reach the node n and $h(n)$ is the cost to get from n to the goal
 - $f(n)$ = estimated cost of the cheapest solution through n

A* search



(a) The initial state



$f = g + h$

Arad	366	Mehadia	241
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Iasi	226	Vaslui	199
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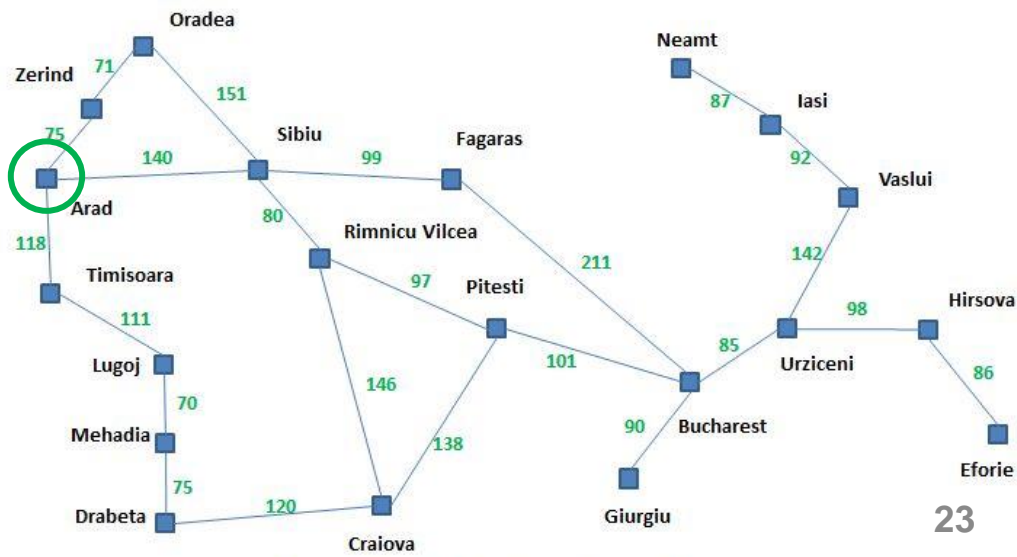
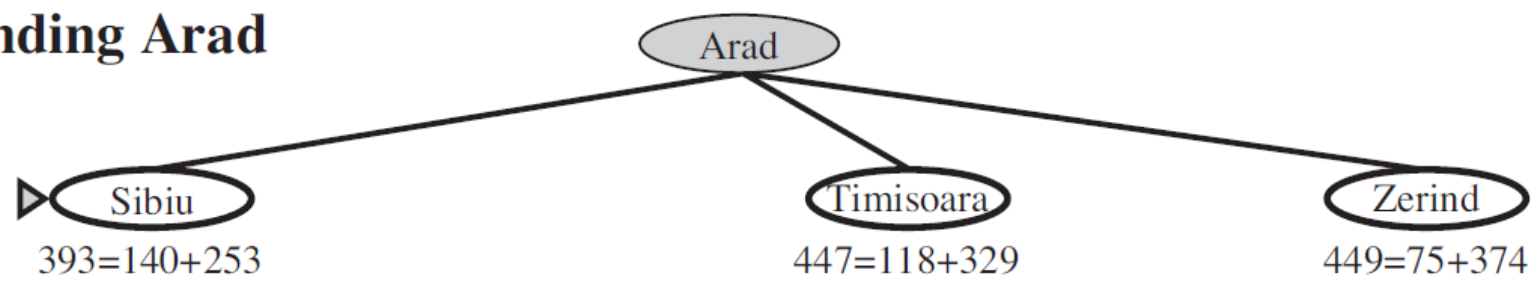


Figure A simplified road map of part of Romania.

(b) After expanding Arad



Arad	366	Mehadia	241
Bucharest	0	Neamt	234
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Drobeta	242	Pitesti	100
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Giurgiu	77	Timisoara	329
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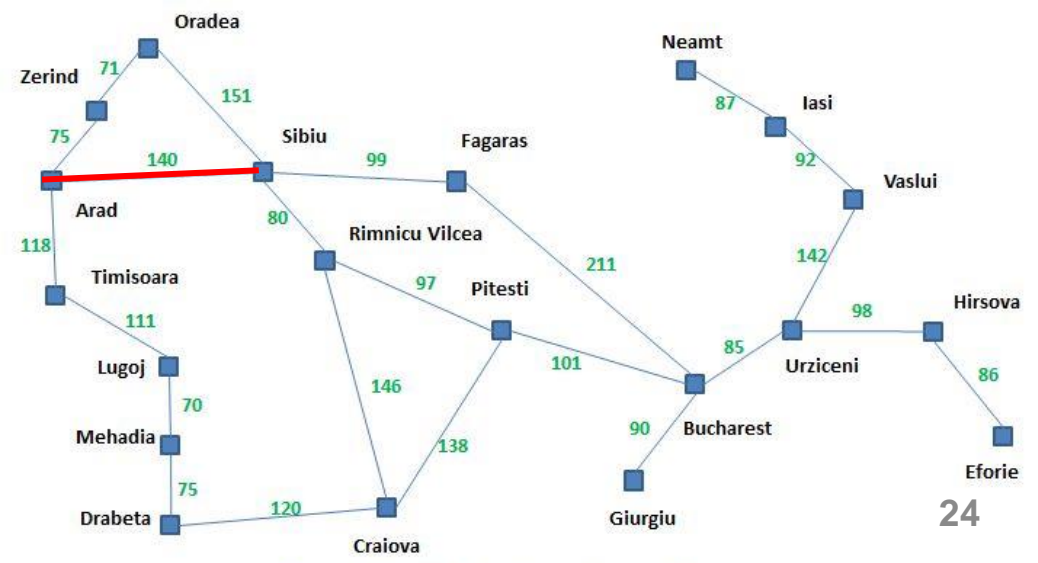
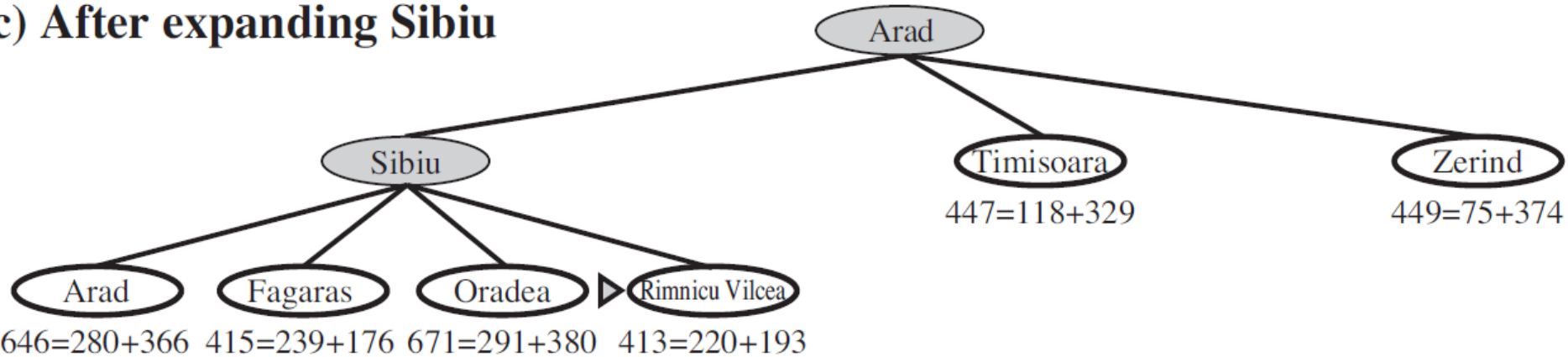


Figure A simplified road map of part of Romania.

(c) After expanding Sibiu



h

Arad	366	Mehadia	241
Bucharest	0	Neamt	234
Craiova	160	Oradea	380
Drobeta	242	Pitesti	100
Eforie	161	Rimnicu Vilcea	193
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Lugoj	244	<u>Zerind</u>	374

