CS 188: Artificial Intelligence
Spring 2007

Lecture 3: Queue-Based Search
1/23/2007

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Many slides over the course adapted from Dan Klein, Stuart Russell or Andrew Moore

Announcements

- Assignment 1 due 1/30 11:59 PM
  - You can do most of it after today
- Sections start this week
- Stay tuned for Python Lab

Summary

- Agents interact with environments through actuators and sensors
  - The agent function describes what the agent does in all circumstances
  - The agent program calculates the agent function
  - The performance measure evaluates the environment sequence
- A perfectly rational agent maximizes expected performance
- PEAS descriptions define task environments
- Environments are categorized along several dimensions:
  - Observable? Deterministic? Episodic? Static? Discrete? Single-agent?
- Problem-solving agents make a plan, then execute it
- State space encodings of problems

Problem-Solving Agents

```
function SIMPLE-PROBLEM-SOLVING-AGENT(percept) returns an action
    static: seq, an action sequence, initially empty
            state, some description of the current world state
            goal, a goal, initially null
            problem, a problem formulation

    state ← UPDATE-STATE(state, percept)
    if seq is empty then
        goal ← FORMULATE-GOAL(state)
        problem ← FORMULATE-PROBLEM(state, goal)
        seq ← SEARCH(problem)
    action ← FIRST(seq); seq ← REST(seq)
    return action
```

This is the hard part!

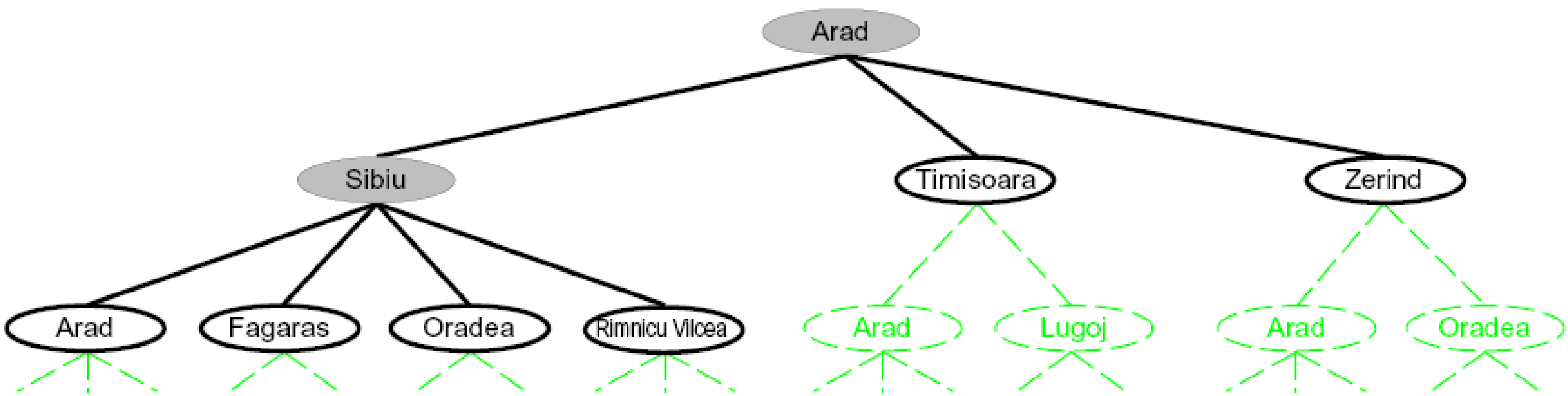
- This offline problem solving!
- Solution is executed “eyes closed.

Tree Search

- Basic solution method for graph problems
  - Offline simulated exploration of state space
  - Searching a model of the space, not the real world

```
function TREE-SEARCH( problem, strategy) returns a solution, or failure
    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
    end
```

A Search Tree



- Search:
  - Expand out possible plans
  - Maintain a fringe of unexpanded plans
  - Try to expand as few tree nodes as possible

Tree Search

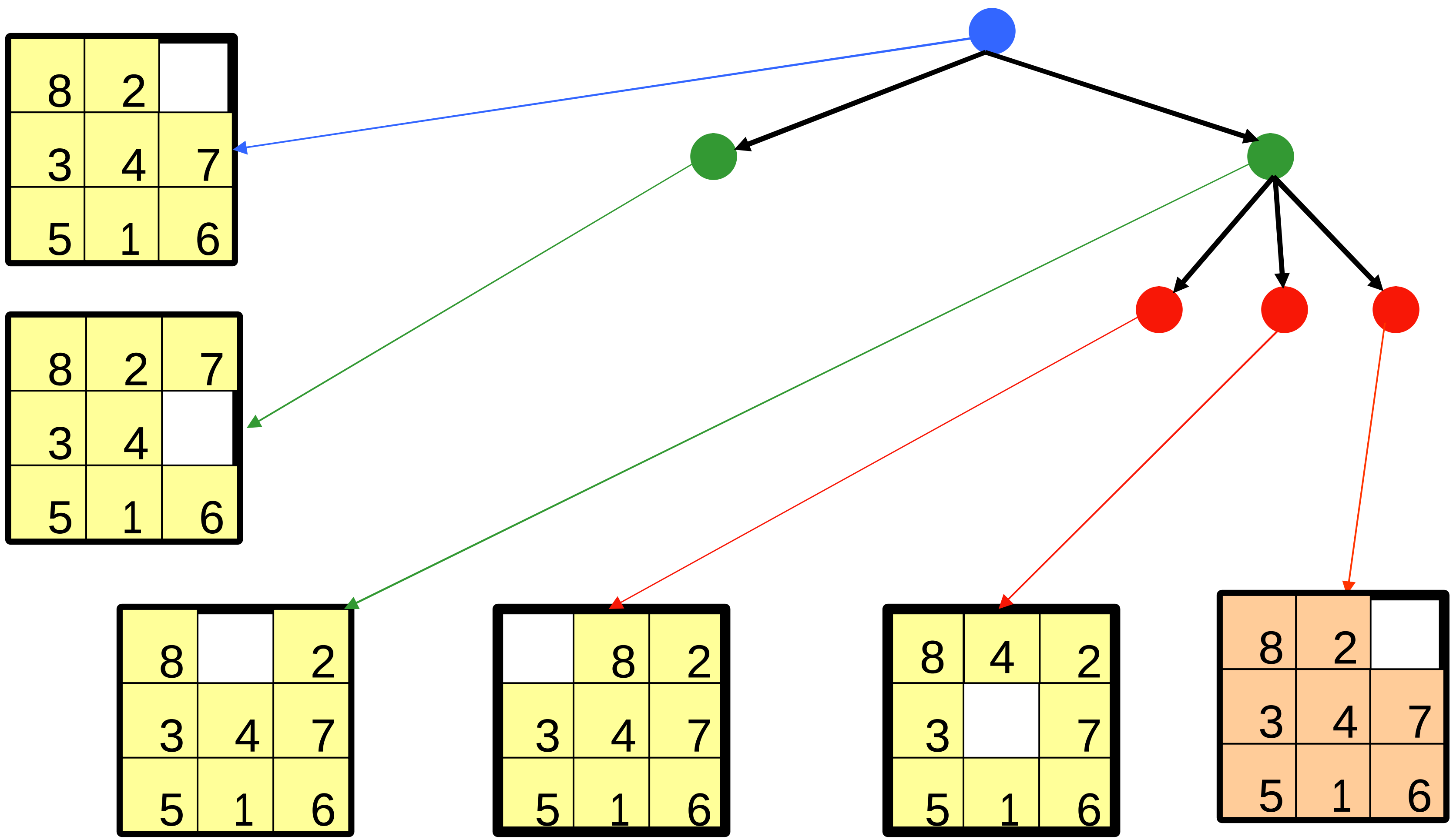
```
function TREE-SEARCH( problem, fringe) returns a solution, or failure
   fringe ← INSERT(MAKE-NODE(INITIAL-STATE[problem]), fringe)
   loop do
       if fringe is empty then return failure
       node ← REMOVE-FRONT(fringe)
       if GOAL-TEST(problem, STATE(node)) then return SOLUTION(node)
       fringe ← INSERTALL(EXPAND(node, problem), fringe)
```

```
function EXPAND( node, problem) returns a set of nodes
   successors ← the empty set; state ← STATE[node]
   for each action, result in SUCCESSOR-FN(problem, state) do
       s ← a new NODE
       PARENT-NODE[s] ← node;  ACTION[s] ← action;  STATE[s] ← result
       PATH-COST[s] ← PATH-COST[node]+STEP-COST(state, action, result)
       DEPTH[s] ← DEPTH[node] + 1
       add s to successors
   return successors
```

