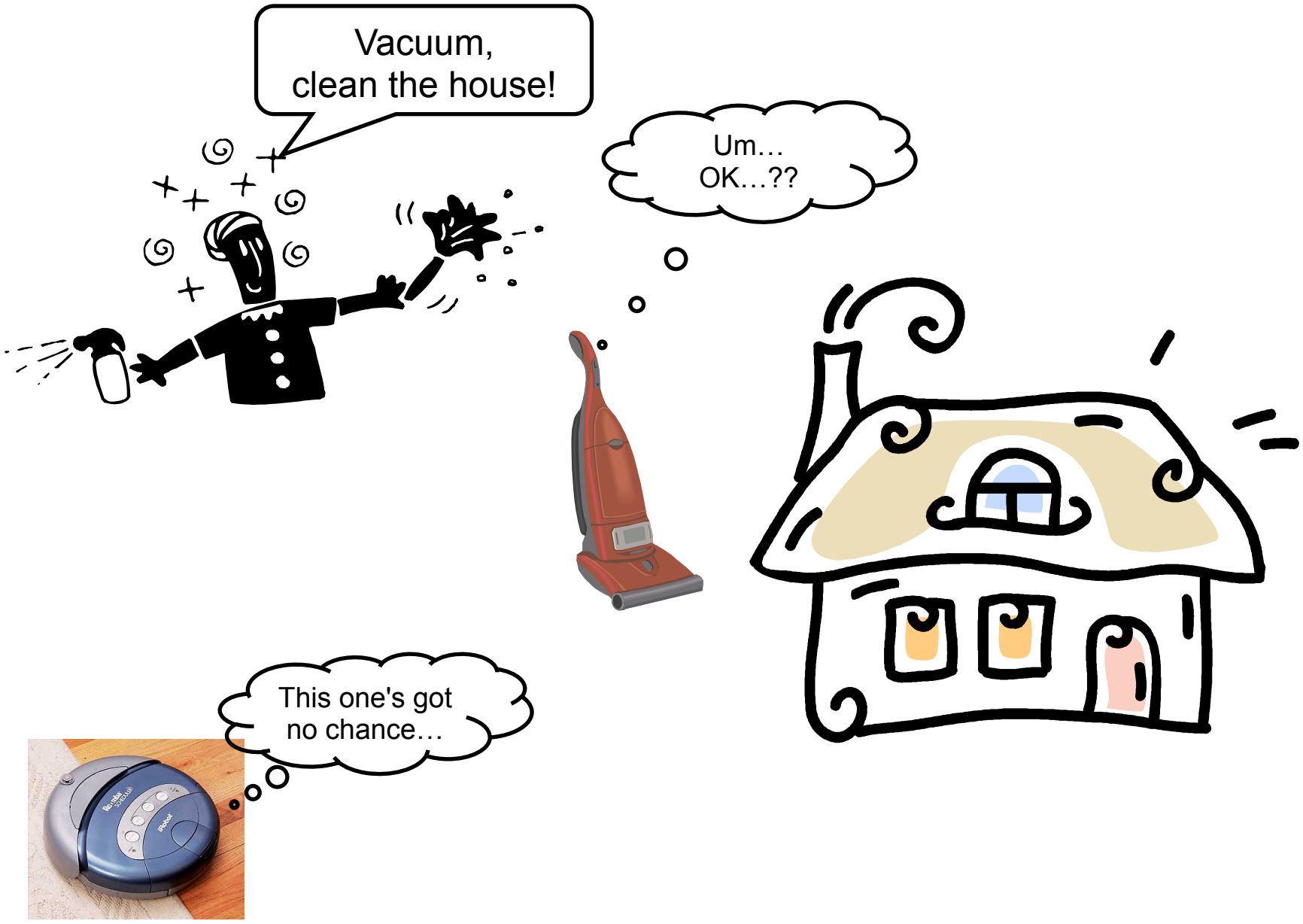
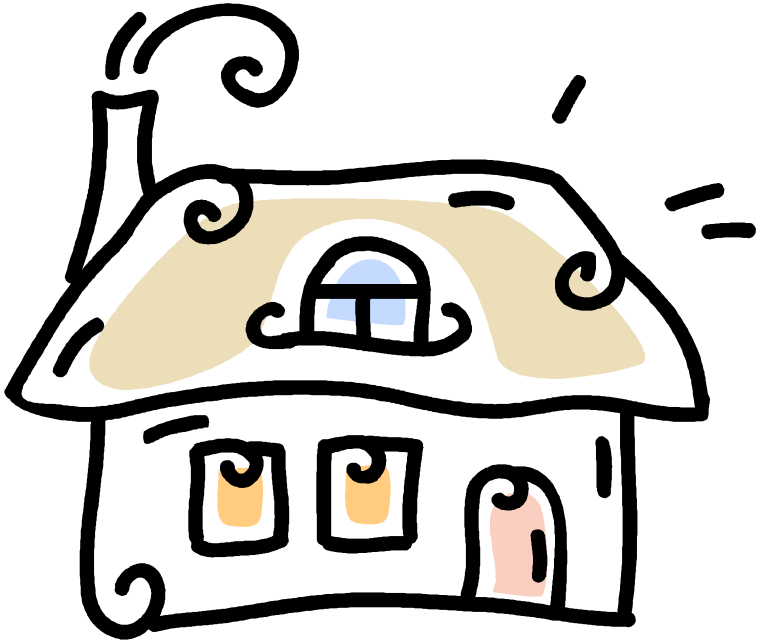
Intelligent Agents, Problem Formulation and Search

How do we make a vacuum "smart?"

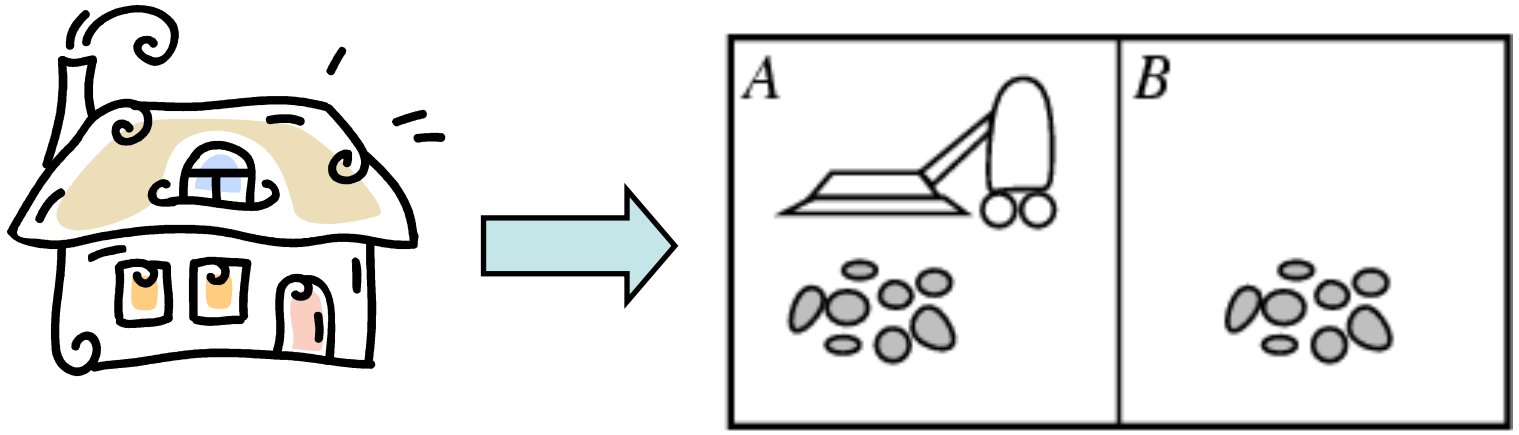


How do we represent this task?