g

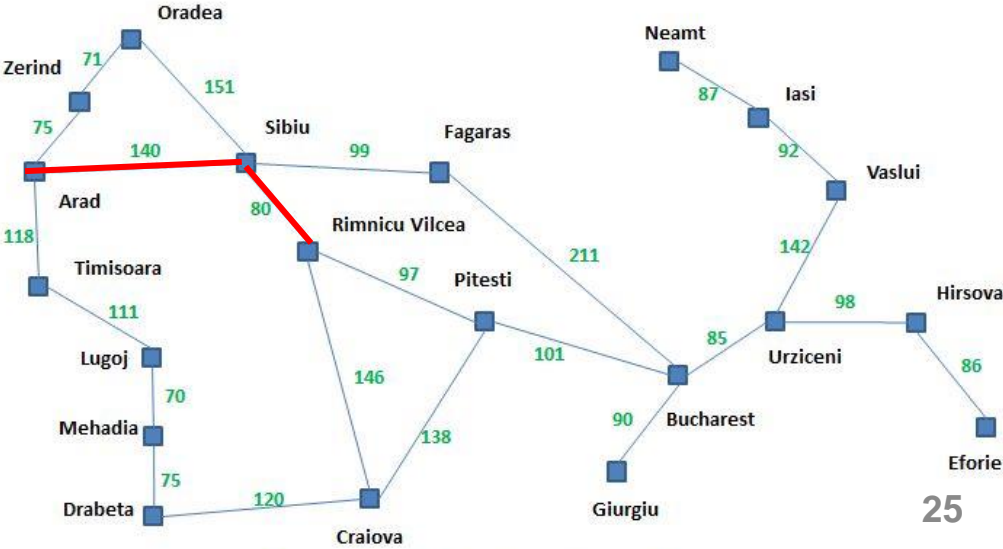
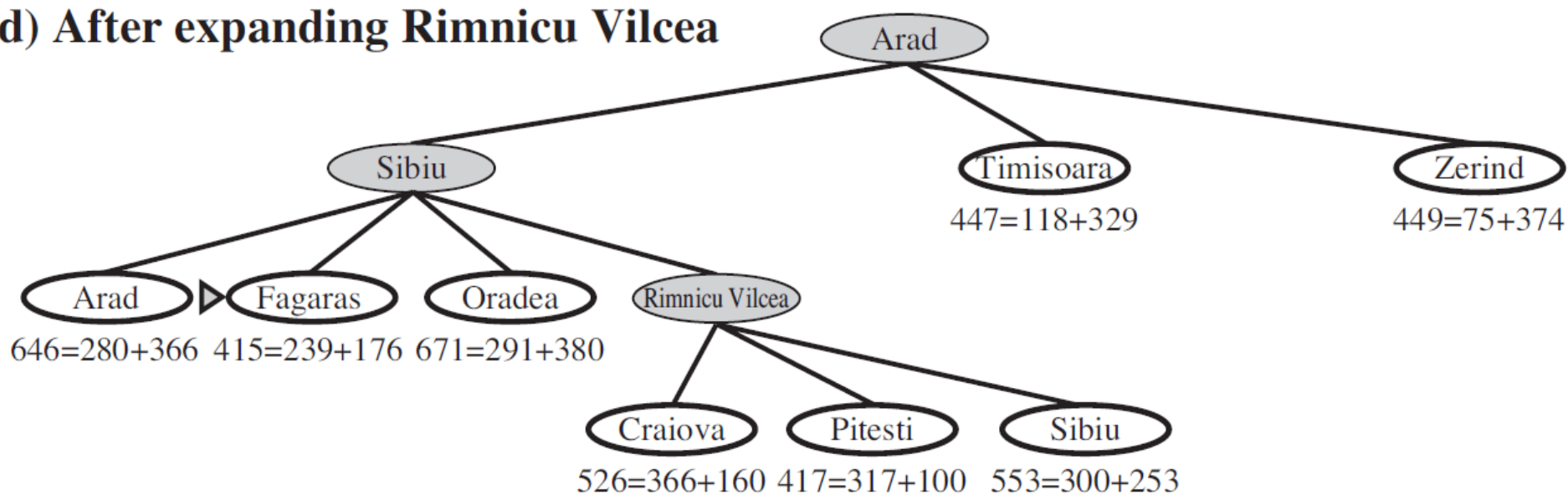
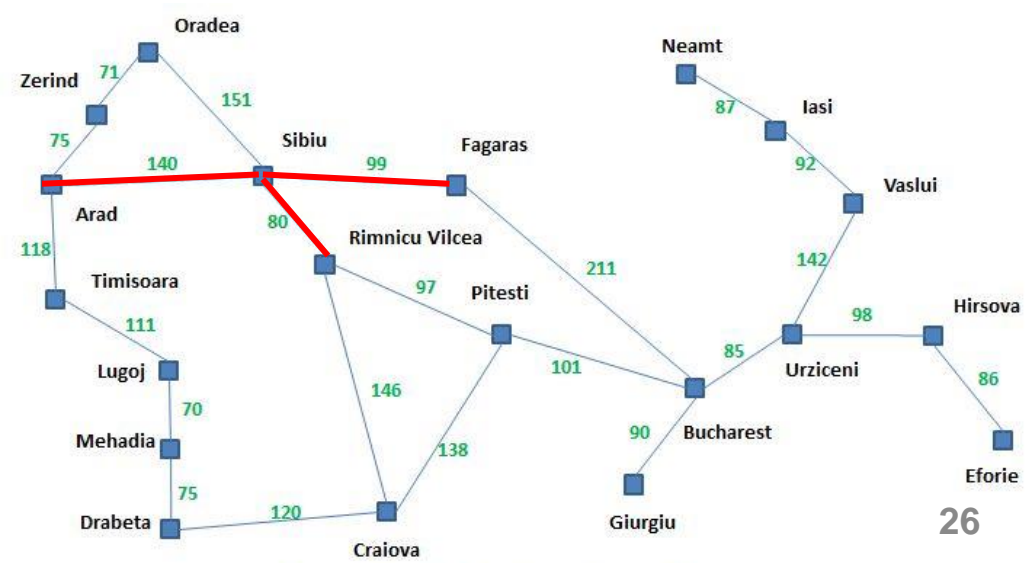


Figure A simplified road map of part of Romania.

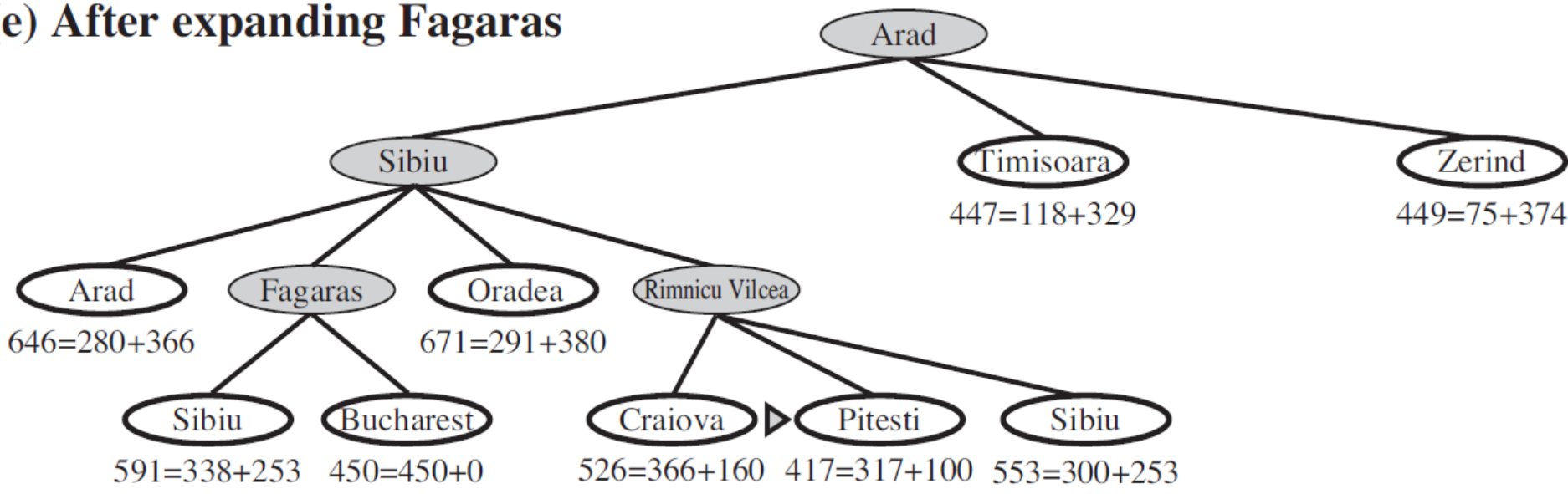
(d) After expanding Rimnicu Vilcea



Arad	366	Mehadia	241
Bucharest	0	Neamt	234
Craiova	160	Oradea	380
Drobeta	242	Pitesti	100
Eforie	161	Rimnicu Vilcea	193
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(e) After expanding Fagaras



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Drobeta	242	Pitesti	100
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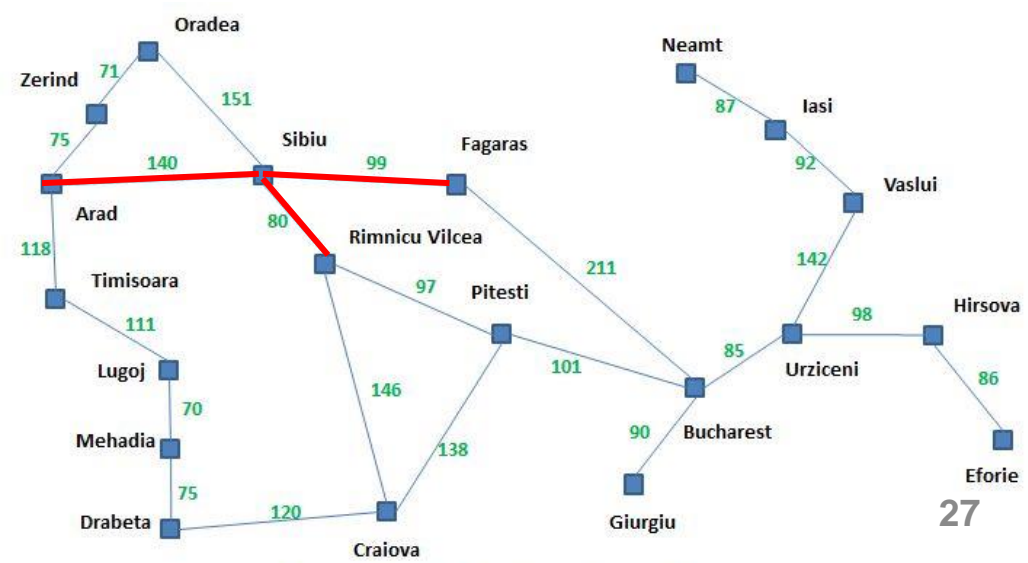
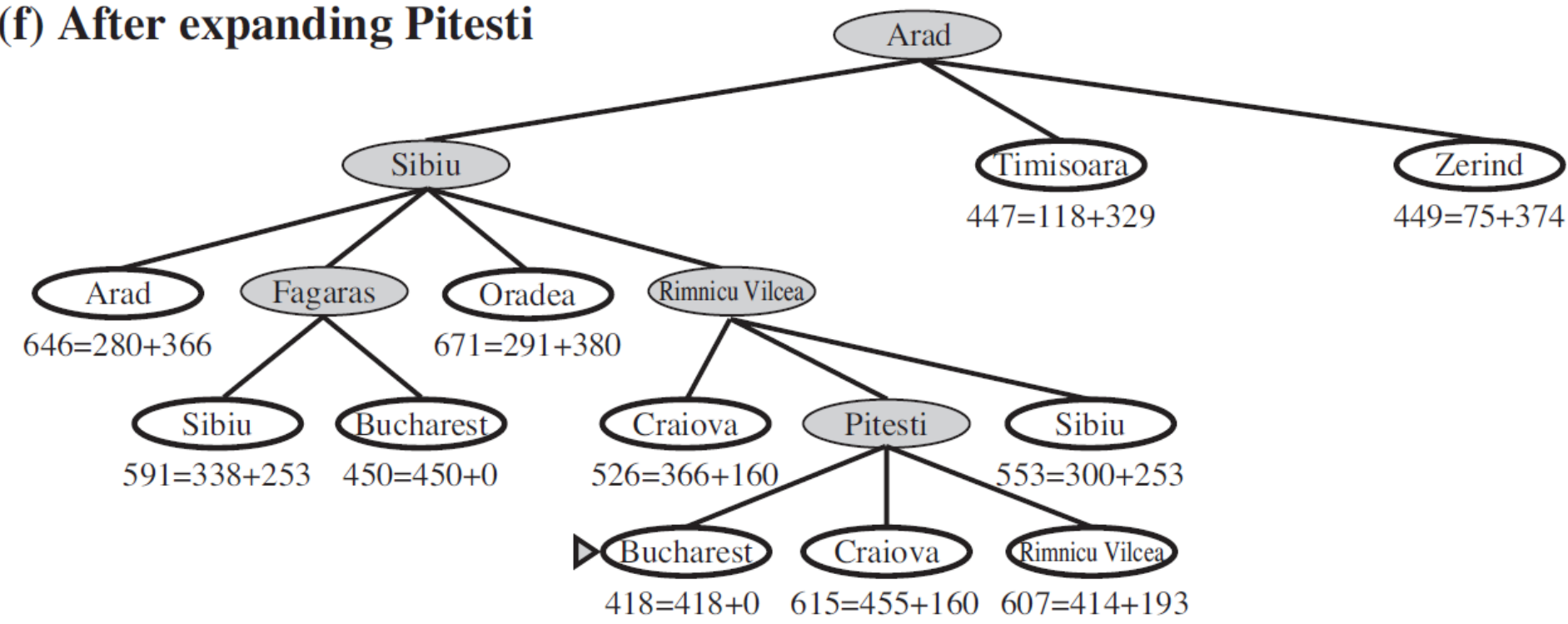


Figure A simplified road map of part of Romania.