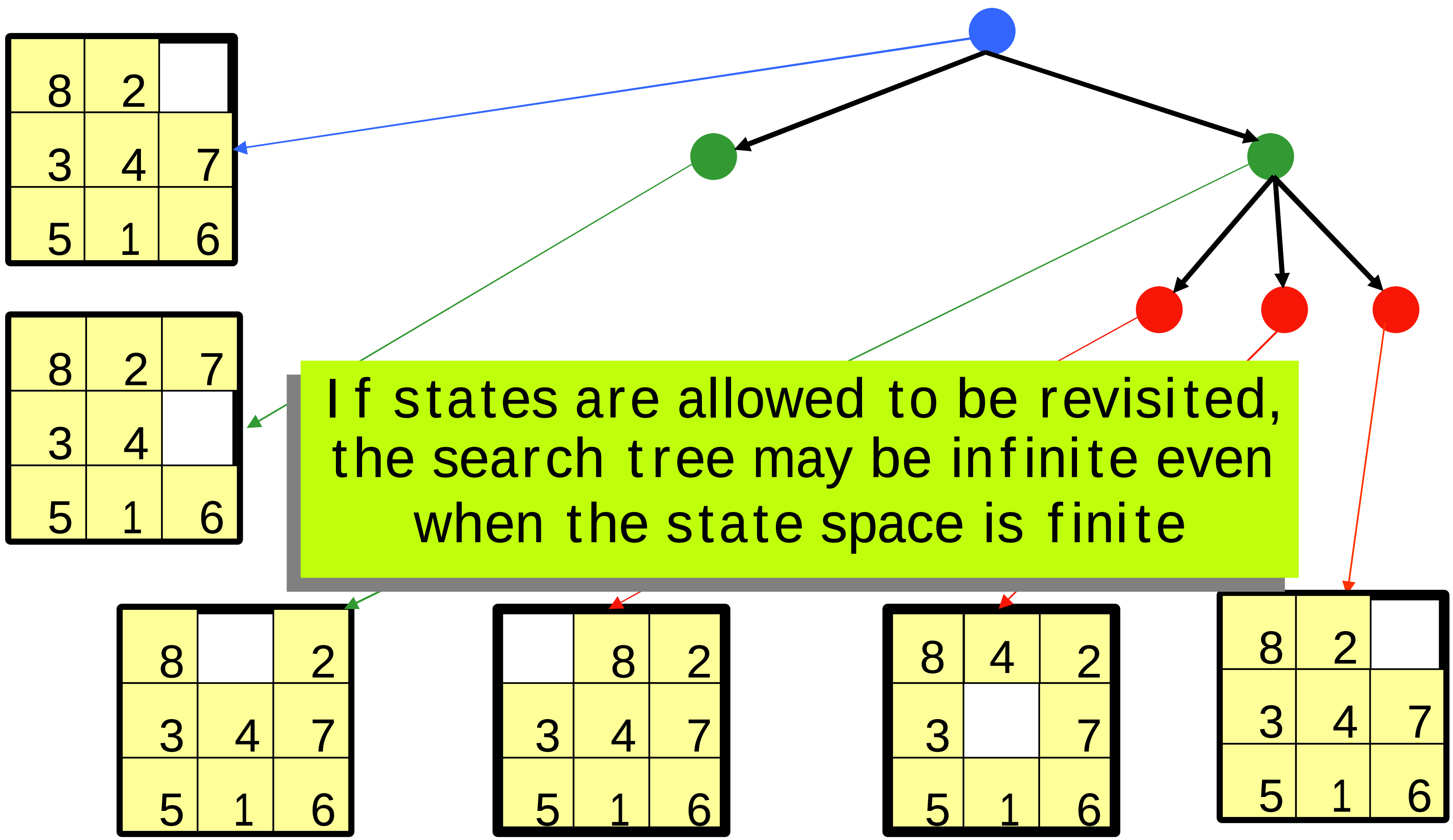
General Tree Search

- Important ideas:
  - Fringe
  - Expansion
  - Exploration strategy
- Main question: which fringe nodes to explore?

Search Nodes vs. States



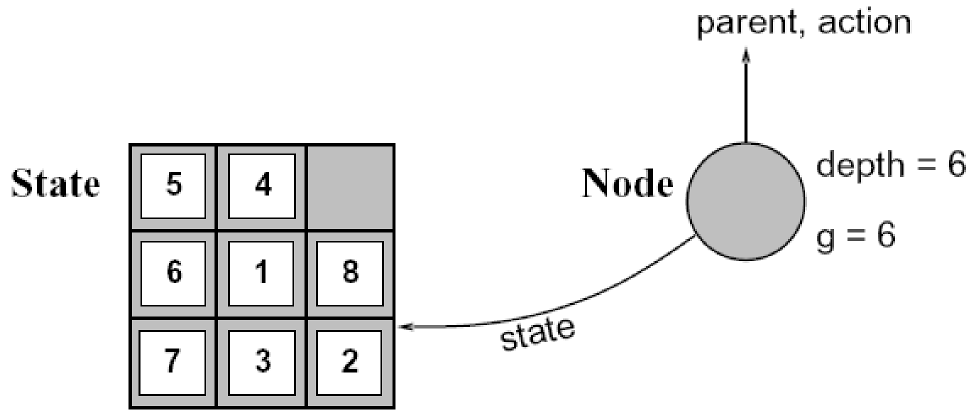
Search Nodes vs. States



If states are allowed to be revisited, the search tree may be infinite even when the state space is finite

States vs. Nodes

- Problem graphs have problem states
  - Have successors
- Search trees have search nodes
  - Have parents, children, depth, path cost, etc.
  - Expand uses successor function to create new search tree nodes
  - The same problem state may be in multiple search tree nodes

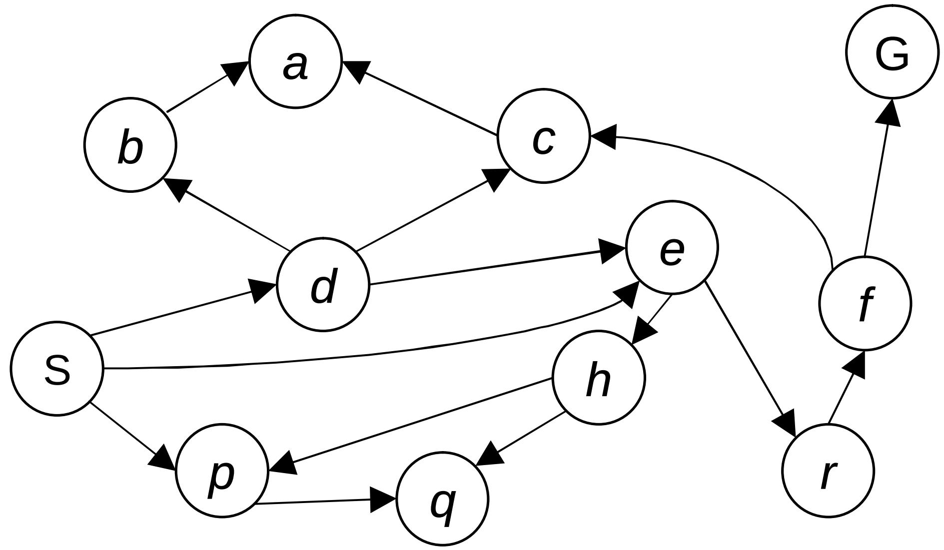


Uninformed search strategies

- (a.k.a. blind search) = use only information available in problem definition.
  - When strategies can determine whether one non-goal state is better than another → *informed search*.
- Categories defined by expansion algorithm:
  - Breadth-first search
  - Depth-first search
  - (Depth-limited search)
  - Iterative deepening search
  - Uniform-cost search
  - Bidirectional search