We want the vacuum to "clean the house." What does this mean? What's involved for the vacuum cleaner? How can we formalize this problem a bit?

Vacuum Cleaner World



- Percepts: location and contents, e.g., [A,Dirty]
- Actions: *Left*, *Right*, *Suck*, *NoOp*

Rational Agents

Rational Agent = An agent (program) that does the "right" thing, given its goals, its abilities, what it perceives of its environment and its prior knowledge

What do we need to know in order to decide if the vacuum cleaner is rational?

What does the agent DO?

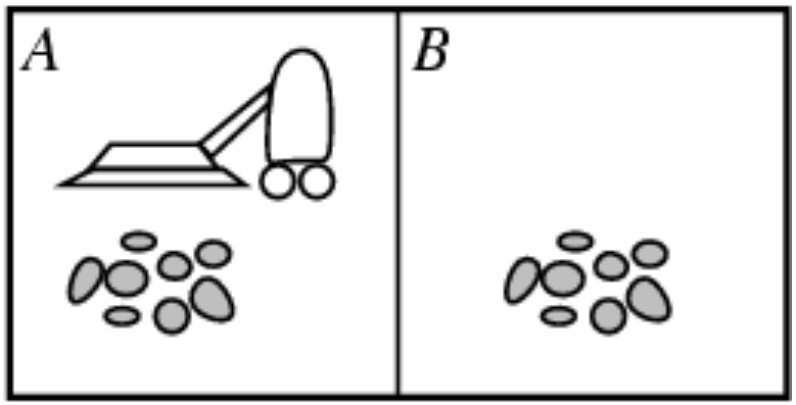
Our goal as AI programmers is develop agents that behave rationally. This means we must specify what the agent does given:

- Its goals
- Its precepts (what is perceives)
- Its possible actions
- Its prior knowledge

- This plan of action is the agent's policy or 'agent function'

AI Programming = Policy Design and Implementation

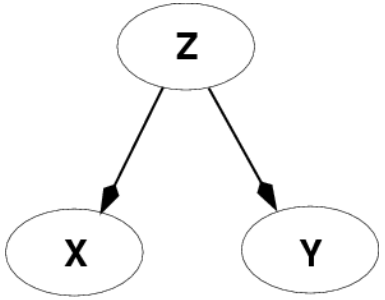
Defining a Policy



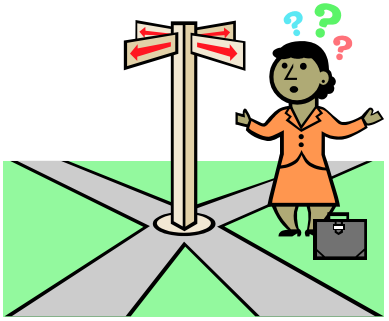
How might we define a policy for the vacuum agent above if the goal is to clean both rooms?

Techniques for Implementing Policies

Search

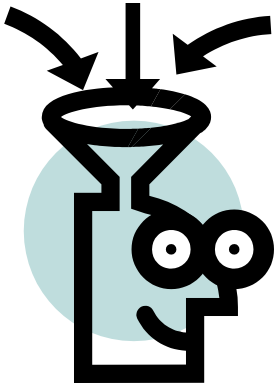


Reasoning with knowledge and uncertainty



Reasoning with Utility

At the core of this class will be several techniques for Policy design and implementation



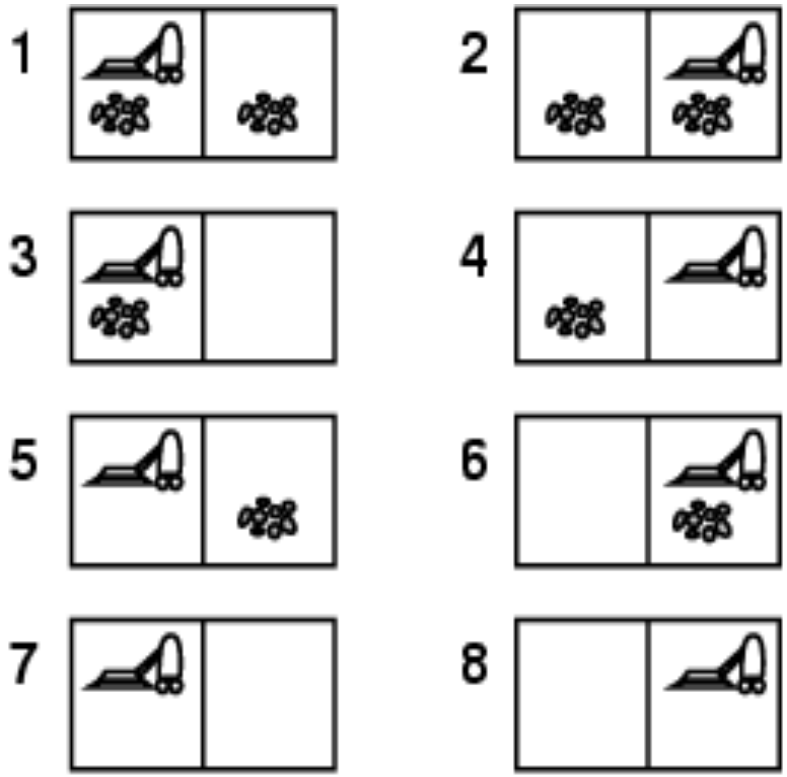
Learning

Task Environments

- Deterministic, fully observable → single-state problem
  - Agent knows exactly which state it will be in; solution is a sequence of actions
- Non-observable → sensorless (conformant) problem
  - Agent may have no idea where it is; solution is a sequence
- Nondeterministic and/or partially observable → contingency problem
  - percepts provide new information about current state
  - often interleave search, execution
- Unknown state space → exploration problem

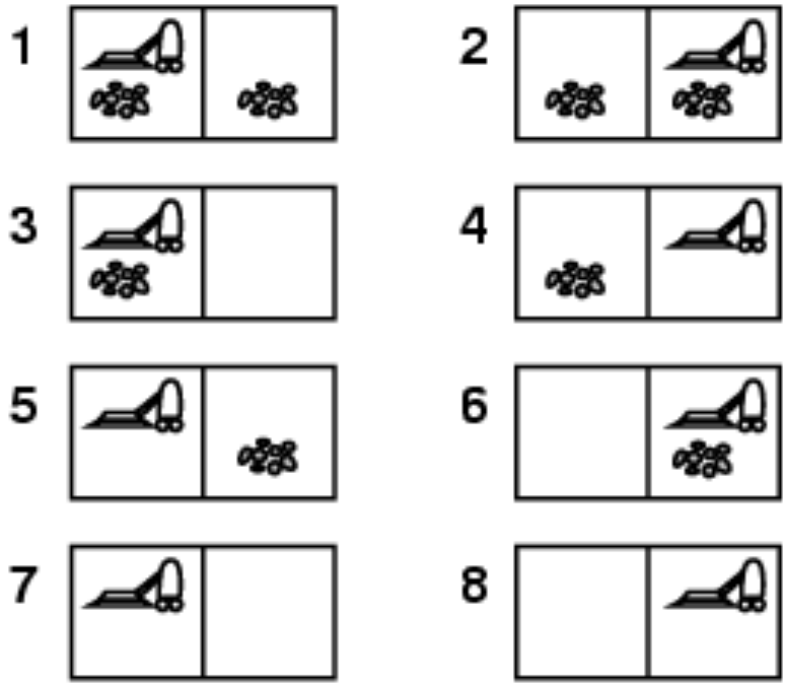
Example: vacuum world

- Single-state, start in #5.