(f) After expanding Pitesti



Arad	366	Mehadia	241
Bucharest	0	Neamt	234
Craiova	160	Oradea	380
Drobeta	242	Pitesti	100
Eforie	161	Rimnicu Vilcea	193
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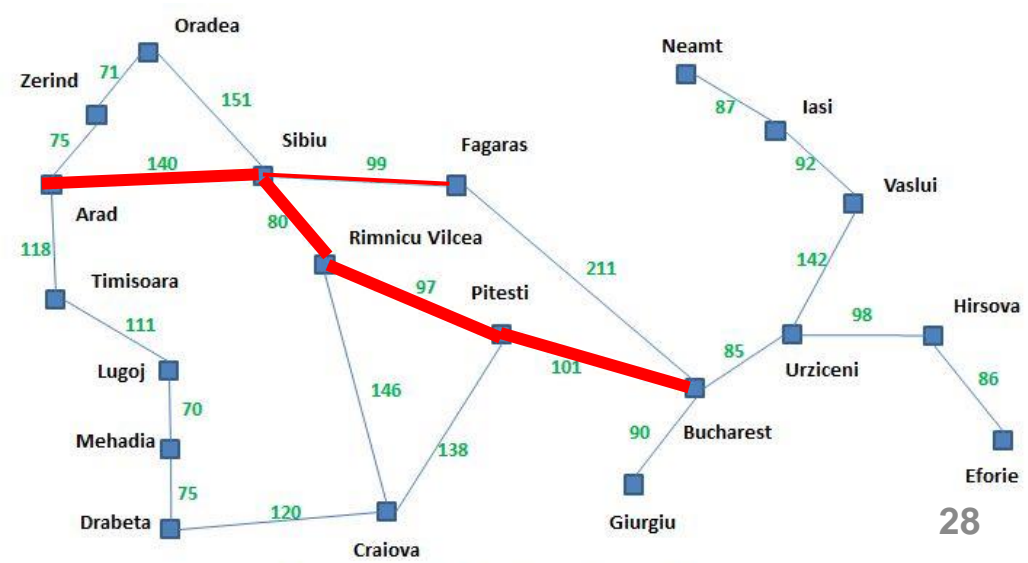


Figure A simplified road map of part of Romania.

An evaluation of A* (graph-search)

- Completeness

- YES if all step costs exceed some finite ϵ and if b is finite
- (review the condition for completeness of UCS)

- Optimality

- YES – with conditions on heuristic being used

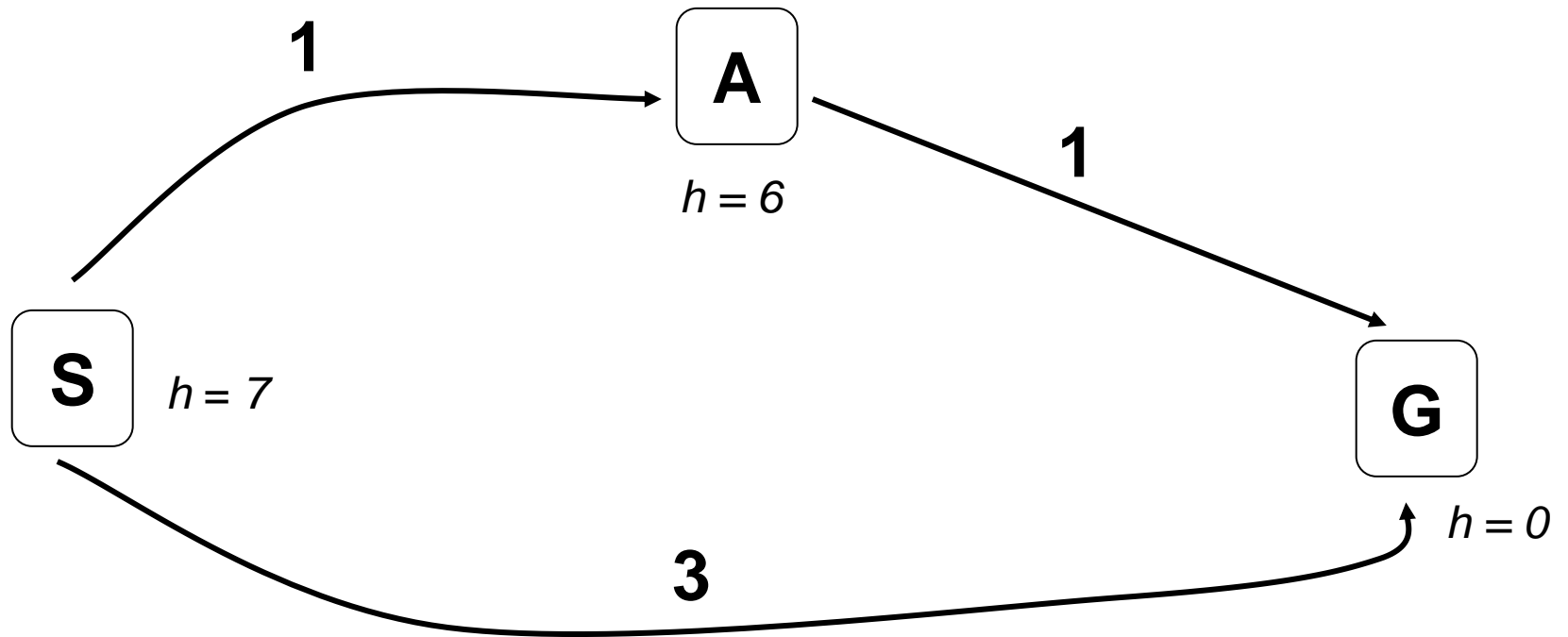
- Time complexity

- Exponential

- Space complexity

- Exponential (keep all nodes in memory)

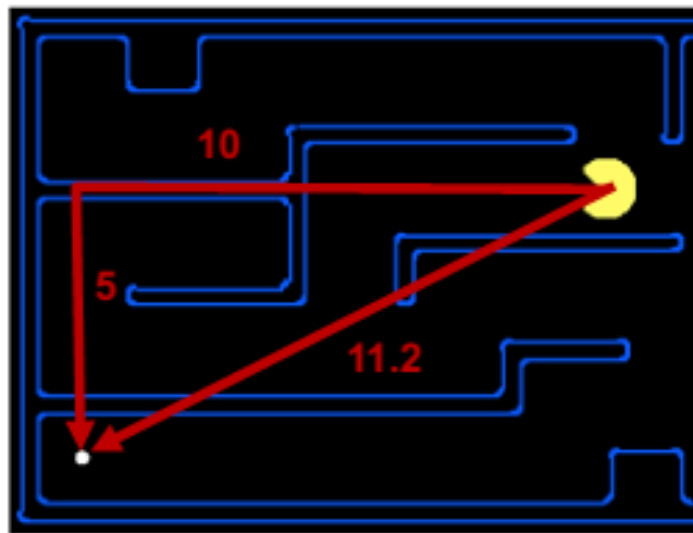
A* is not always optimal...



In what conditions, A* is optimal?

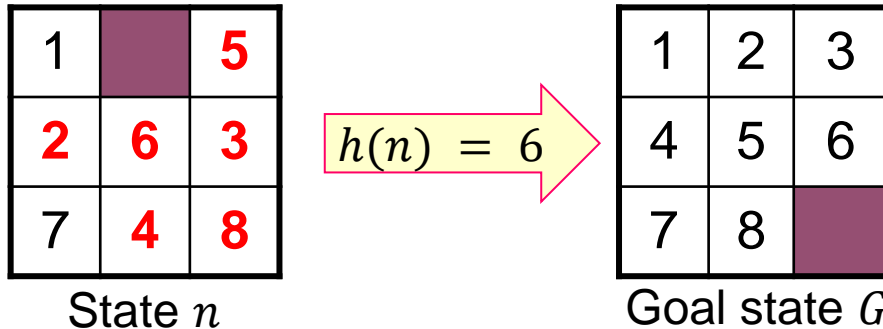
Conditions for optimality: Admissibility

- $h(n)$ must be an **admissible heuristic**
 - Never overestimate the cost to reach the goal → **optimistic**
 - E.g., the straight-line distance h_{SLD}