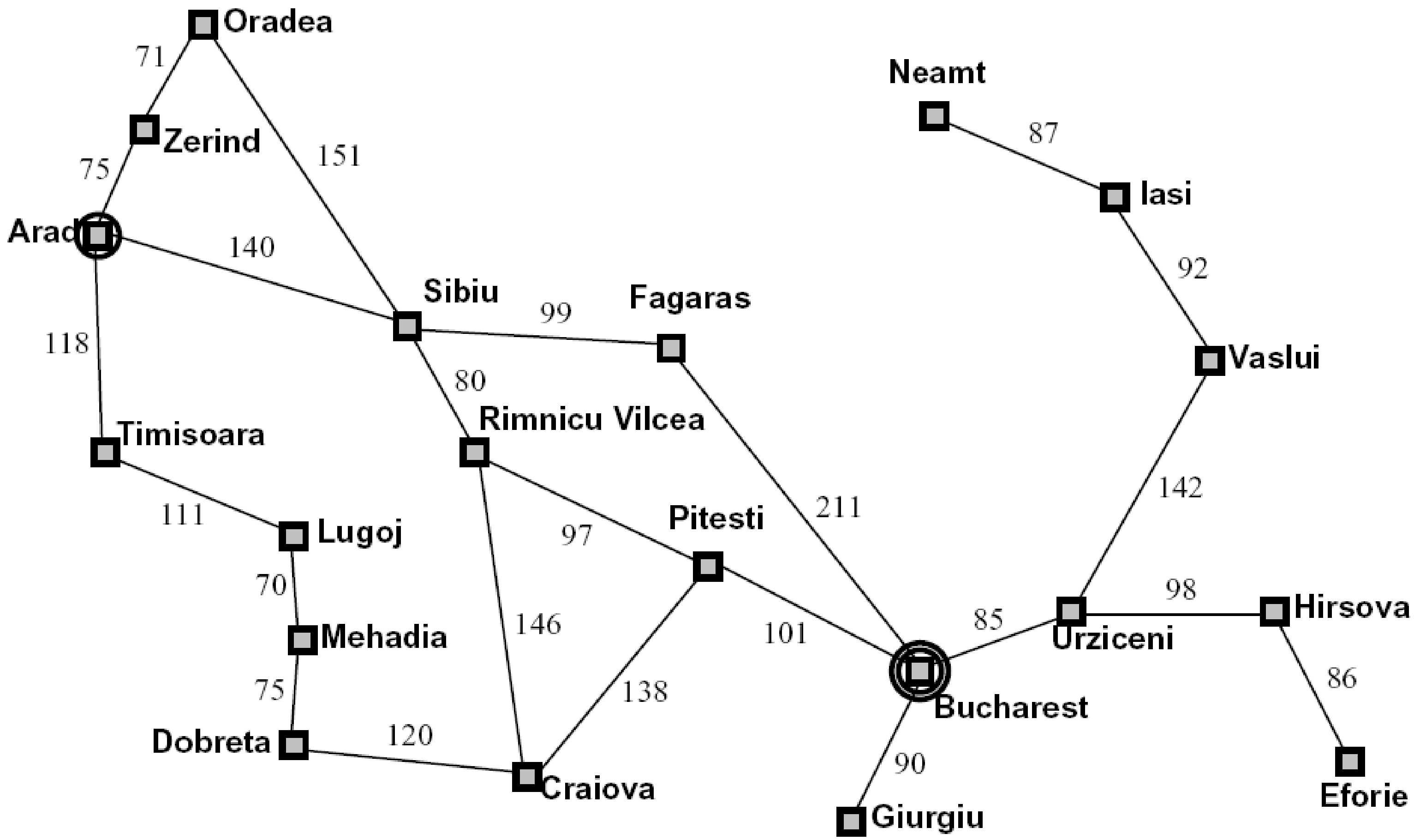
State Space Graphs

- There's some big graph in which
  - Each state is a node
  - Each successor is an outgoing arc
- Important: For most problems we could never actually build this graph
- How many states in 8-puzzle?

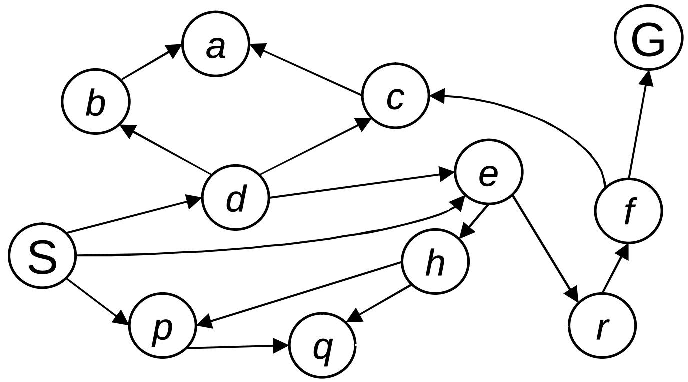


Laughably tiny search graph for a tiny search problem

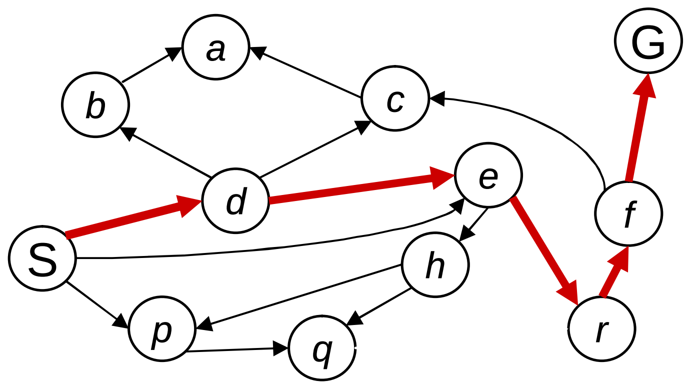
Example: Romania



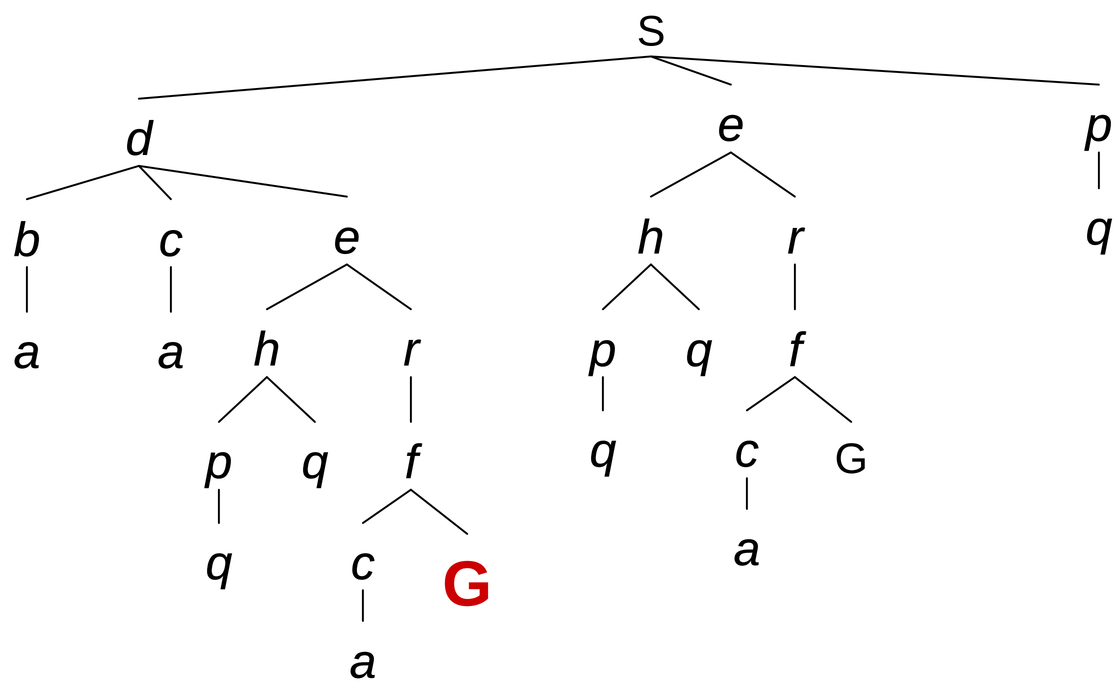
Example: Tree Search



State Graphs vs Search Trees



Each NODE in in the search tree is an entire PATH in the problem graph.