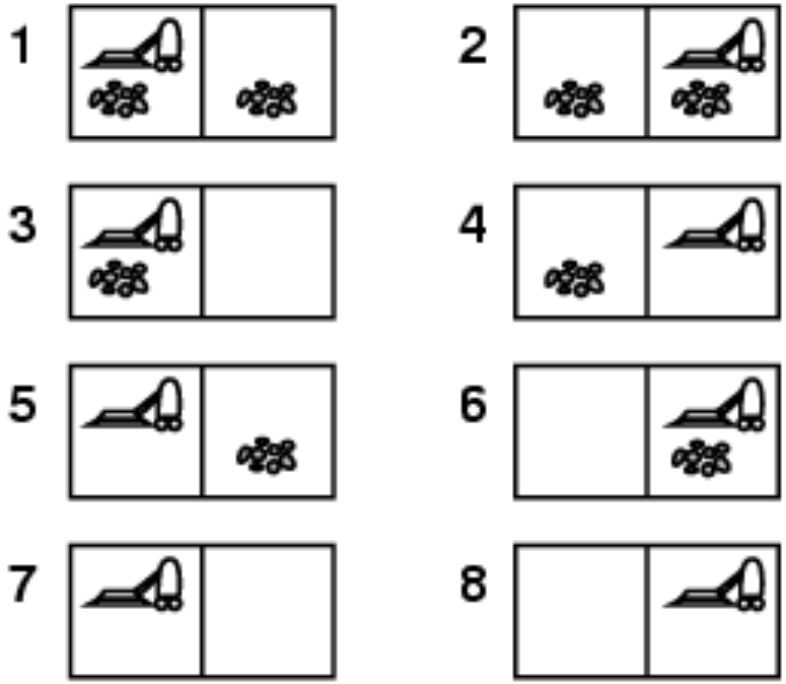


Example: vacuum world

- Sensorless, start in {*1,2,3,4,5,6,7,8*} e.g., *Right* goes to {*2,4,6,8*}

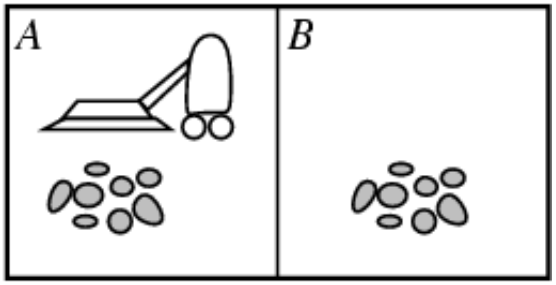


Example: Vacuum world



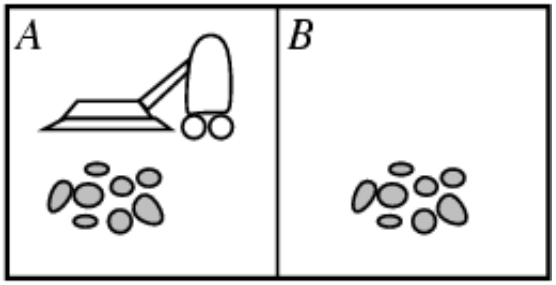
- Contingency
  - Nondeterministic: *Suck* may dirty a clean carpet
  - Partially observable: location, dirt at current location.
  - Percept: *[L, Clean],* i.e., start in #5 or #7

Vacuum world Search-based agent



1. Formulate problem and goal
2. Search for a sequence of actions that will lead to the goal (the policy)
3. Execute the actions one at a time

Vacuum world Search-based agent



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2. Search for a sequence of actions that will lead to the goal (the policy)
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Well-defined problem:
(State space)