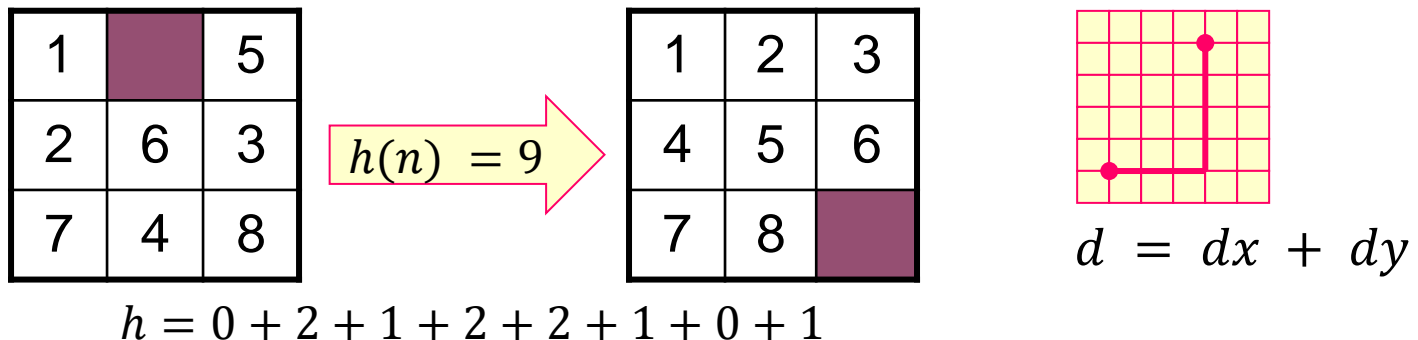


Admissible heuristics for 8-puzzle

- $h(n)$ = number of misplaced numbered tiles

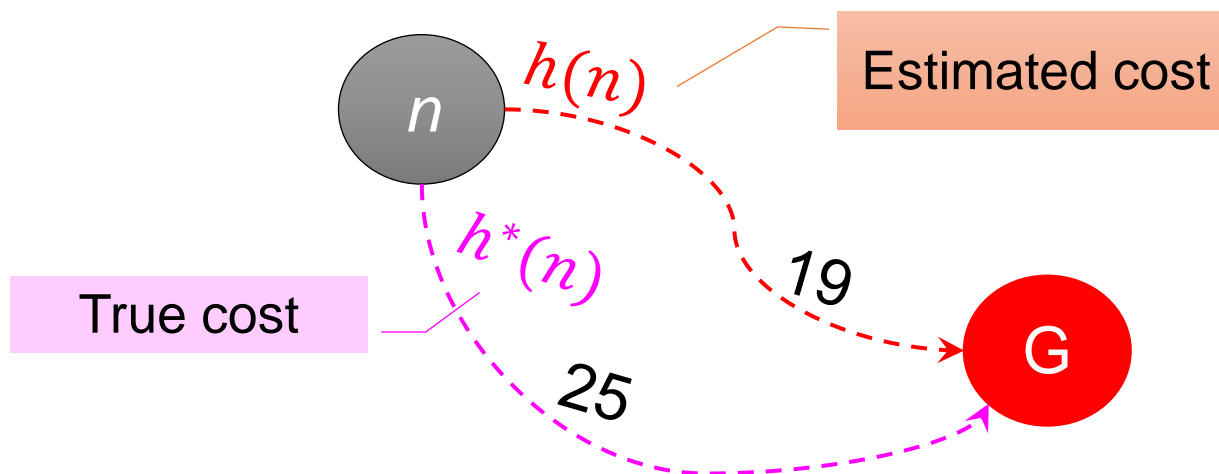


- $h(n)$ = sum of the (Manhattan) distance of every numbered tile to its goal position



Conditions for optimality: Admissibility

- $h(n)$ 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



- Hence, $f(n)$ never overestimates the true cost of a solution along the current path through n .
 - $g(n)$ is the **actual** cost to reach n along the current path

Conditions for optimality: Admissibility

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

- 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 .

- $f(G_2) = g(G_2)$ since $h(G_2) = 0$
- $g(G_2) > g(G)$ since G_2 is suboptimal
- $f(G) = g(G)$ since $h(G) = 0$

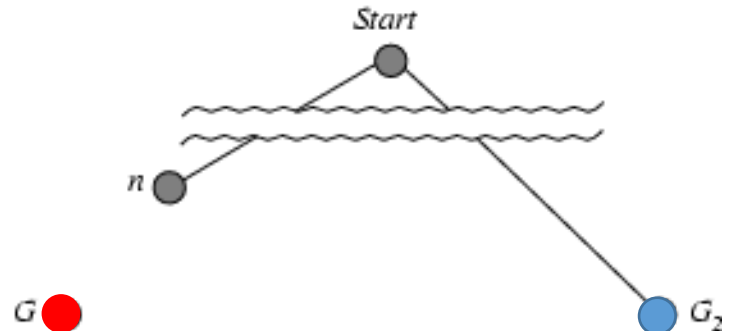
$$f(G_2) > f(G) \quad (1)$$

- $h(n) \leq h^*(n)$ since h is admissible

- $g(n) + h(n) \leq g(n) + h^*(n)$

$$f(n) \leq f(G) \quad (2)$$

- From (1), (2): $f(G_2) > f(n) \rightarrow A^*$ will never select G_2 for expansion

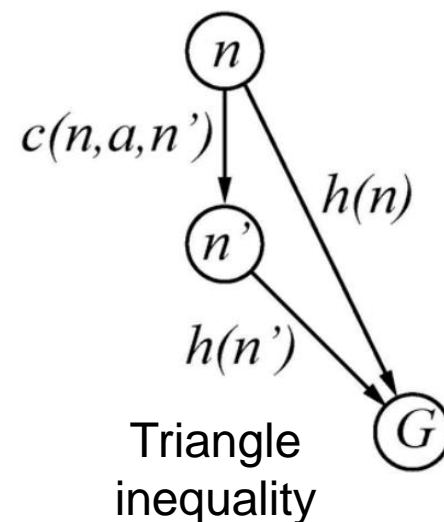


Conditions for optimality: Consistency

- Admissibility is insufficient for graph search.
 - The optimal path to a repeated state could be discarded if it is not the first one selected.
- $h(n)$ is **consistent** if for every node n , every successor n' of n generated by any action a ,

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

- Every consistent heuristic is also admissible.



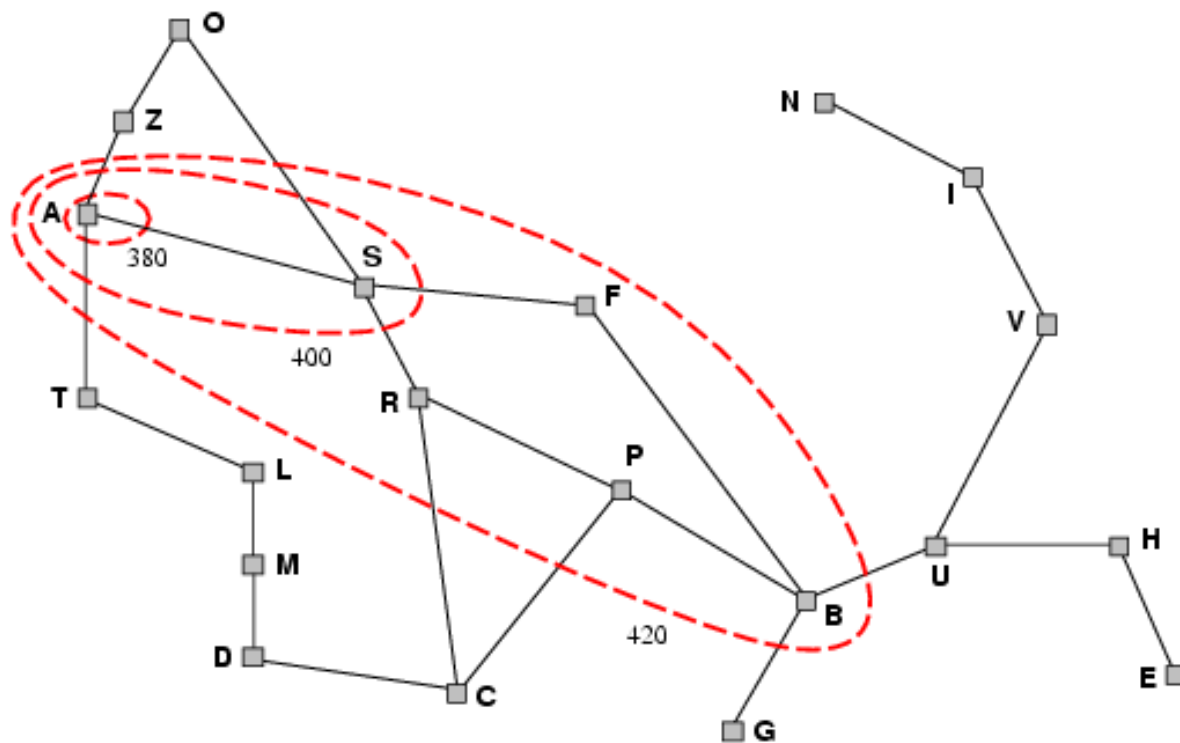
Conditions for optimality: Consistency

If $h(n)$ is consistent, A^* using **GRAPH-SEARCH** is optimal

- If $h(n)$ is consistent, the values of $f(n)$ along any path are non-decreasing.
 - Suppose n' is a successor of $n \rightarrow g(n') = g(n) + c(n, a, n')$
 - $f(n') = g(n') + h(n') = g(n) + c(n, a, n') + h(n') \geq g(n) + h(n) = f(n)$
- Whenever A^* selects a node n for expansion, the optimal path to that node has been found.
 - Proof by contradiction: There would have to be another frontier node n' on the optimal path from the start node to n (by the graph separation property)
 - f is nondecreasing along any path $\rightarrow f(n') < f(n) \rightarrow n'$ would have been selected first

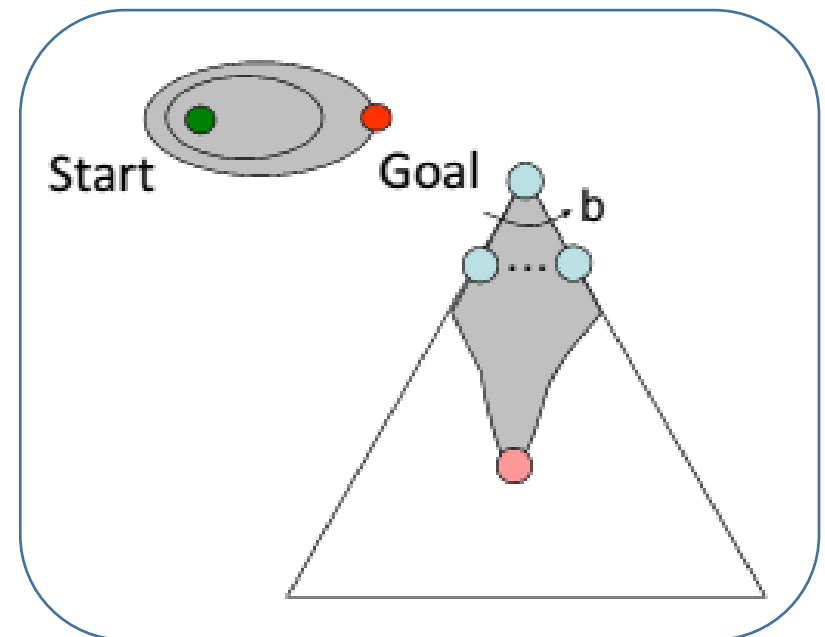
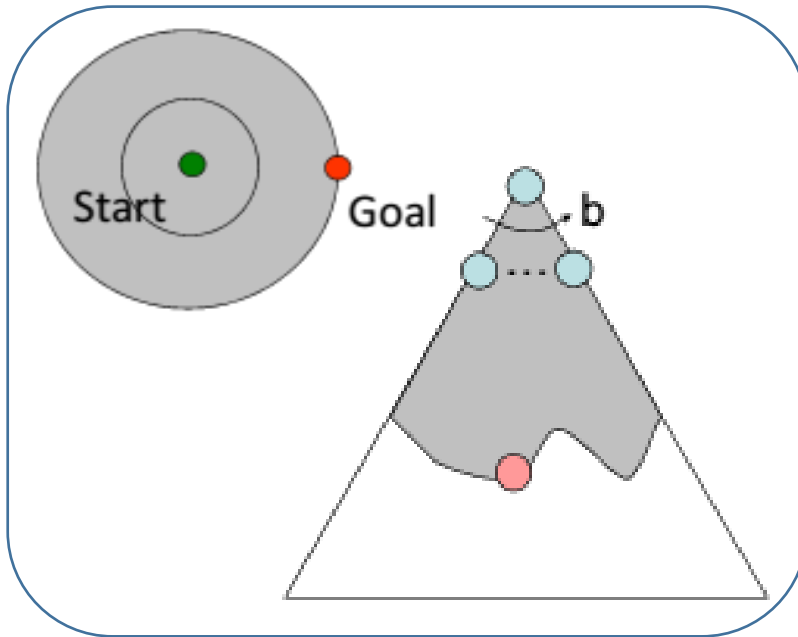
Contours of A* search

- A* expands nodes in order of increasing f -value
- Gradually adds " f -contours" of nodes such that contour i has all nodes with $f = f_i$ where $f_i < f_{i+1}$
- A* will expand all nodes with costs $f(n) < C^*$



A* contours vs. UCS contours

- The bands of UCS will be “circular” around the start state.