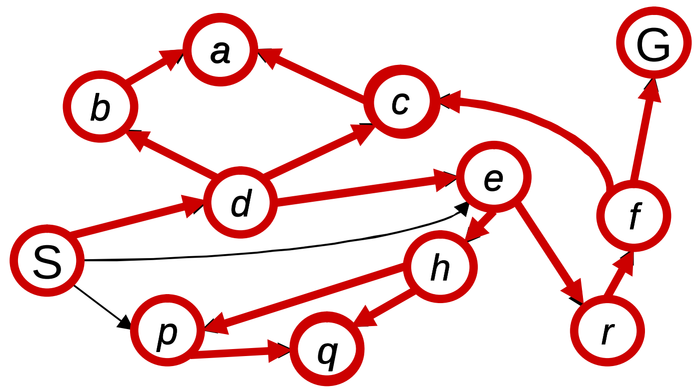


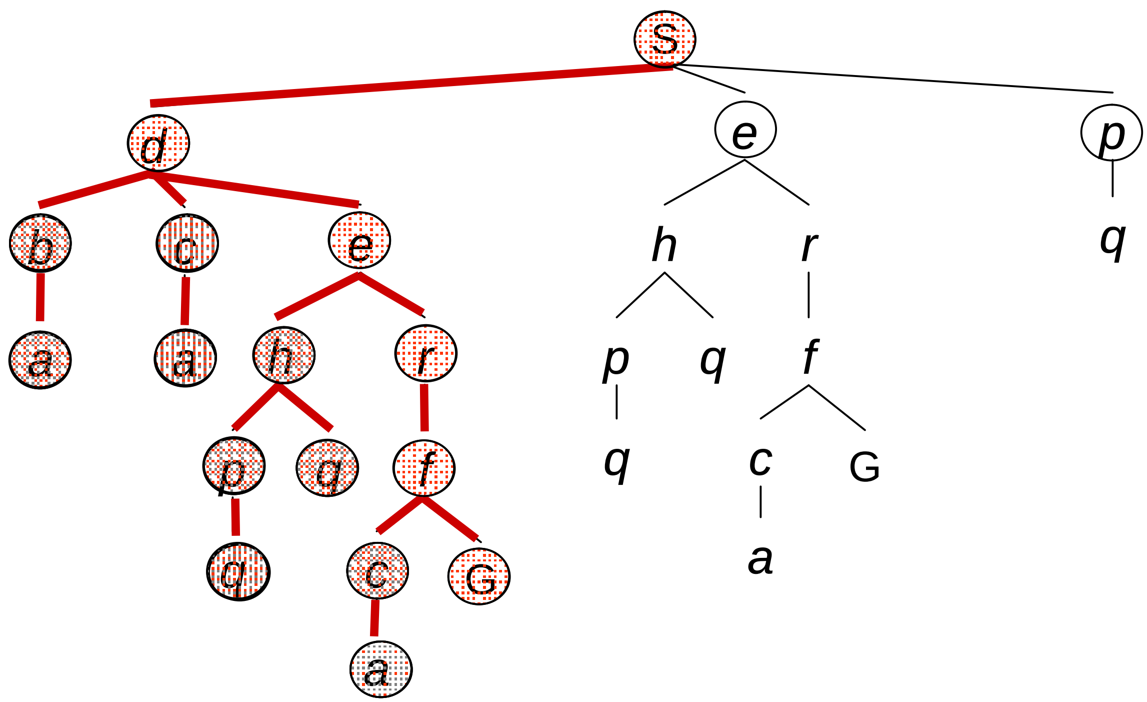
We almost always construct both on demand – and we construct as little as possible.

Review: Depth First Search

Strategy: expand deepest node first

Implementation: Fringe is a LIFO stack

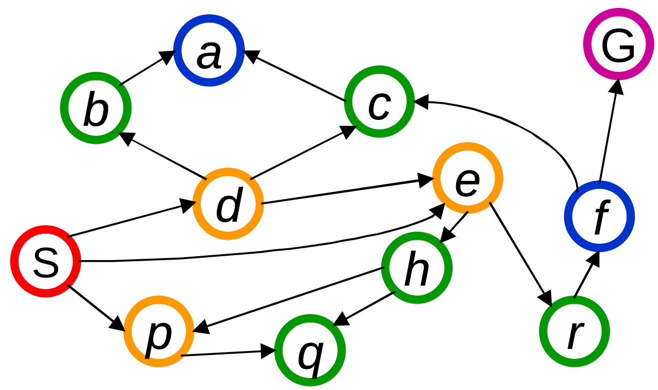




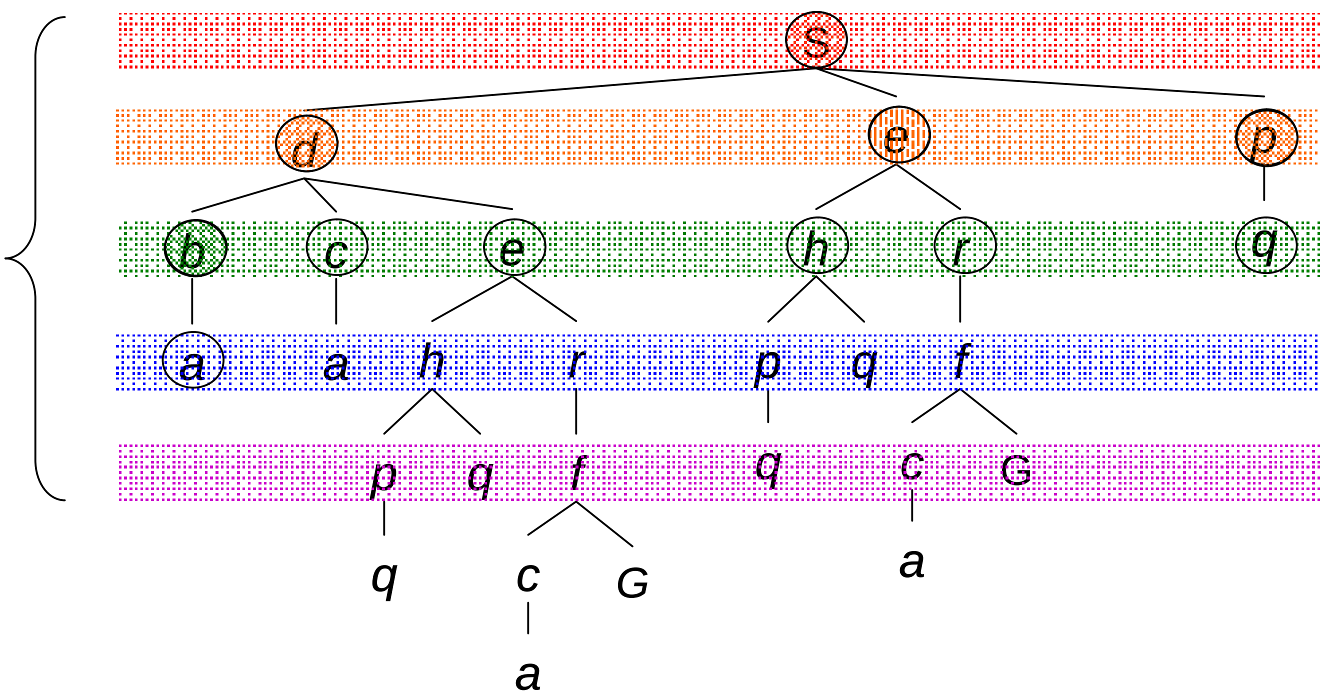
Review: Breadth First Search

Strategy: expand shallowest node first

Implementation: Fringe is a FIFO queue



Search Tiers



Search Algorithm Properties

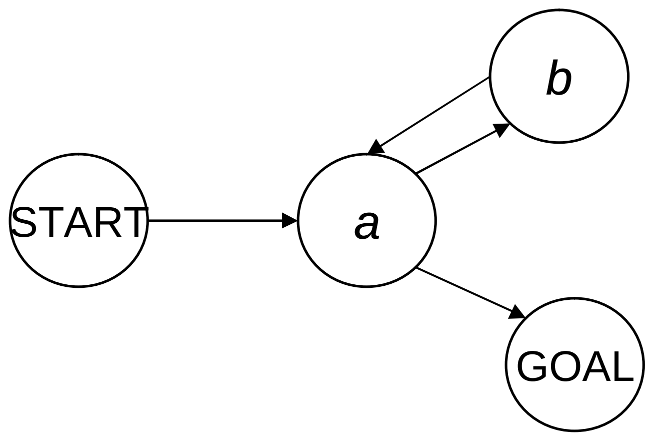
- Complete? Guaranteed to find a solution if one exists?
- Optimal? Guaranteed to find the least cost path?
- Time complexity?
- Space complexity?