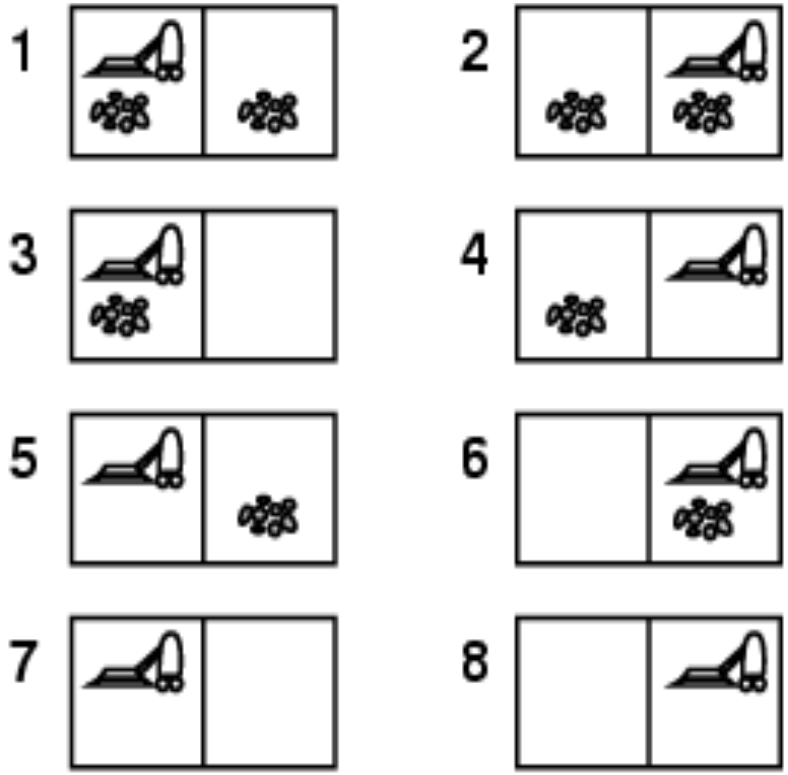
Initial state

Goal test

Actions/Successor function

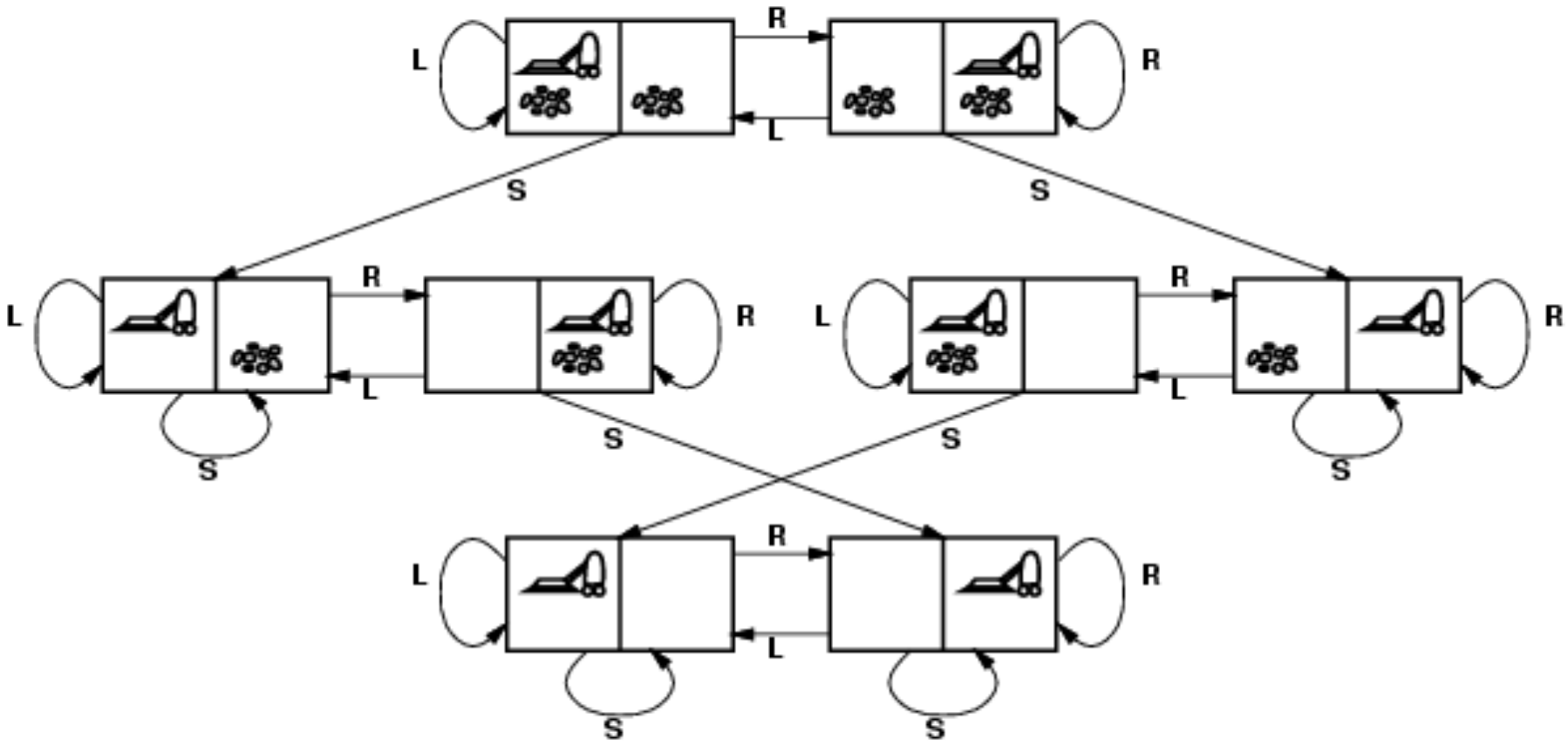
Path cost

Vacuum world



States: Shown above
Actions: R, L, S, NoOp
Successor function given by *state graph* (next slide)
Goal test: In state 7 or 8?
Path cost: +1 for each move and each suck

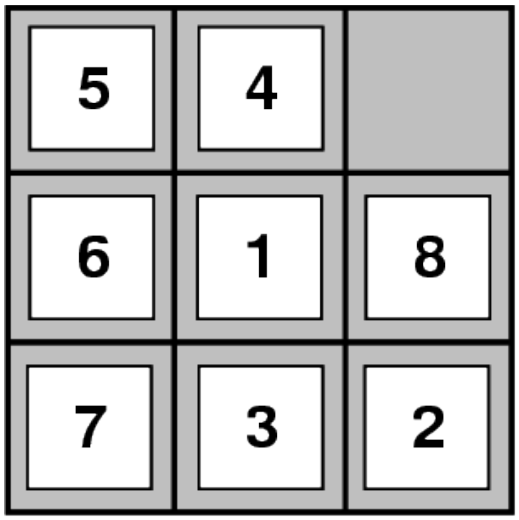
Vacuum world state space graph



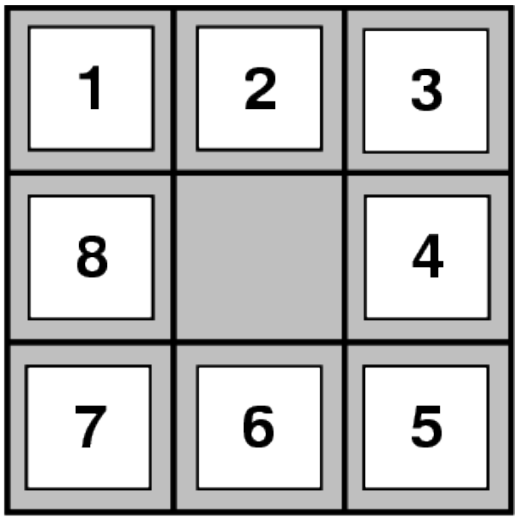
Some example problems

- Toy problems and micro-worlds
  - 8-Puzzle
  - Missionaries and Cannibals
  - Water Jug Problem
  - Roomers
  - NQueens
- Real-world problems

Another problem: 8-Puzzle



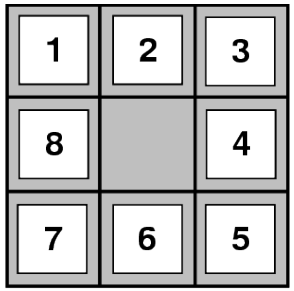
Start State



Goal State

8-puzzle

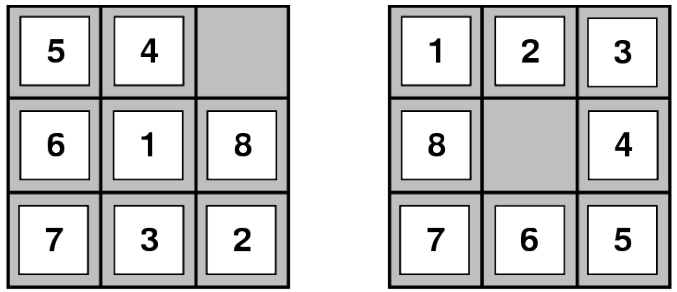
- goal
- states?
- actions?
- path cost?



Goal State

8-Puzzle

- **state:**
  - all 3 x 3 configurations of the tiles on the board
- **actions:**
  - Move Blank Square Left, Right, Up or Down.
  - This is a more efficient encoding than moving each of the 8 distinct tiles
- **path cost:**
  - +1 for each action