- The bands of A*, with more accurate heuristics, will stretch toward the goal state and become more narrowly focused around the optimal path.

Comments on A*: The good

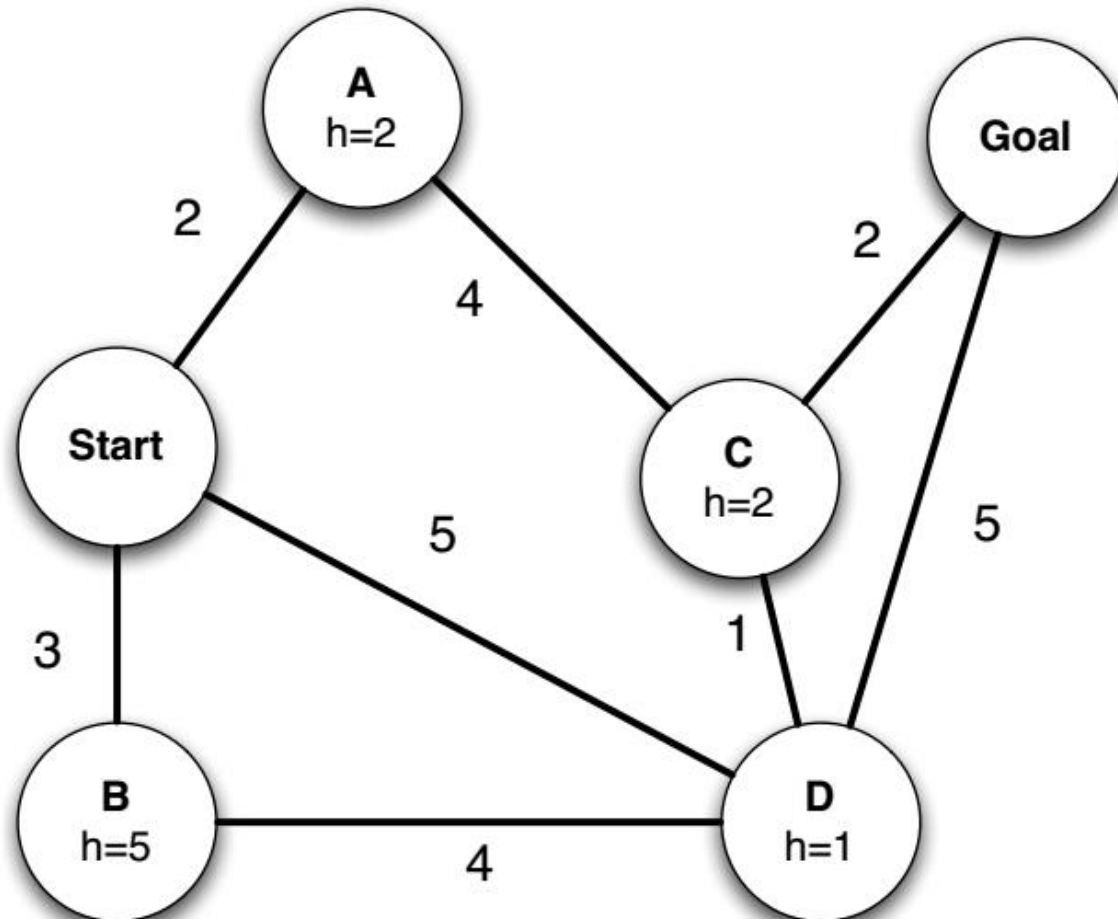
- Never expand nodes with $f(n) > C^*$
 - All nodes like these are pruned while still guaranteeing optimality
- Optimally efficient for any given consistent heuristic
 - No other optimal algorithm is guaranteed to expand fewer nodes

Comments on A*: The bad

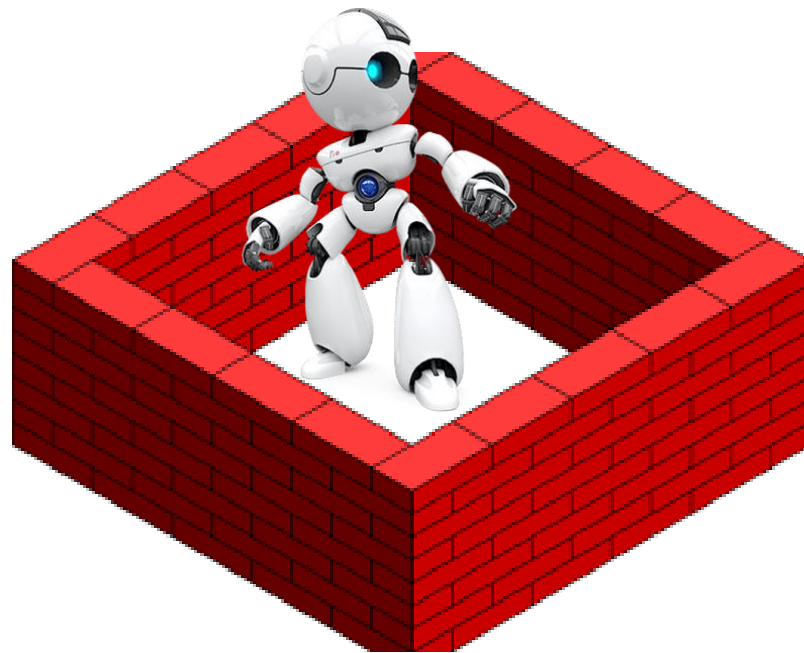
- A* expands all nodes with $f(n) < C^*$ (and possibly some nodes with $f(n) = C^*$) with before selecting a goal node.
 - This can still be exponentially large
 - A* usually runs out of space before it runs out of time
 - Exponential growth will occur unless error in $h(n)$ grows no faster than $\log(\text{true path cost})$
 - In practice, error is usually proportional to true path cost (not log)
 - So exponential growth is common
- Not practical for many large-scale problems

Quiz 02: A*

- Work out the order in which states are expanded, as well as the path returned by graph search. Assume ties resolve in such a way that states with earlier alphabetical order are expanded first.

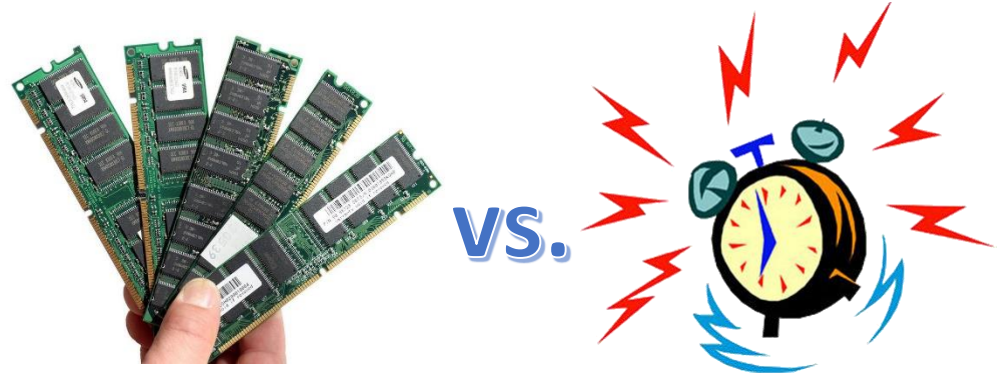


Memory-bounded heuristic search



Memory-bound heuristic search

- In practice, A^* usually runs out of space long before it runs out of time.



- **Idea:** try something like DFS, but not forget everything about the branches we have partially explored

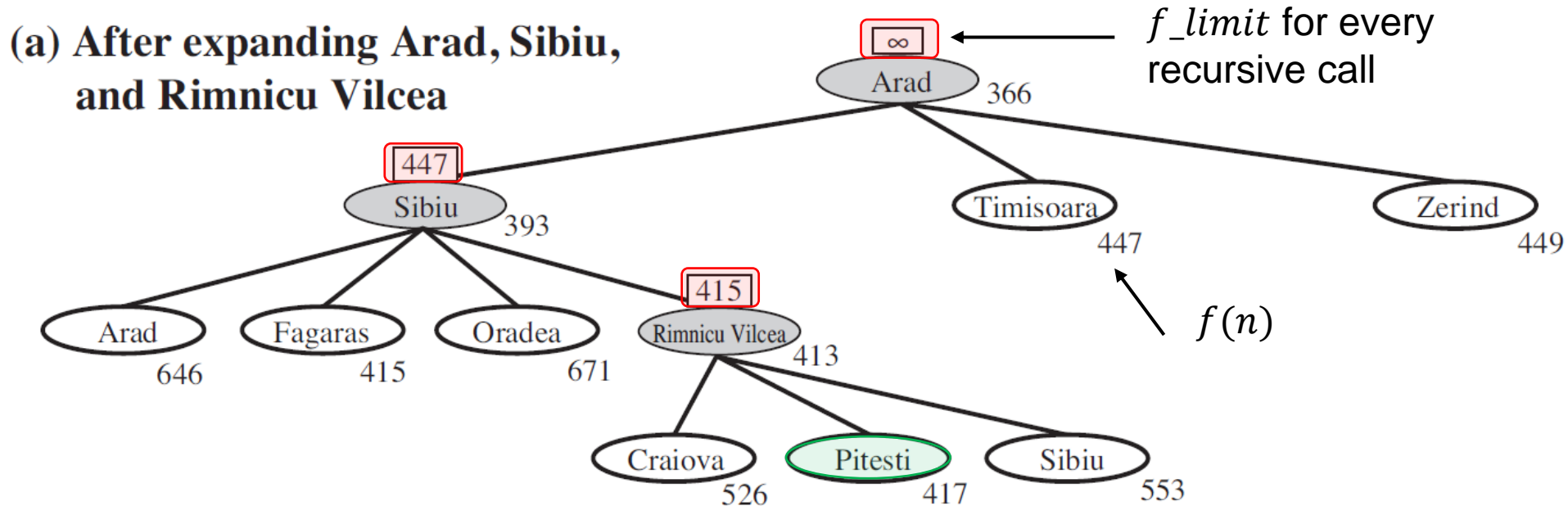
Iterative-deepening A* (IDA*)