Variables:

n	Number of states in the problem
b	The average branching factor *B* (the average number of successors)
C^*	Cost of least cost solution
s	Depth of the shallowest solution
m	Max depth of the search tree

DFS

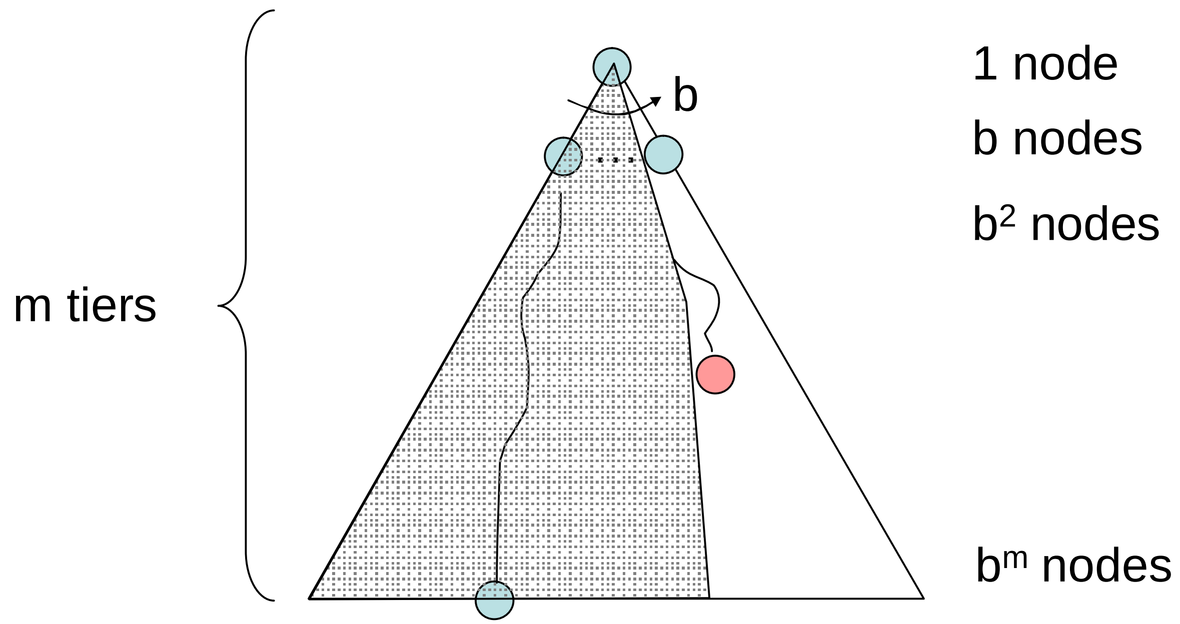
Algorithm		Complete	Optimal	Time	Space
DFS	Depth First Search	N	N	Infinite	Infinite



- Infinite paths make DFS incomplete…
- How can we fix this?

DFS

- With cycle checking, DFS is complete.

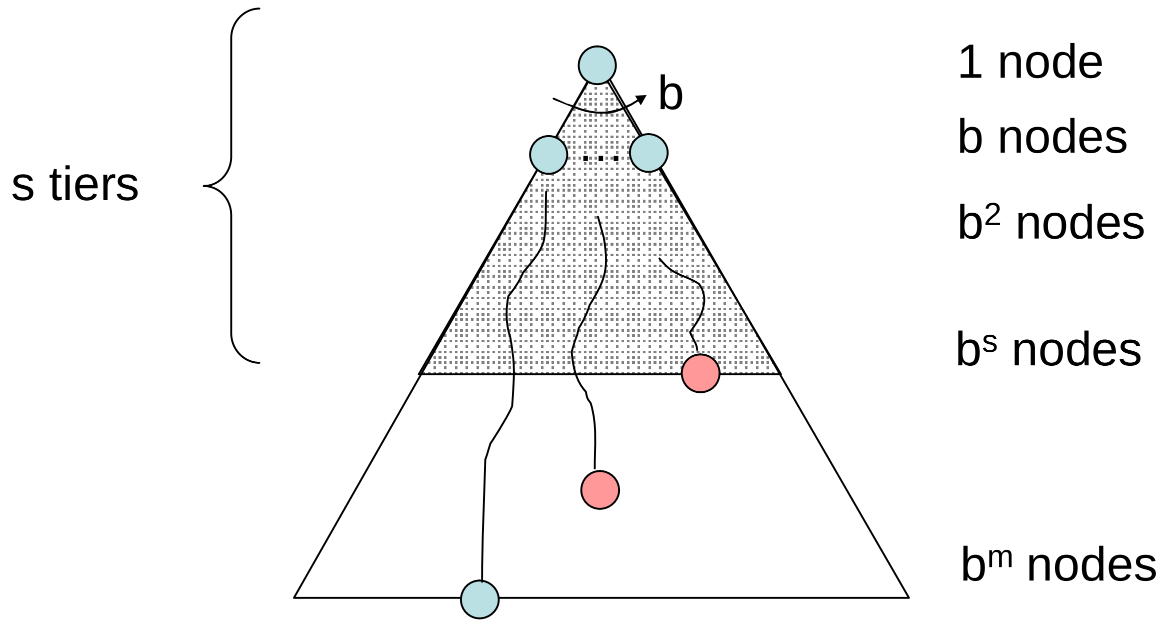


Algorithm		Complete	Optimal	Time	Space
DFS	w/ Path Checking	Y	N	$O(b^m)$	$O(bm)$

- When is DFS optimal?

BFS

Algorithm		Complete	Optimal	Time	Space
DFS	w/ Path Checking	Y	N	$O(b^m)$	$O(bm)$
BFS		Y	N*	$O(b^{s+1})$	$O(b^{s+1})$

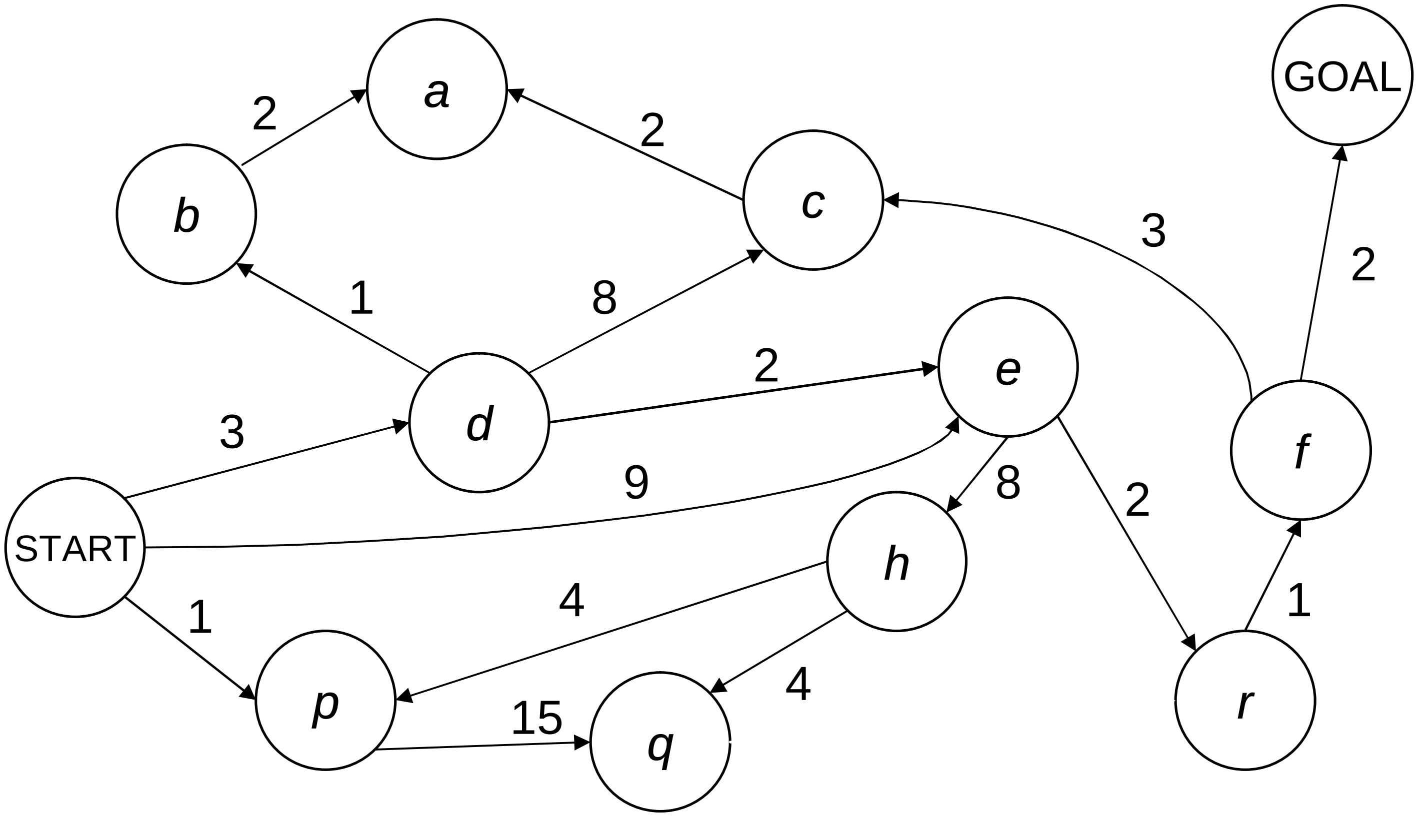


- When is BFS optimal?

Comparisons

- When will BFS outperform DFS?
- When will DFS outperform BFS?