Start State Goal State

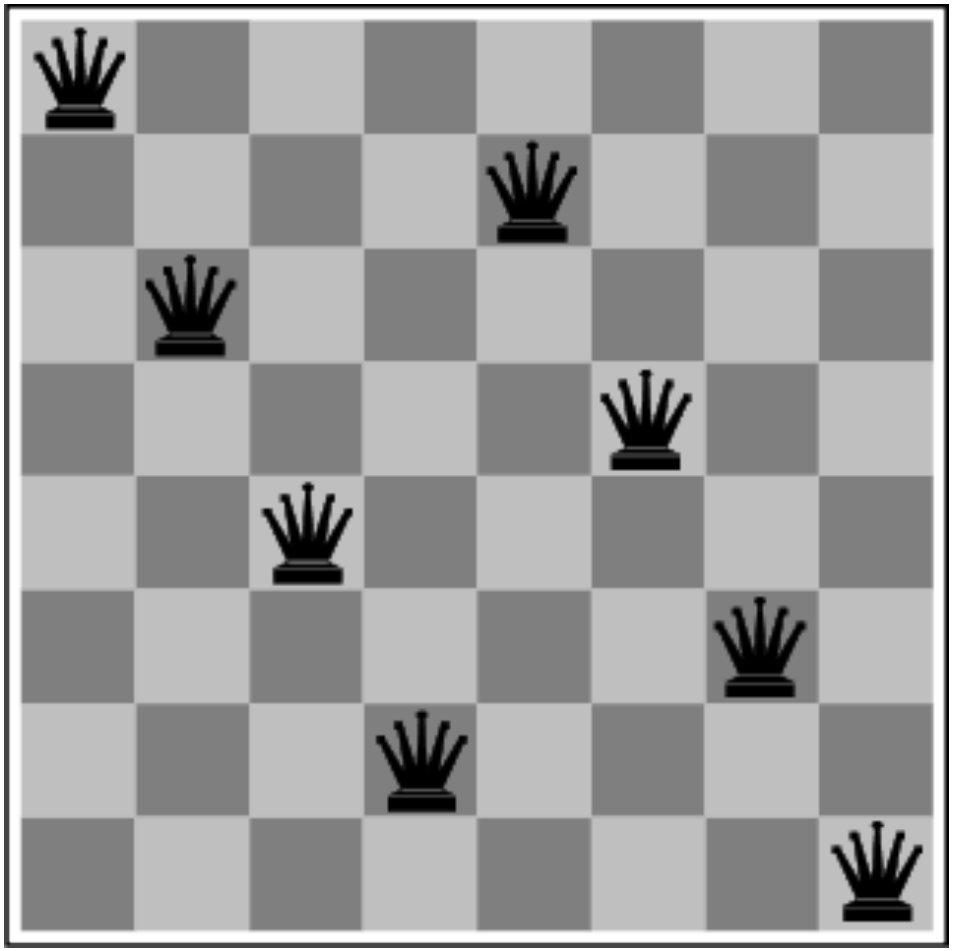
The 8-Queens Problem

State transition: ?

Initial State: ?

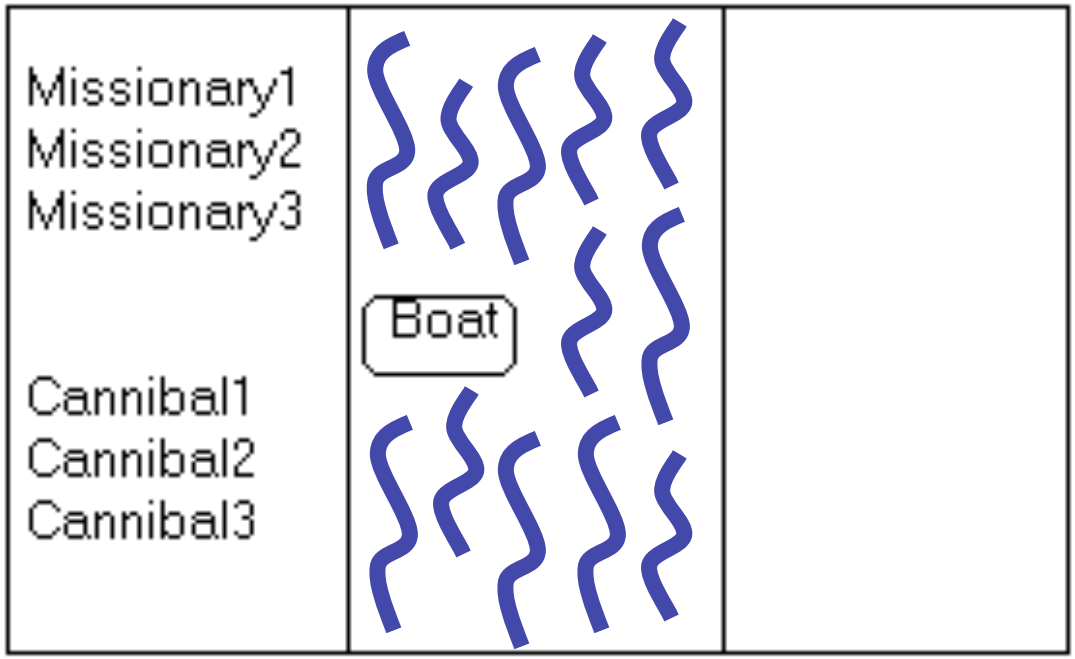
Actions: ?

Goal: Place eight queens on a chessboard such that no queen attacks any other!



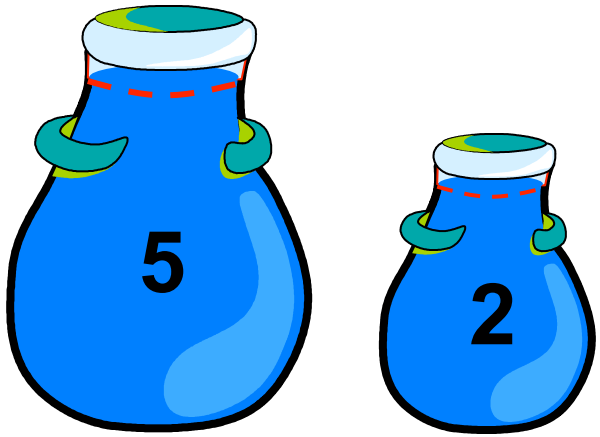
Missionaries and Cannibals

Three missionaries and three cannibals wish to cross the river. They have a small boat that will carry up to two people. Everyone can navigate the boat. If at any time the Cannibals outnumber the Missionaries on either bank of the river, they will eat the Missionaries. Find the smallest number of crossings that will allow everyone to cross the river safely.



Water Jug Problem

Given a full 5-gallon jug and a full 2-gallon jug, fill the 2-gallon jug with exactly one gallon of water.



Roomers: Baker, Cooper, Fletcher, Miller, and Smith live on different floors of an apartment house that contains only five floors. Baker does not live on the top floor. Cooper does not live on the bottom floor. Fletcher does not live on either the top or the bottom floor. Miller lives on a higher floor than does Cooper. Smith does not live on a floor adjacent to Fletcher's. Fletcher does not live on a floor adjacent to Cooper's. Where does everyone live?

[Taken verbatim from Abelson and Sussman, Structure and Interpretation of Computer Programs, second edition, M.I.T. Press, 1996. The authors attribute the puzzle to Dinesman, Superior Mathematical Puzzles, Simon and Schuster, 1968.]

Some real-world problems

- Route finding
  - directions, maps
  - computer networks
  - airline travel
- VLSI layout
- Touring (traveling salesman)
- Agent planning

Search-based agent

1. Formulate problem and goal
2. **Search for a sequence of actions that will lead to the goal (the policy)**
3. Execute the actions one at a time

Search algorithms

- We've defined the problem
- Now we want to find the solution!
- Use search techniques
  - offline, simulated exploration of state space by generating successors of already-explored states (a.k.a. expanding states)
  - Start at the initial state and search for a goal state
- What are candidate search techniques?
  - BFS
  - DFS

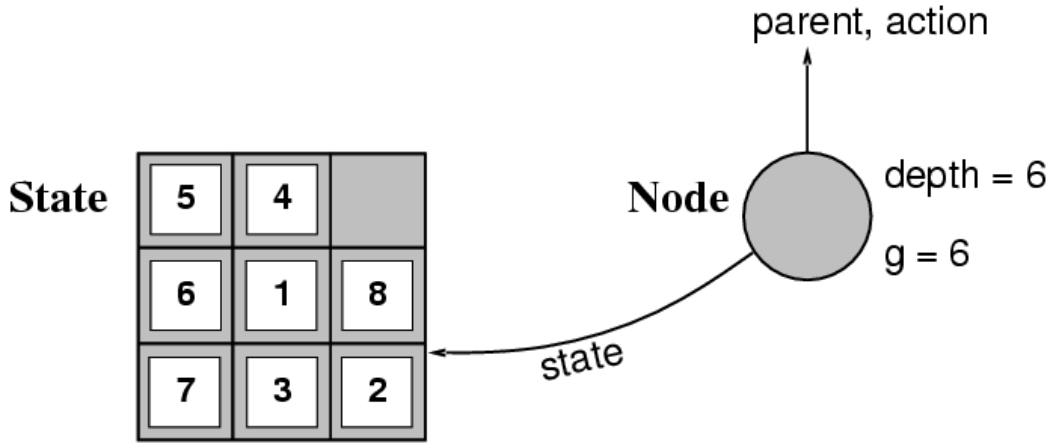
Finding the path: Tree search algorithms

- Basic idea:
  - offline, simulated exploration of state space by generating successors of already-explored states (a.k.a. expanding states)

```
def TreeSearch(problem, strategy):
  initialize search tree using information in the problem
  while true:
    if there are no candidates for expansion, return failure
    choose a leaf node for expansion according to strategy
    if node contains goal state, return solution
    else expand node and add resulting nodes to search tree
```

Careful! states vs. nodes

- A state is a (representation of) a physical configuration
- A node is a data structure constituting part of a search tree includes state, parent node, action, path cost *g(x)*, depth



- The `Expand` function creates new nodes, filling in the various fields and using the `SuccessorFn` of the problem to create the corresponding states.