- The main difference with IDS
 - **Cut-off** use the **f -value** ($g + h$) rather than the depth =>save memory
 - At each iteration, the cutoff value is the smallest f -value of any node that exceeded the cutoff on the previous iteration
- Avoid the substantial overhead associated with keeping a sorted queue of nodes.
- Practical for many problems with **unit step costs**, yet difficult with **real valued costs**

Recursive best-first search (RBFS)

- Keep track of the f -value of the **best alternative path** available from any ancestor of the current node
 - backtrack when the current node exceeds f_limit
- As it backtracks, replace the f -value of each node along the path with the best $f(n)$ value of its children

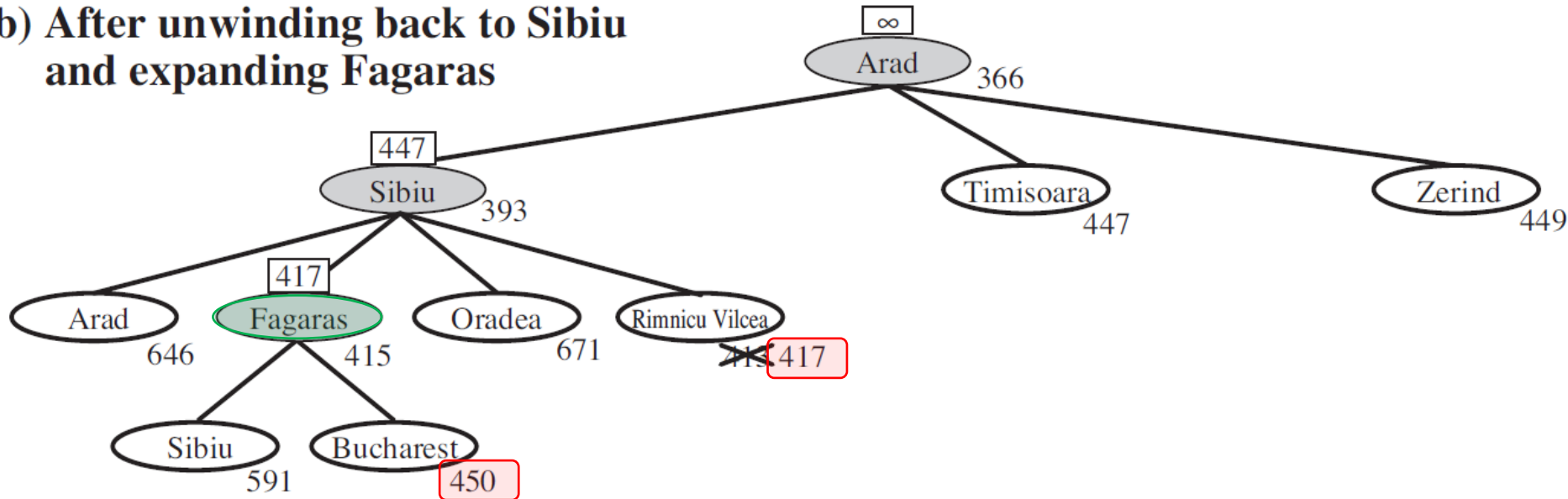
RBFS: An example



- Path until Rimnicu Vilcea is already expanded
- The path is followed until Pitesti, whose f -value worse than the f -limit

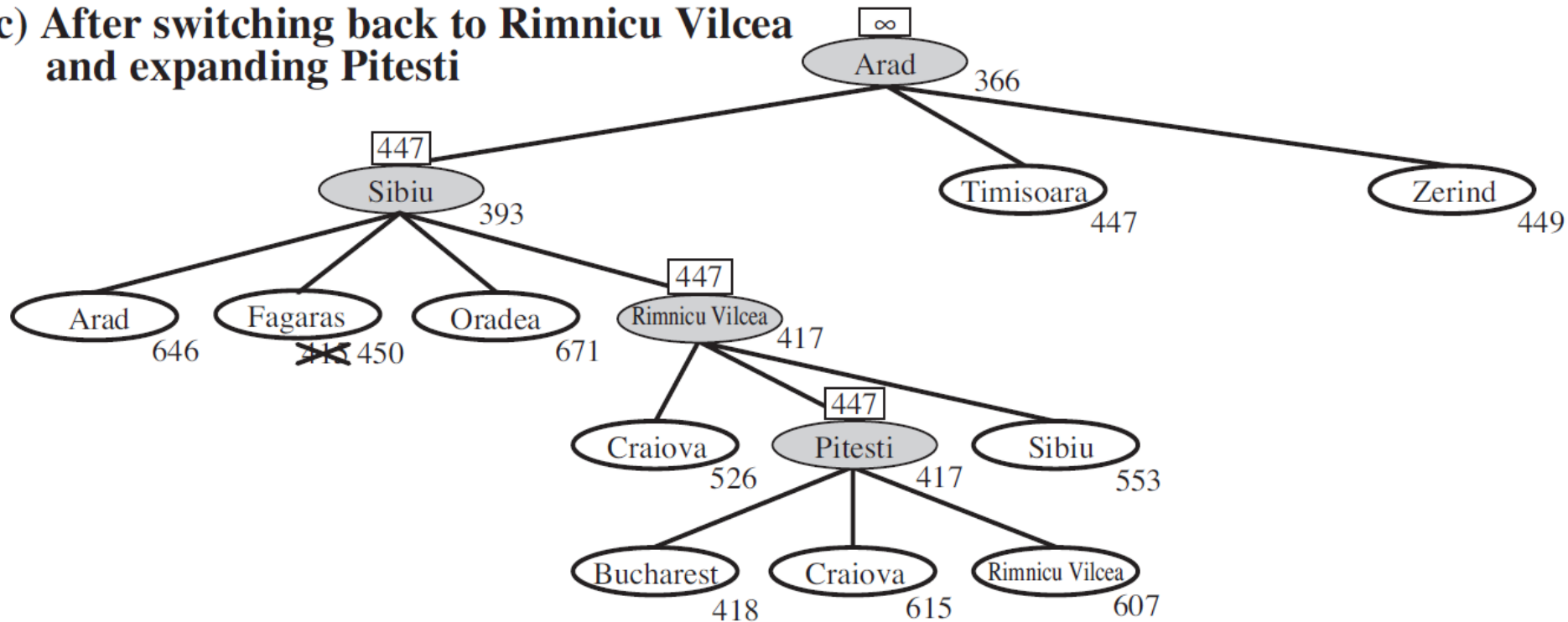
Recursive best-first search (RBFS)

(b) After unwinding back to Sibiu and expanding Fagaras



- Unwind recursion and store best f -value for current best leaf Rimnicu Vilcea
 - $result, best.f \leftarrow RBFS(problem, best, \min(f_limit, alternative))$
- $best$ is now **Fagaras**. Call RBFS for new $best$
 - $best$ value is now 450

(c) After switching back to Rimnicu Vilcea and expanding Pitesti



- Unwind recursion and store best f -value for current best leaf of Fagaras
 - $result, best.f \leftarrow RBFS(problem, best, \min(f_limit, alternative))$
- $best$ is now **Rimnicu Viclea** (again). Call RBFS for new $best$
 - Subtree is again expanded
 - Best alternative subtree is now through Timisoara
- Solution is found since because $447 > 418$.

Recursive best-first search (RBFS)

function RECURSIVE-BEST-FIRST-SEARCH(*problem*) **returns** a solution, or failure
return RBFS(*problem*, MAKE-NODE(*problem*.INITIAL-STATE), ∞)

function RBFS(*problem*, *node*, *f_limit*) **returns** a solution, or failure and a new *f*-cost limit
if *problem*.GOAL-TEST(*node*.STATE) **then return** SOLUTION(*node*)
successors \leftarrow []
for each *action* **in** *problem*.ACTIONS(*node*.STATE) **do**
 add CHILD-NODE(*problem*, *node*, *action*) into *successors*
if *successors* is empty **then return** failure, ∞
for each *s* **in** *successors* **do** /* update *f* with value from previous search, if any */
 s.f \leftarrow max(*s.g*+*s.h*, *node.f*)
loop do
 best \leftarrow the lowest *f*-value node in *successors*
 if *best.f* > *f_limit* **then return** failure, *best.f*
 alternative \leftarrow the second-lowest *f*-value among *successors*
 result, *best.f* \leftarrow RBFS(*problem*, *best*, min(*f_limit*, *alternative*))
 if *result* \neq failure **then return** *result*

Evaluation of RBFS

- Optimality

- Like A^* , optimal if $h(n)$ is admissible

- Time complexity

- Difficult to characterize
- Depends on accuracy of $h(n)$ and how often best path changes
- Can end up “switching” back and forth

- Space complexity

- Linear time: $O(bd)$
- Other extreme to A^* - uses **too little** memory even if more memory were available

(Simplified) Memory-bound A^* – (S)MA *

- Like A^* , but **delete the worst node** (largest f -value) when memory is full
- Also backs up the value of the forgotten node to its parent
 - If there is a tie (equal f -values), delete the oldest nodes first
- Find an **optimal reachable solution** given memory constraint
 - The depth of the shallowest goal node is less than the memory size (expressed in nodes).
- Time can still be exponential.