Costs on Actions



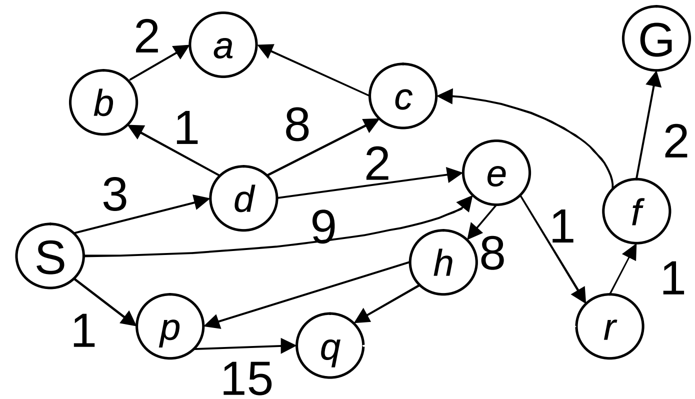
Notice that BFS finds the shortest path in terms of number of transitions. It does not find the least-cost path.

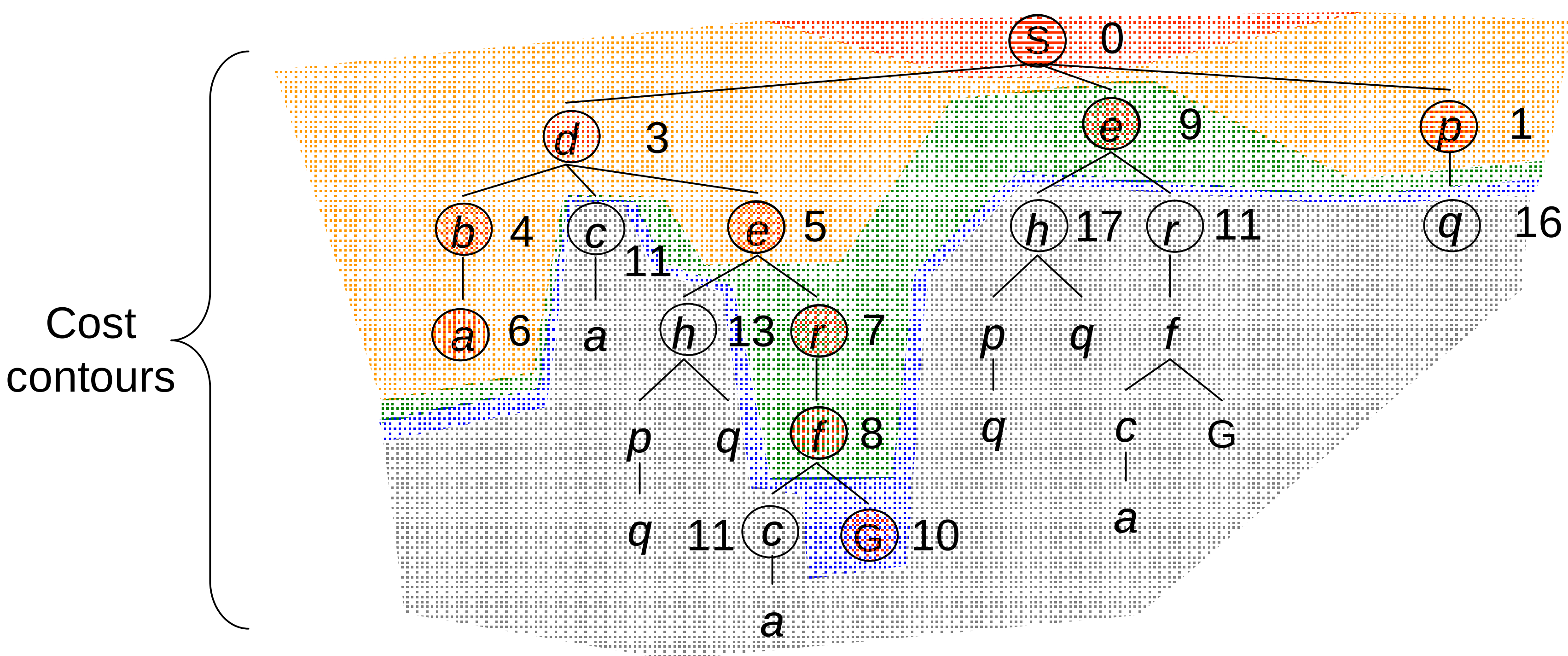
We will quickly cover an algorithm which does find the least-cost path.

Uniform Cost Search

Expand cheapest node first:

Fringe is a priority queue





Priority Queue Refresher

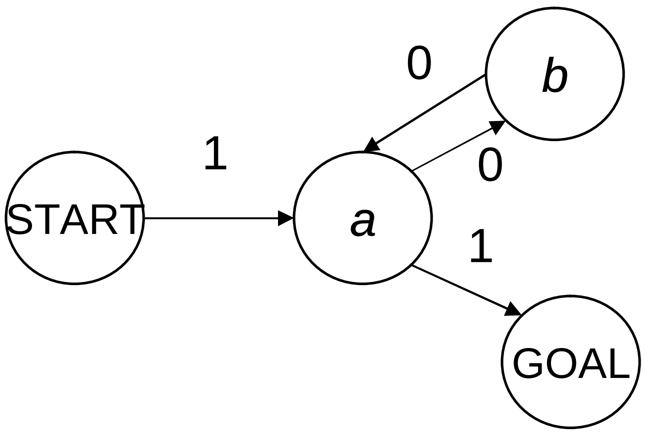
- A priority queue is a data structure in which you can insert and retrieve (key, value) pairs with the following operations:

pq.push(key, value)	inserts *(key, value)* into the queue.
pq.pop()	returns the key with the lowest value, and removes it from the queue.

- You can promote or demote keys by resetting their priorities
- Unlike a regular queue, insertions into a priority queue are not constant time, usually O(log *n*)
- We'll need priority queues for most cost-sensitive search methods.

Uniform Cost Search

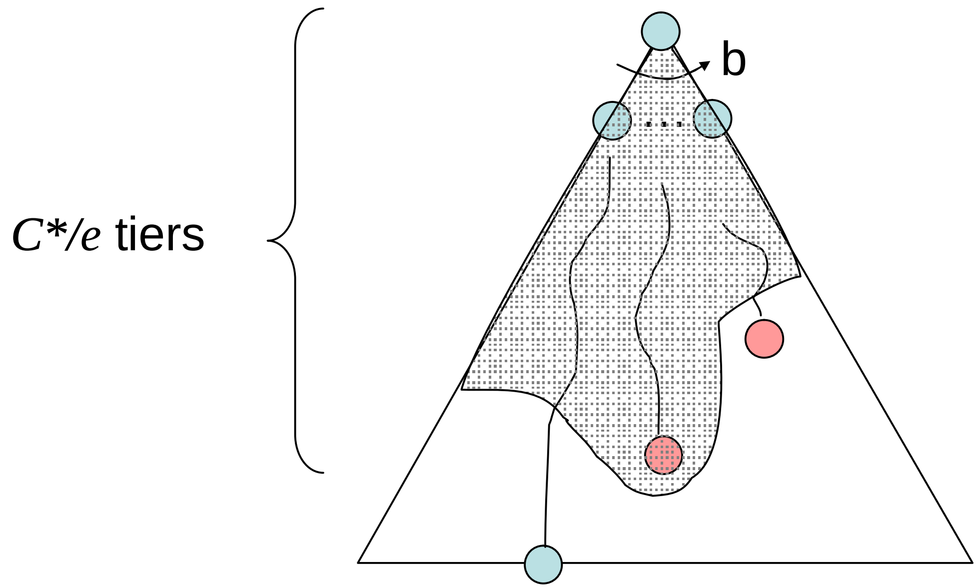
- What will UCS do for this graph?



- What does this mean for completeness?