Implementation: general 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
    for each action, result in SUCCESSOR-FN[problem](STATE[node]) do
        s ← a new NODE
        PARENT-NODE[s] ← node;  ACTION[s] ← action;  STATE[s] ← result
        PATH-COST[s] ← PATH-COST[node] + STEP-COST(node, action, s)
        DEPTH[s] ← DEPTH[node] + 1
        add s to successors
    return successors
```

Tree Search Algorithm

1. Add the initial state (root) to the <fringe>
2. **Choose a node (curr) to examine from the <fringe>** (if there is nothing in <fringe> - FAILURE)
3. Is curr a goal state?
   - If so, SOLUTION
   - If not, continue
4. Expand curr by applying all possible actions (add the new resulting states to the <fringe>)
5. Go to step 2

Search strategies

- A search strategy is defined by picking the order of node expansion
- How to evaluate a strategy?

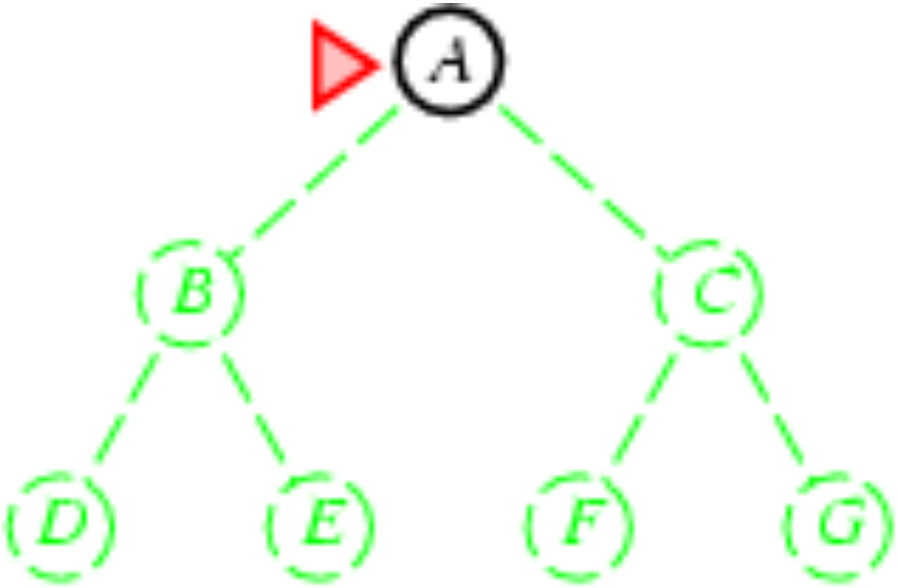
Uninformed search strategies

- Uninformed search strategies use only the information available in the problem definition
  - Depth First Search
  - Breadth First Search

Breadth-first search

- Expand shallowest unexpanded node

- Implementation:
  - *fringe* is a FIFO queue, i.e., new successors go at end



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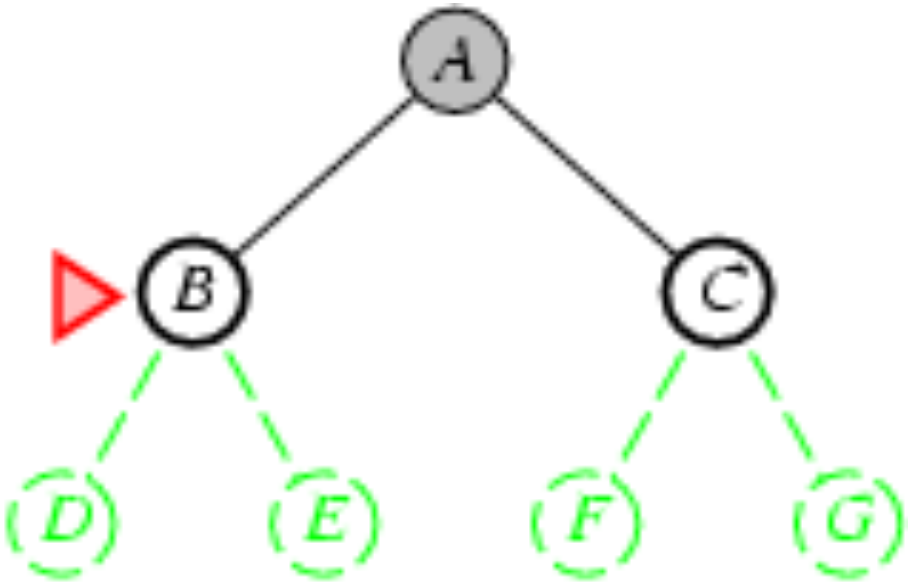

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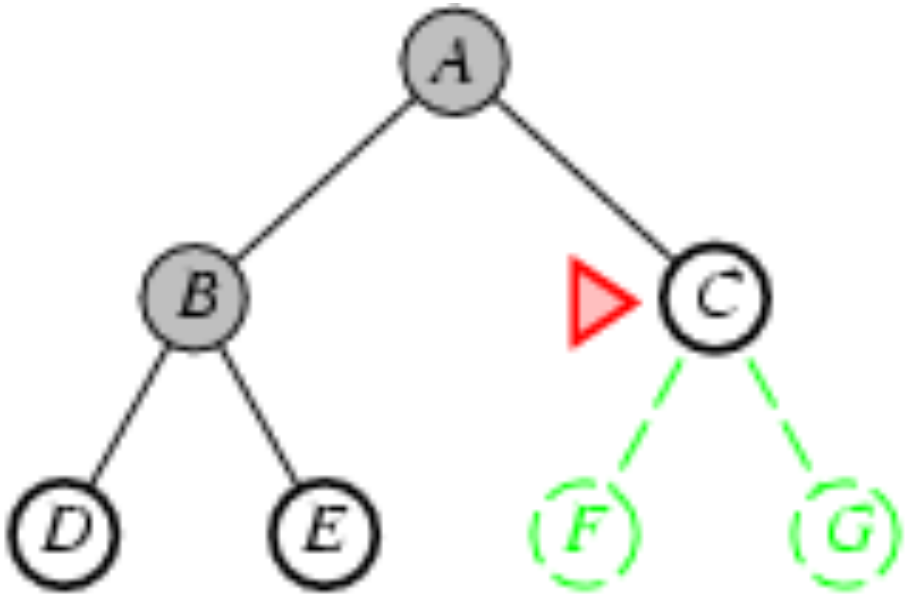

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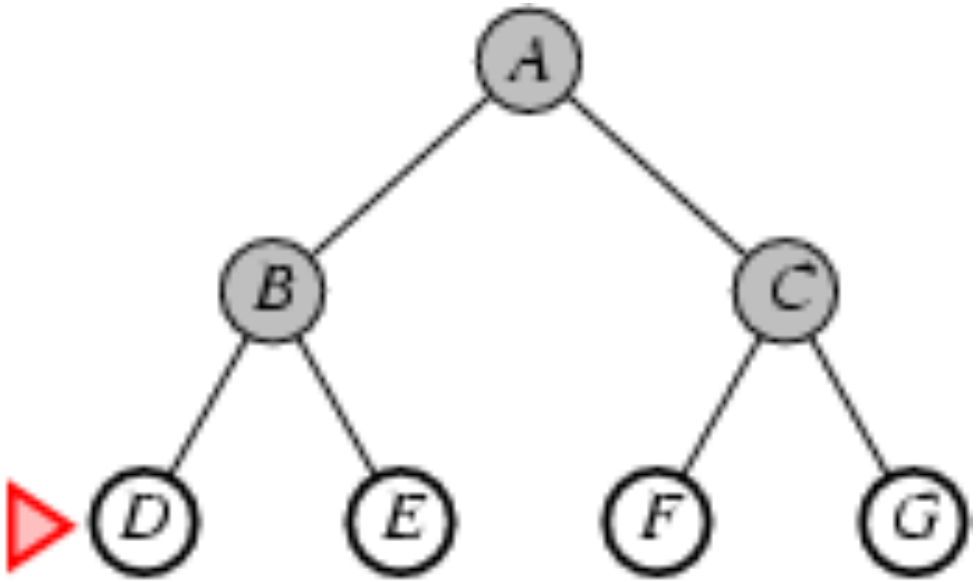