Learning to search better

- *Could an agent learn how to search better?* **YES**
- **Metalevel state space:** in which each state captures the internal (computational) state of a program that is searching in an **object-level state space**.
- For example, the map of Romania problem,
 - The internal state of the A* algorithm is the current search tree.
 - Each action in the metalevel state space is a computation step that alters the internal state, e.g., [expands a leaf node and adds its successors to the tree]

Learning to search better

- The expansion of Fagaras is not helpful → harder problems may even include more such missteps

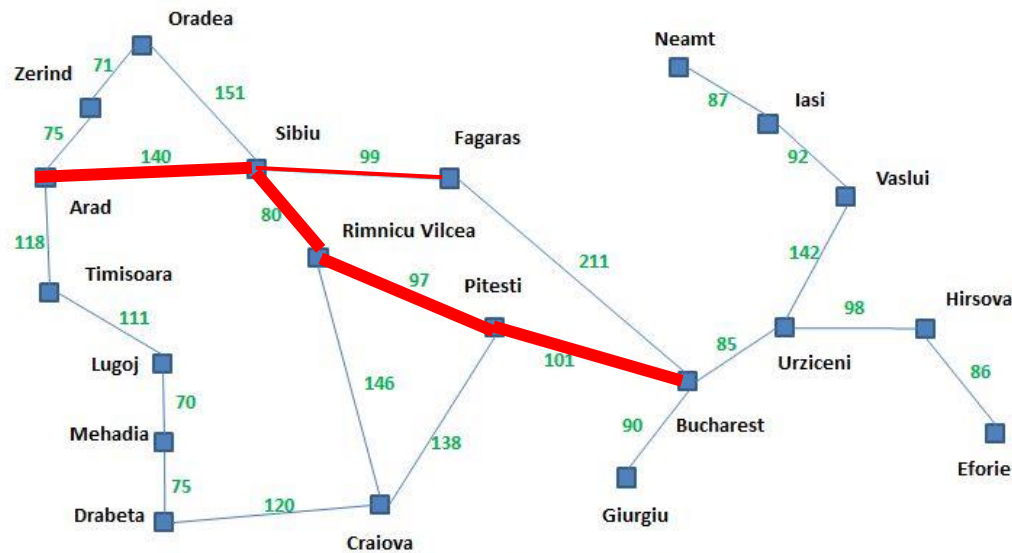


Figure A simplified road map of part of Romania.

- A metalevel learning algorithm gains from these experiences to avoid exploring unpromising subtrees
→ reinforcement learning

The 8-puzzle problem

7	2	4
5		6
8	3	1

	1	2
3	4	5
6	7	8

A typical instance of the 8-puzzle. The solution is 26 steps long.

- Average solution cost: about 22 steps, branching factor ~ 3 .
- 8-puzzle: $9!/2 = 181,440$ reachable states
- 15-puzzle: 1.05×10^{13} possible states

Admissible heuristics for 8-puzzle

- $h_1(n)$ = number of **misplaced** numbered tiles (Hamming distance)

8	1	3
4		2
7	6	5

board

1	2	3	4	5	6	7	8
×	×	✓	✓	×	×	✓	×

1	2	3	4	5	6	7	8
1	2	0	0	2	2	0	3

Hamming = 5

Manhattan = 10
(1 + 2 + 2 + 2 + 3)

1	2	3
4	5	6
7	8	

goal

<= real distance => admissible

<= real distance => admissible

- $h_2(n)$ = sum of the (**Manhattan**) distance of every numbered tile to its goal position

$$0 \leq h_1 < h_2 < h^*$$

0: UCS -> chậm nhất

càng gần h^* thì càng nhanh => h_2 tốt hơn h_1

Quiz 03: Admissible heuristics

real distance

- Knowing that $h(n) \leq h^*(n)$
- For 8-puzzle, which of the following heuristics is admissible? ^(A)

- $h_1(n)$ = total number of misplaced tiles ^(A)
- $h_2(n)$ = total Manhattan distance ^(A)
- $h_3(n) = 0$ ^(A) \Rightarrow UCS: slow
- $h_4(n) = 1$ non-admissible (goal: 0)
- $h_5(n) = h^*(n)$ ^(A)
- $h_6(n) = \min(2, h^*(n))$ ^(A)
- $h_7(n) = \max(2, h^*(n))$ ^(non-A)

The effect of heuristic on performance

hs phân nhánh => càng nhỏ càng tốt

- **Effective branching factor b^*** : the factor that a uniform tree of depth d would have to contain $N + 1$ nodes

$$N + 1 = 1 + b^* + (b^*)^2 + \dots + (b^*)^d$$

- where N is the total number of nodes generated by A^* for a particular problem and d is the solution depth
- E.g., A^* finds a solution at depth 5 using 52 nodes $\rightarrow b^* = 1.92$
- b^* varies across problem instances, but fairly constant for sufficiently hard problems
- A well-designed heuristic would have a value of b^* close to 1
 \rightarrow fairly large problems solved at reasonable cost

Search cost vs. Branching factor

d	Search Cost (nodes generated)			Effective Branching Factor		
	IDS	$A^*(h_1)$	$A^*(h_2)$	IDS	$A^*(h_1)$	$A^*(h_2)$
2	10	6	6	2.45	1.79	1.79
4	112	13	12	2.87	1.48	1.45
6	680	20	18	2.73	1.34	1.30
8	6384	39	25	2.80	1.33	1.24
10	47127	93	39	2.79	1.38	1.22
12	3644035	227	73	2.78	1.42	1.24
14	—	539	113	—	1.44	1.23
16	—	1301	211	—	1.45	1.25
18	—	3056	363	—	1.46	1.26
20	—	7276	676	—	1.47	1.27
22	—	18094	1219	—	1.48	1.28
24	—	39135	1641	—	1.48	1.26

Comparison of the search costs and effective branching factors for the ITERATIVE-DEEPENING-SEARCH and A^* algorithms with h_1 , h_2 . Data are averaged over 100 instances of the 8-puzzle for each of various solution lengths d .

Heuristic dominance

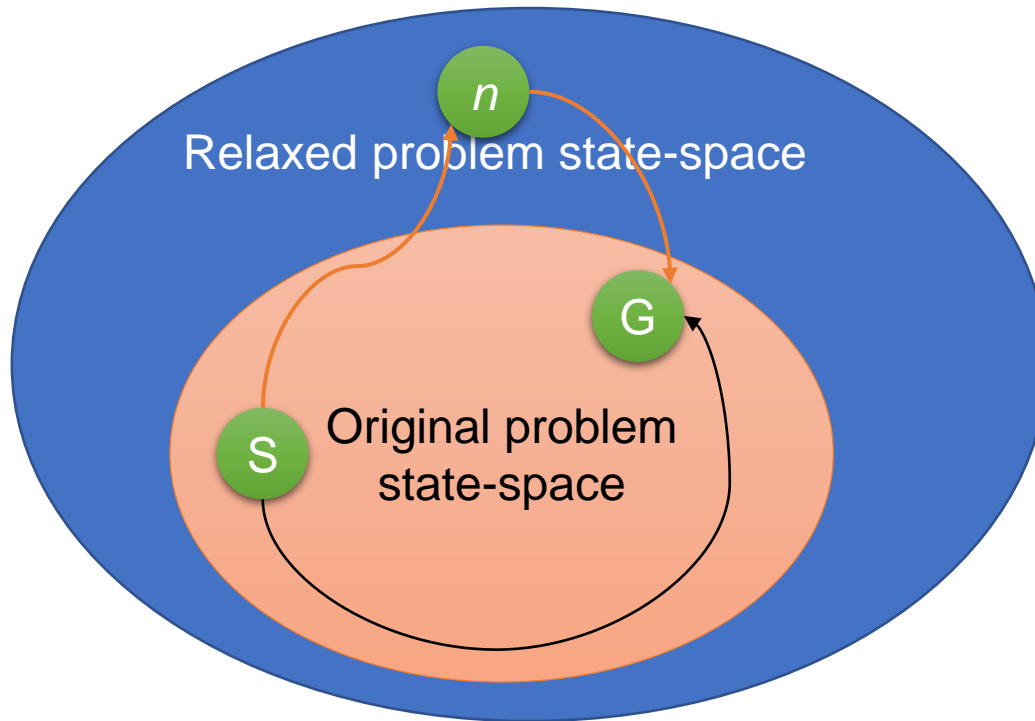
- Given two admissible heuristics, h_1 and h_2
- If $h_2(n) \geq h_1(n)$, for all n , then h_2 ^{áp đảo} **dominates** h_1
 - A* using h_2 will **never expand more nodes** than A* using h_1
- Better to use a heuristic function with **higher values**, provided it is **consistent** and its **computation time** is **not too long**.

How might one have come up with h_2 ?
Is it possible to invent such a heuristic mechanically?

Relaxed problems

loại bỏ 1 số ràng buộc: (vd 8puzzle: 2 ô kề, ô B là ô trống) => loại bỏ

- Problems with **fewer restrictions** on the actions



The state-space graph of the relaxed problem is a *supergraph* of the original state space

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

Relaxed problems of the 8-puzzle

- Original problem:
 - A tile can move from square A to square B if A is horizontally or vertically adjacent to B and B is blank
- Relaxed problems are generated by removing one or both conditions
 - A tile can move from square A to square B if A is adjacent to B.
 - A tile can move from square A to square B if B is blank.
 - A tile can move from square A to square B.

Misplaced
tiles

Manhattan
distance

It is **crucial** that the relaxed problems generated by this technique can be solved essentially *without search*

Relaxed problems

- Given a collection of **admissible** heuristics, h_1, h_2, \dots, h_m , available for a problem and none of them dominates any of the others.
- The **composite heuristic function** is defined as
$$h(n) = \max\{h_1(n), h_2(n), \dots, h_m(n)\}$$
- $h(n)$ is consistent and dominates all component heuristics

h_1 : 4 5 2 1

h_2 : 5 4 1 4 $\Rightarrow h_1, h_2$ k có h nào dominate cái khác nên lấy max

$h\#$: 5 5 2 4

A **subproblem** of the 8-puzzle instance

$9 \times 8 \times 7 \times 6 = 3024$ state

bài gốc: $9!$ state

*	2	4
*		*
*	3	1

Start State

	1	2
3	4	*
*	*	*

Goal State

- Get tiles 1, 2, 3, and 4 into their correct positions, without worrying about what happens to the other tiles
 - **Optimal cost** of this **subproblem** \leq cost of the **original problem**
 - **More accurate** than **Manhattan** distance in some cases