Uniform Cost Search

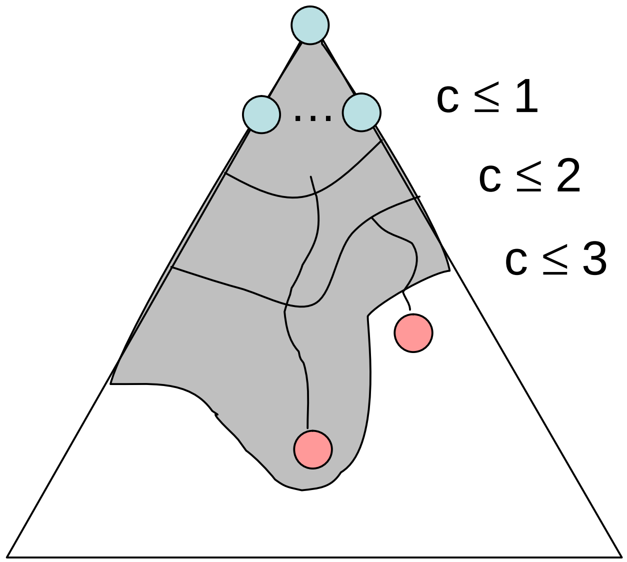
Algorithm		Complete	Optimal	Time	Space
DFS	w/ Path Checking	Y	N	$O(b^m)$	$O(bm)$
BFS		Y	N	$O(b^{s+1})$	$O(b^{s+1})$
UCS		Y*	Y	$O(b^{C*/e})$	$O(b^{C*/e})$

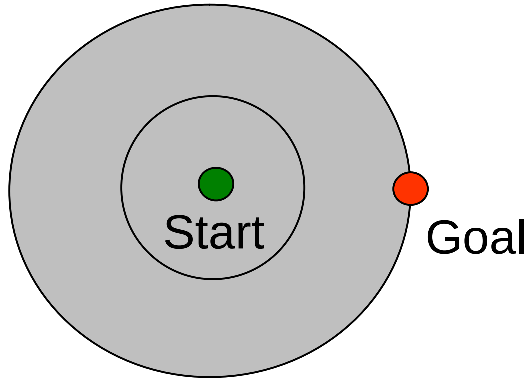


We'll talk more about uniform cost search's failure cases later…

Uniform Cost Problems

- Remember: explores increasing cost contours
- The good: UCS is complete and optimal!
- The bad:
  - Explores options in every “direction”
  - No information about goal location





Depth-limited search

depth-first search with depth limit *l*,

i.e., nodes at depth *l* have no successors

- Recursive implementation:

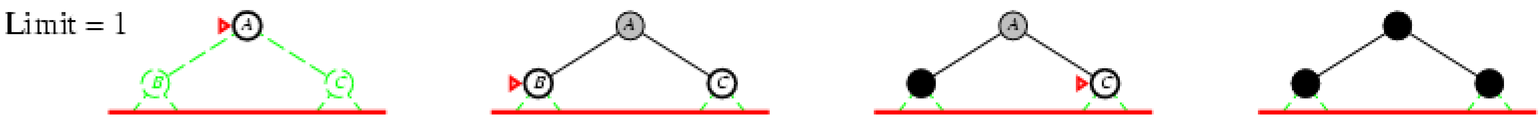
```
function DEPTH-LIMITED-SEARCH( problem, limit) returns soln/fail/cutoff
   RECURSIVE-DLS(MAKE-NODE(INITIAL-STATE[problem]), problem, limit)

function RECURSIVE-DLS(node, problem, limit) returns soln/fail/cutoff
   cutoff-occurred? ← false
   if GOAL-TEST[problem](STATE[node]) then return SOLUTION(node)
   else if DEPTH[node] = limit then return cutoff
   else for each successor in EXPAND(node, problem) do
        result ← RECURSIVE-DLS(successor, problem, limit)
        if result = cutoff then cutoff-occurred? ← true
        else if result ≠ failure then return result
   if cutoff-occurred? then return cutoff else return failure
```

Iterative deepening search

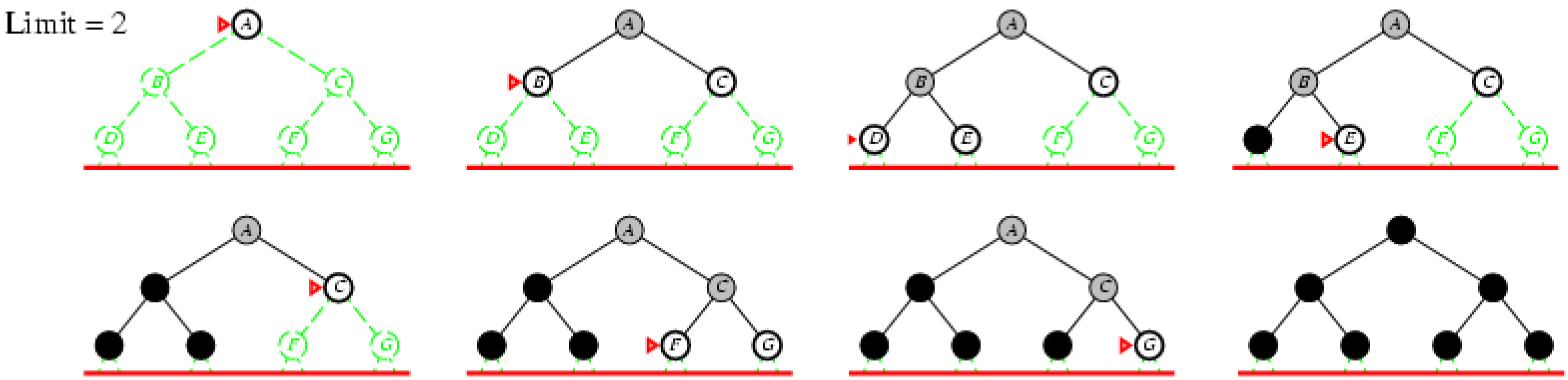
```
function ITERATIVE-DEEPENING-SEARCH( problem) returns a solution, or fail-
ure
    inputs: problem, a problem
    for depth ← 0 to ∞ do
        result ← DEPTH-LIMITED-SEARCH( problem, depth)
        if result ≠ cutoff then return result
```

Iterative deepening search *l* =0

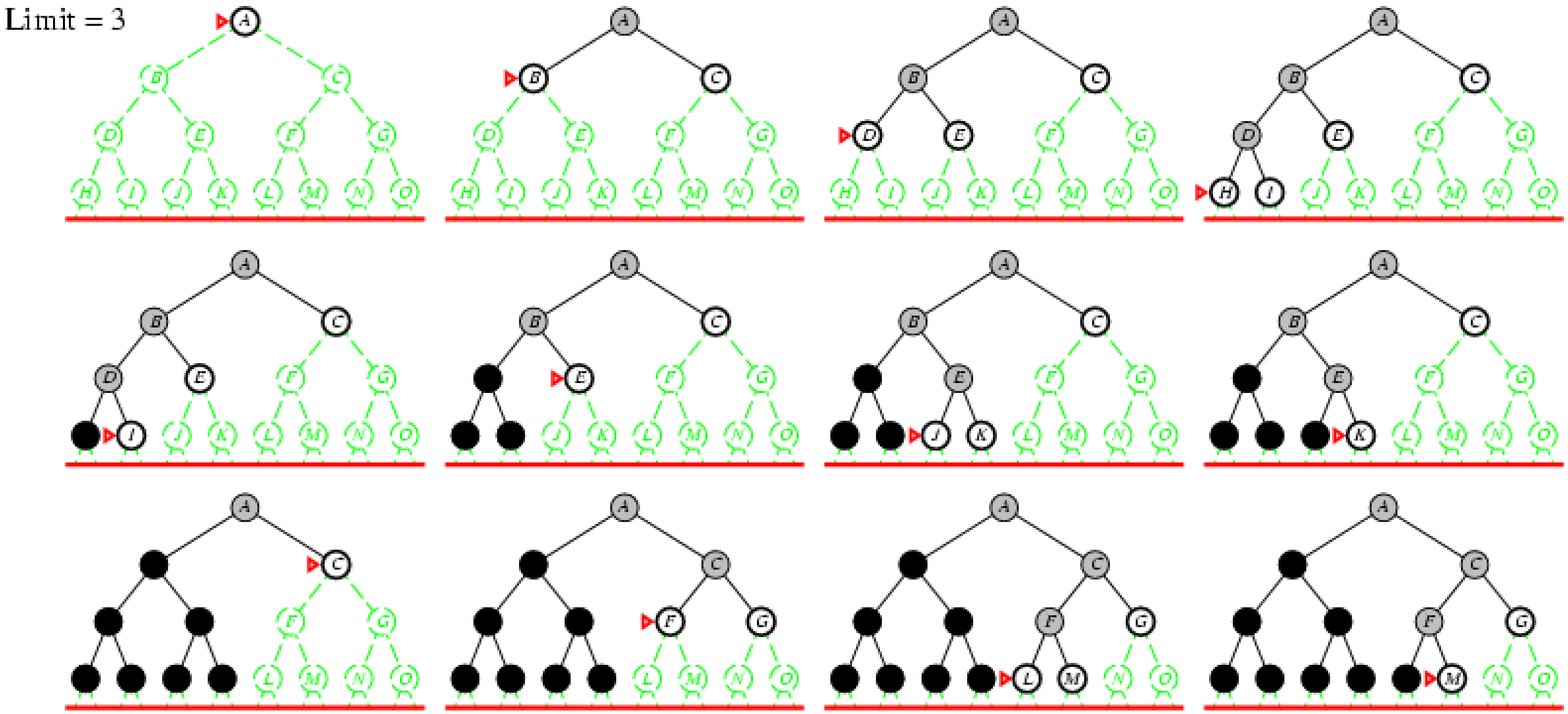
Iterative deepening search *l* =1



Iterative deepening search *l* =2



Iterative deepening search *l* =3



Iterative deepening search

- Number of nodes generated in a depth-limited search to depth *d* with branching factor *b*:

$$N_{DLS} = b^0 + b^1 + b^2 + \ldots + b^{d-2} + b^{d-1} + b^d$$

- Number of nodes generated in an iterative deepening search to depth *d* with branching factor *b*:

$$N_{IDS} = (d+1)b^0 + d\ b\text{^}^1 + (d-1)b\text{^}^2 + \ldots + 3b^{d-2} + 2b^{d-1} + 1b^d$$