Pattern database heuristics

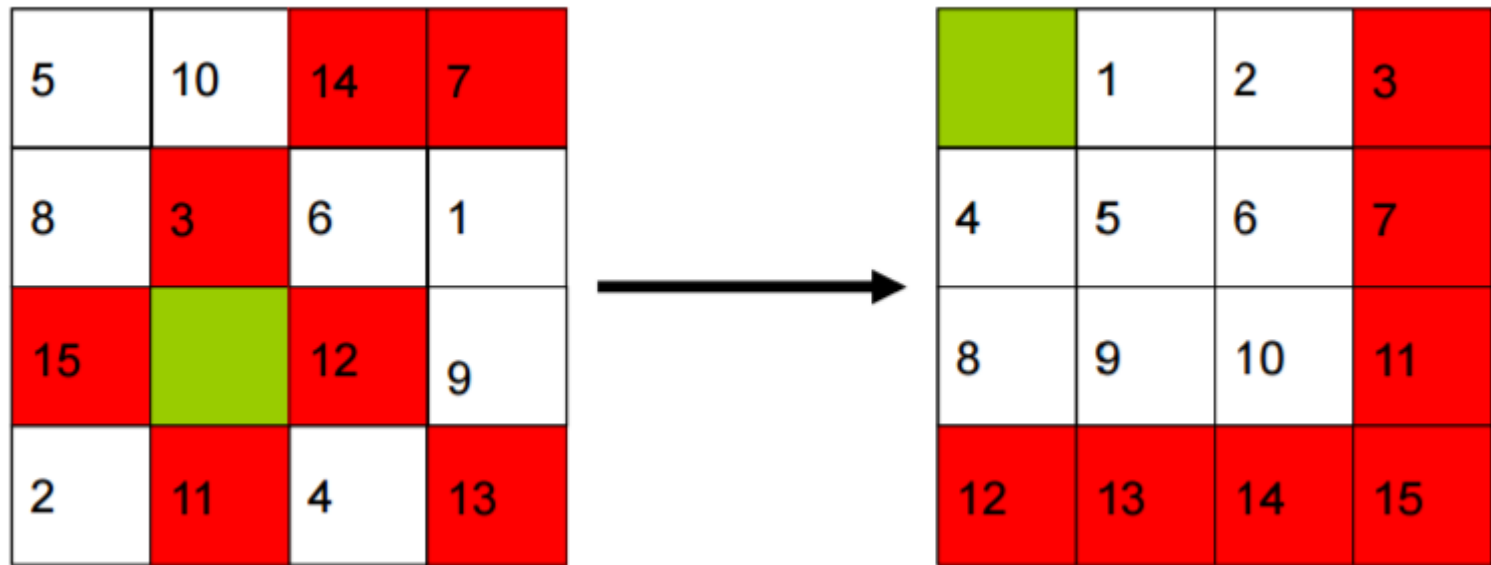
- Admissible heuristics can also be derived from the **solution cost** of a **subproblem** of the given problem.
 - This cost is a **lower bound** on the cost of the complete problem.
- **Pattern databases (PDB)**: store the exact solution costs for every possible subproblem instances
 - E.g., a 7-tile pattern database for the 15-puzzle problem contains 519 million entries.
- The **complete heuristic** is constructed using the patterns in the databases.

Source:

<https://courses.cs.washington.edu/courses/cse473/12sp/slides/04-heuristics.pdf>

Traditional pattern databases

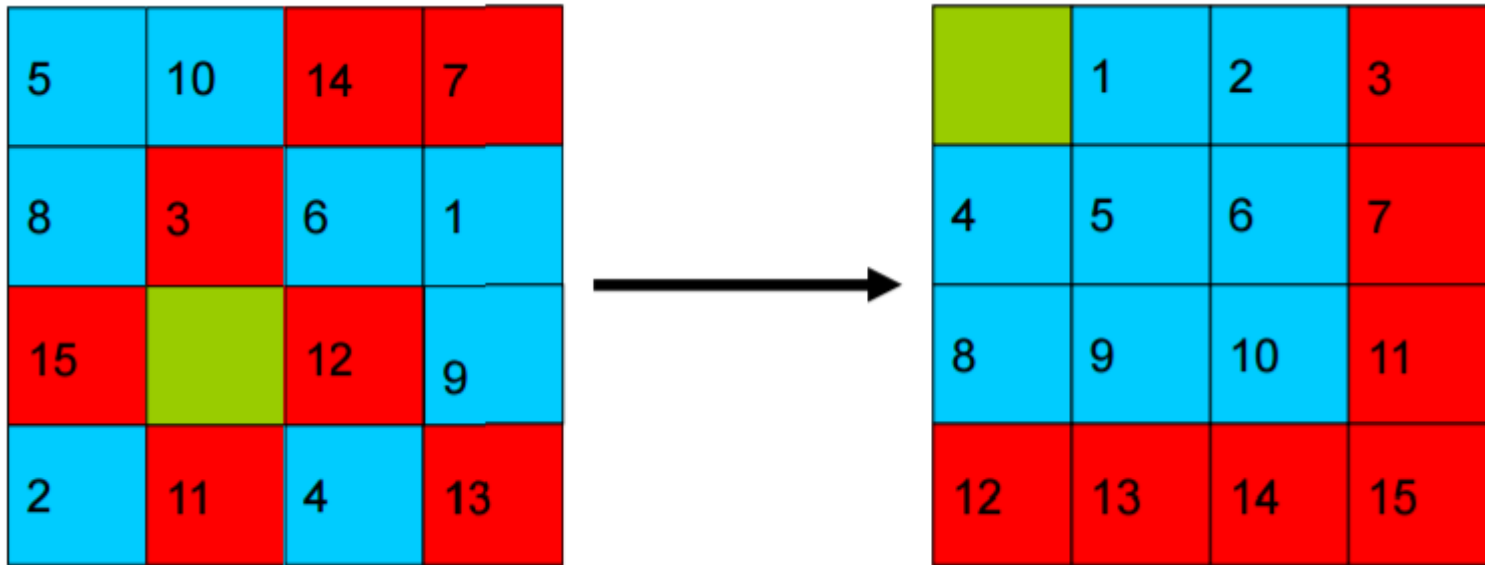
- Culberson, Joseph C., and Jonathan Schaeffer. "Pattern databases." Computational Intelligence 14.3 (1998): 318-334.
- Count all moves needed to correctly position the pattern tiles



31 moves is a lower bound on the total number of moves needed to solve this state.

Traditional pattern databases

- Take max → diminish returns on additional DBs



31 moves needed to solve red tiles. 22 moves needed to solve blue tiles

→ Overall heuristic is maximum of 31 moves

Additive pattern databases

- Korf, Richard E., and Ariel Felner. "Disjoint pattern database heuristics." *Artificial intelligence* 134.1-2 (2002): 9-22.
- Felner, Ariel, Richard E. Korf, and Sarit Hanan. "Additive pattern database heuristics." *Journal of Artificial Intelligence Research* 22 (2004): 279-318.
- Count only moves of the pattern tiles while ignoring non-pattern moves
- If no tile belongs to more than one pattern, we can add their heuristic values.
 - Manhattan distance is a special case of this, where each pattern contains a single tile.

Additive pattern databases

- **Disjoint PDB:** partition tiles into disjoint sets and precompute the optimal length for each instance of the set.

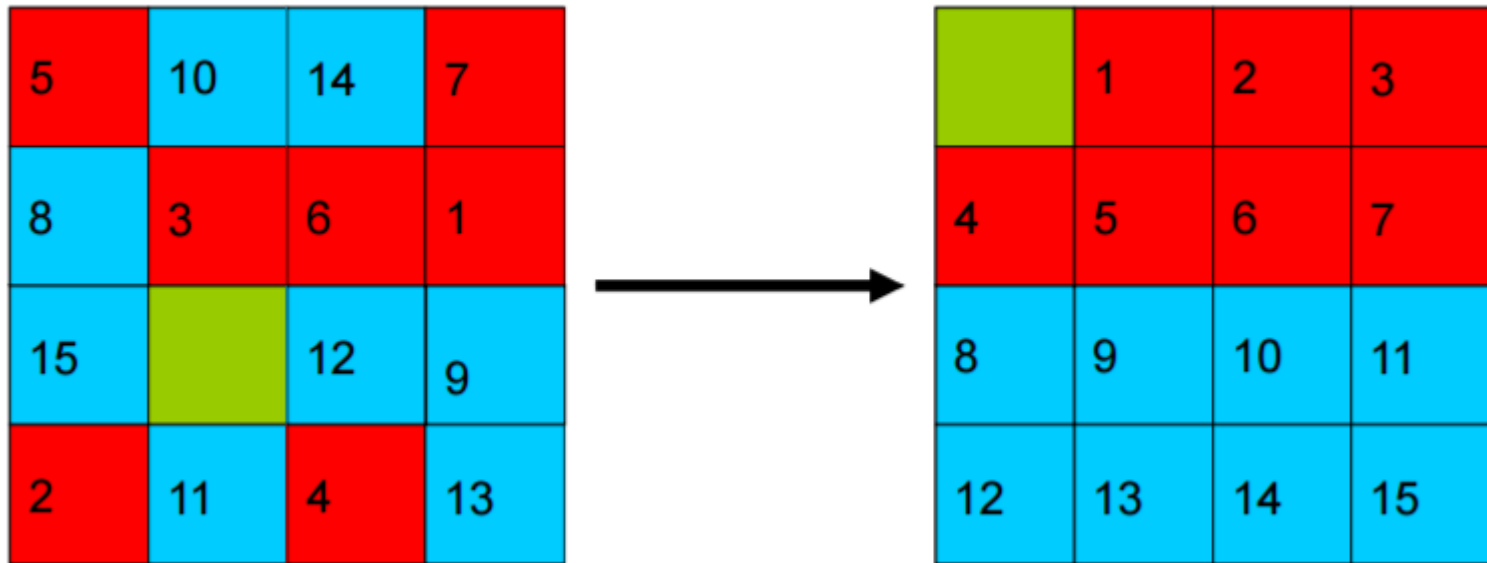
The 7-tile database contains 58 million entries.

The 8-tile database contains 519 million entries.

	1	2	3
4	5	6	7
8	9	10	11
12	13	14	15

Additive pattern databases

- During search: look up heuristic values for each set and add the values without overestimating



20 moves needed to solve red tiles. 25 moves needed to solve blue tiles.

→ Overall heuristic is $20 + 25 = 45$ moves

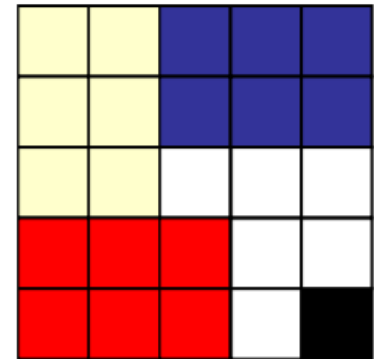
Pattern database heuristics

- **15 Puzzle**

- 2000× speedup vs. Manhattan distance
- IDA* with the two DBs solves 15-puzzles optimally in 30 milliseconds

- **24 Puzzle**

- 12 million × speedup vs. Manhattan
- IDA* can solve random instances in 2 days.
- Requires 4 DBs as shown
 - Each DB has 128 million entries
- Without PDBs: 65,000 years



Learning heuristics from experience

- Experience means solving a lot of instances of a problem.
 - E.g., solving lots of 8-puzzles
- Each optimal solution to a problem instance provides examples from which $h(n)$ can be learned
- Learning algorithms
 - Neural nets
 - Decision trees
 - Inductive learning
 - ...



THE END