- For *b = 10*, *d = 5*,
  - N_{DLS} = 1 + 10 + 100 + 1,000 + 10,000 + 100,000 = 111,111
  - N_{IDS} = 6 + 50 + 400 + 3,000 + 20,000 + 100,000 = 123,456

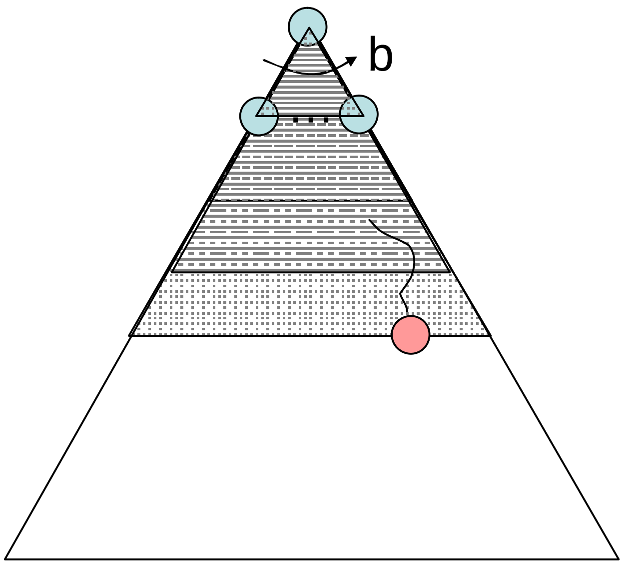
- Overhead = (123,456 - 111,111)/111,111 = 11%

Iterative Deepening

Iterative deepening uses DFS as a subroutine:

1. Do a DFS which only searches for paths of length 1 or less. (DFS gives up on any path of length 2)
2. If “1” failed, do a DFS which only searches paths of length 2 or less.
3. If “2” failed, do a DFS which only searches paths of length 3 or less.

….and so on.



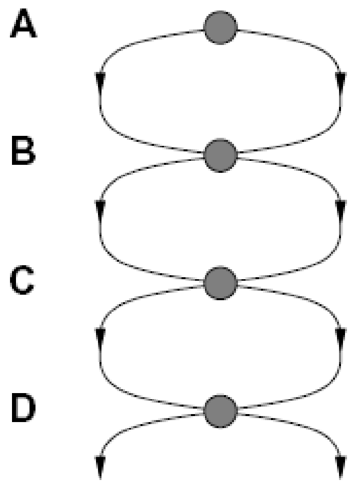
Algorithm		Complete	Optimal	Time	Space
DFS	w/ Path Checking	Y	N	$O(b^m)$	$O(bm)$
BFS		Y	N*	$O(b^{s+1})$	$O(b^{s+1})$
ID		Y	N*	$O(b^d)$	$O(bd)$

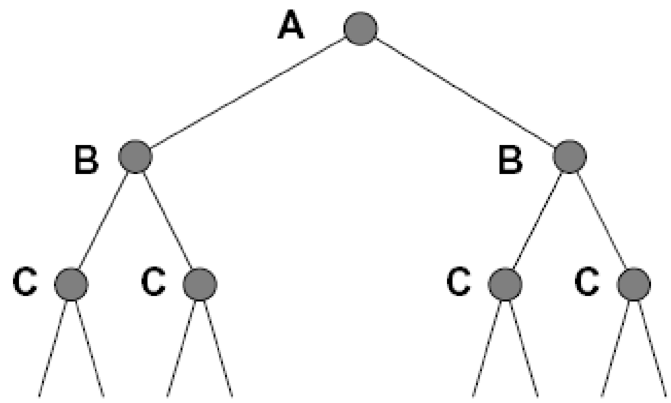
Summary of algorithms

Criterion	Breadth-First	Uniform-Cost	Depth-First	Depth-Limited	Iterative Deepening
Complete?	Yes	Yes	No	No	Yes
Time	$O(b^{d+1})$	$O(b^{\lceil C^*/\epsilon \rceil})$	$O(b^m)$	$O(b^l)$	$O(b^d)$
Space	$O(b^{d+1})$	$O(b^{\lceil C^*/\epsilon \rceil})$	$O(bm)$	$O(bl)$	$O(bd)$
Optimal?	Yes	Yes	No	No	Yes

Extra Work?

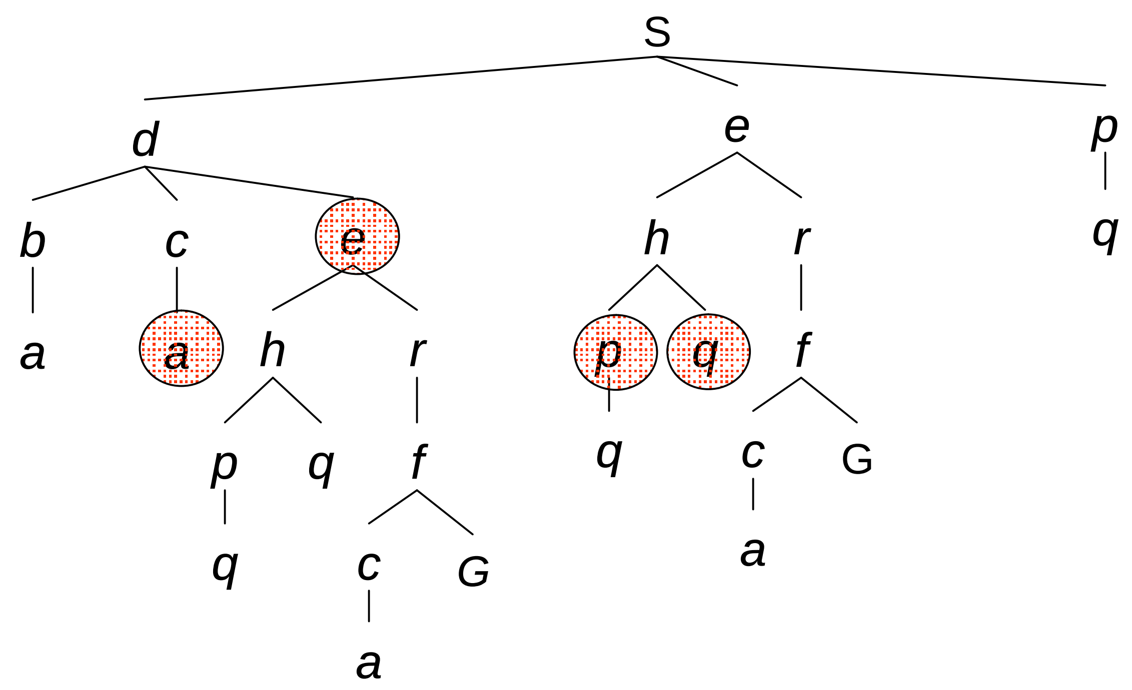
- Failure to detect repeated states can cause exponentially more work. Why?





Graph Search

- In BFS, for example, we shouldn't bother expanding the circled nodes (why?)



Graph Search

- Very simple fix: never expand a node twice

```
function GRAPH-SEARCH(problem, fringe) returns a solution, or failure

    closed ← an empty set
    fringe ← INSERT(MAKE-NODE(INITIAL-STATE[problem]), fringe)
    loop do
        if fringe is empty then return failure
        node ← REMOVE-FRONT(fringe)
        if GOAL-TEST(problem, STATE[node]) then return node
        if STATE[node] is not in closed then
            add STATE[node] to closed
            fringe ← INSERTALL(EXPAND(node, problem), fringe)
    end
```

- Can this wreck correctness? Why or why not?

Search Gone Wrong?