Depth-first search

- Expand deepest unexpanded node
- Implementation:
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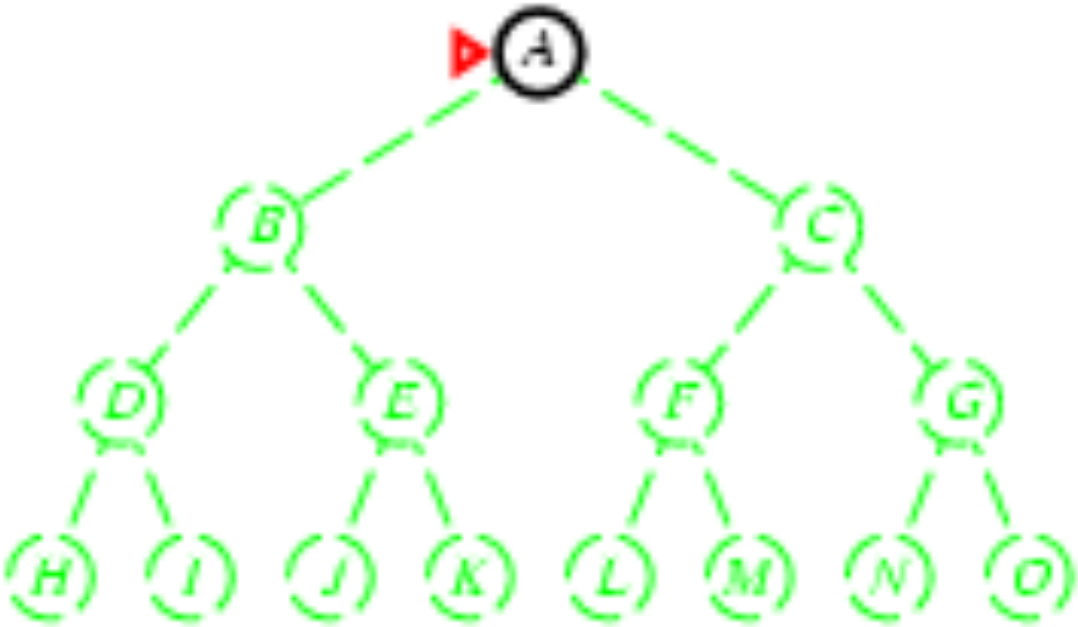

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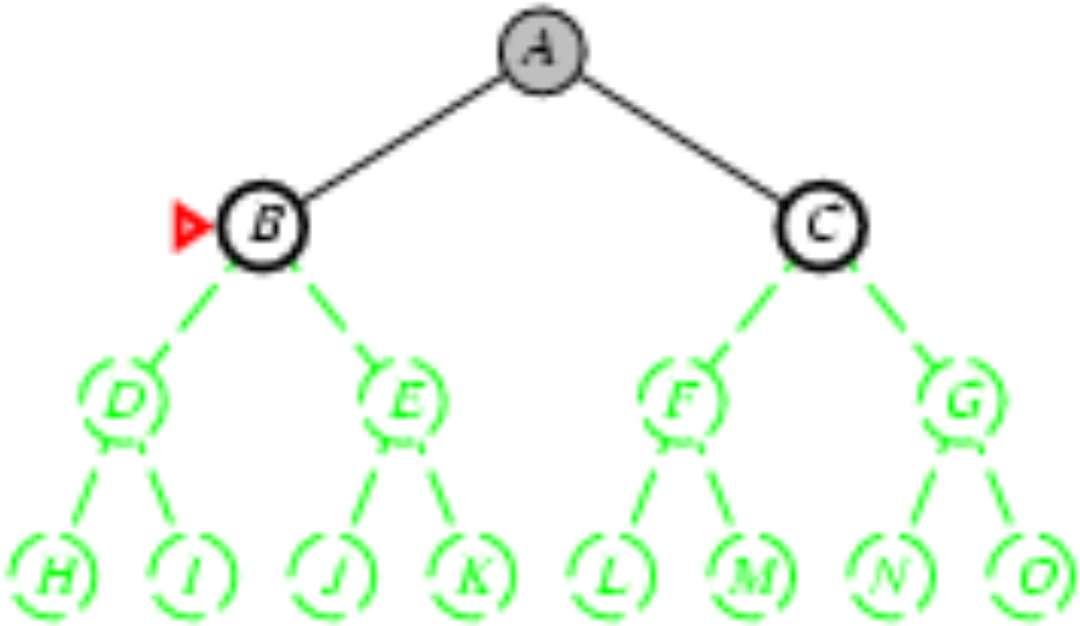

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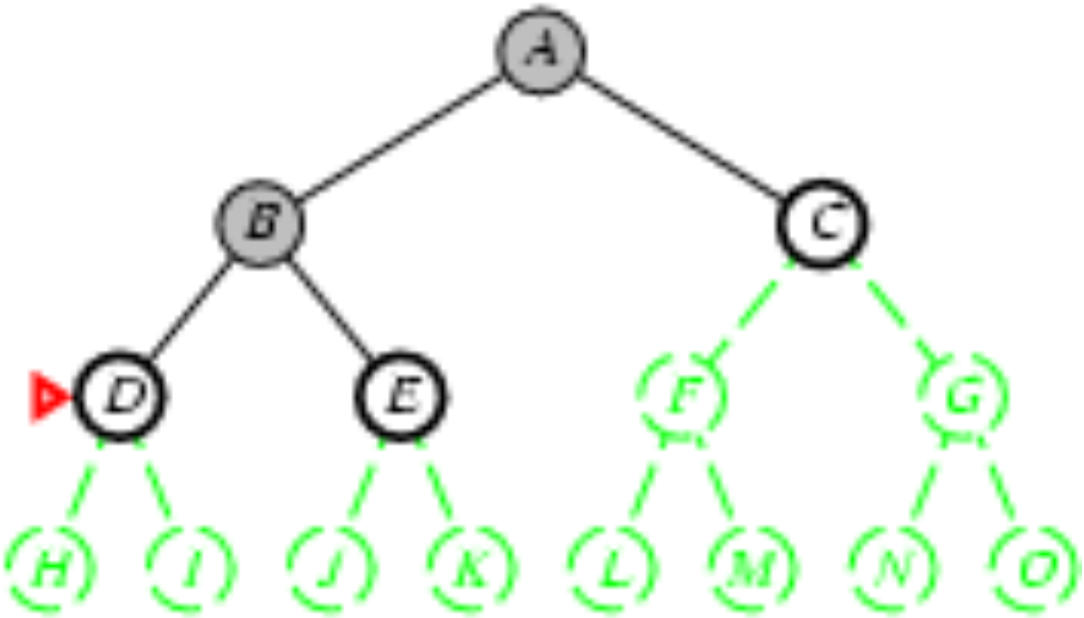

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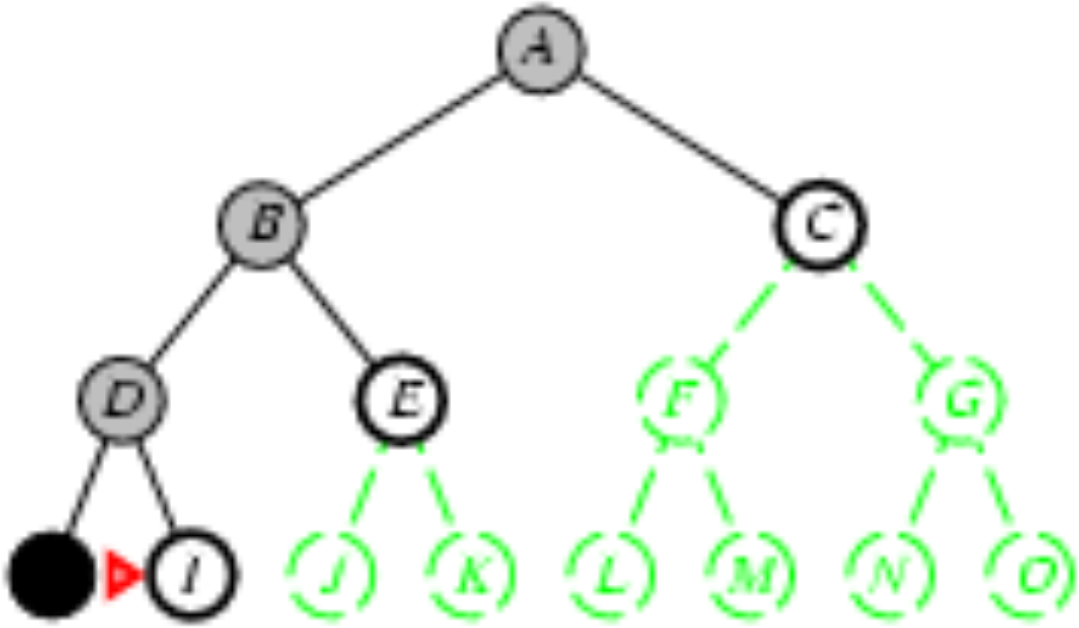

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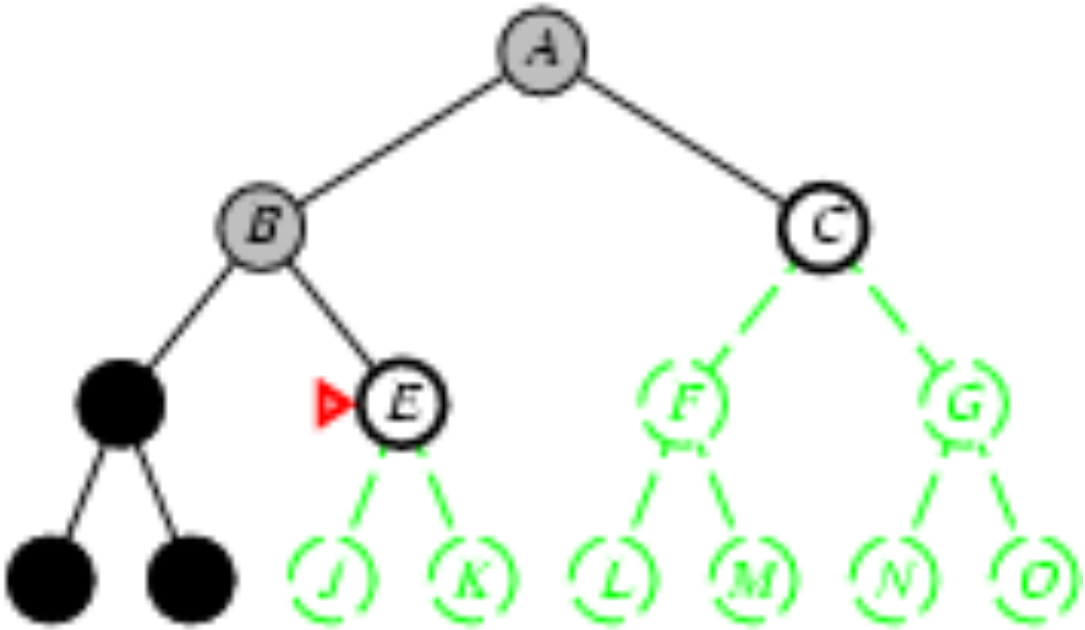

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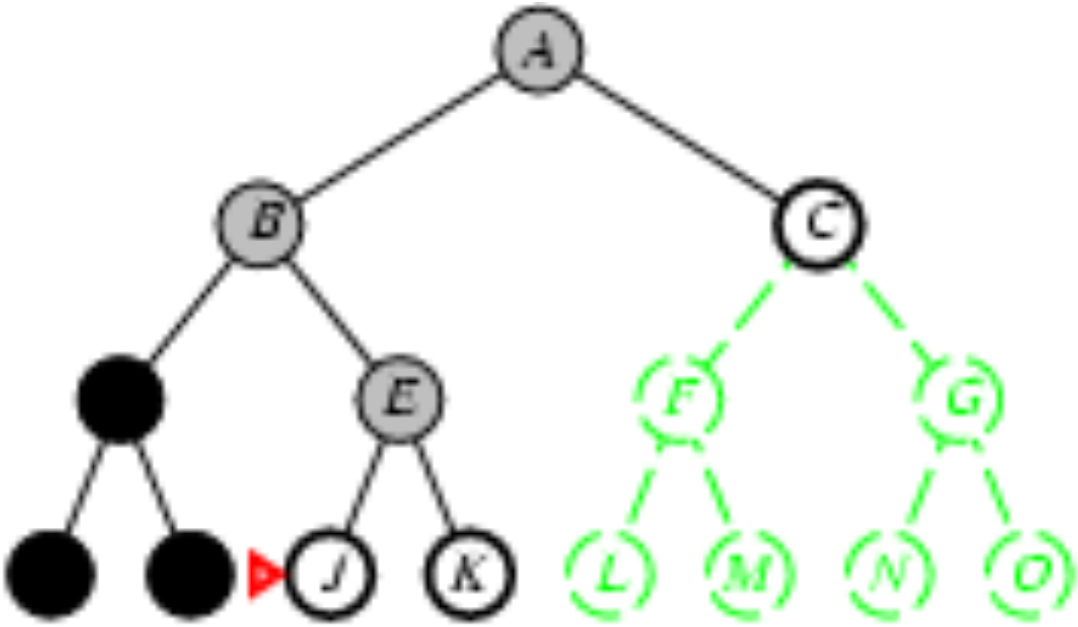

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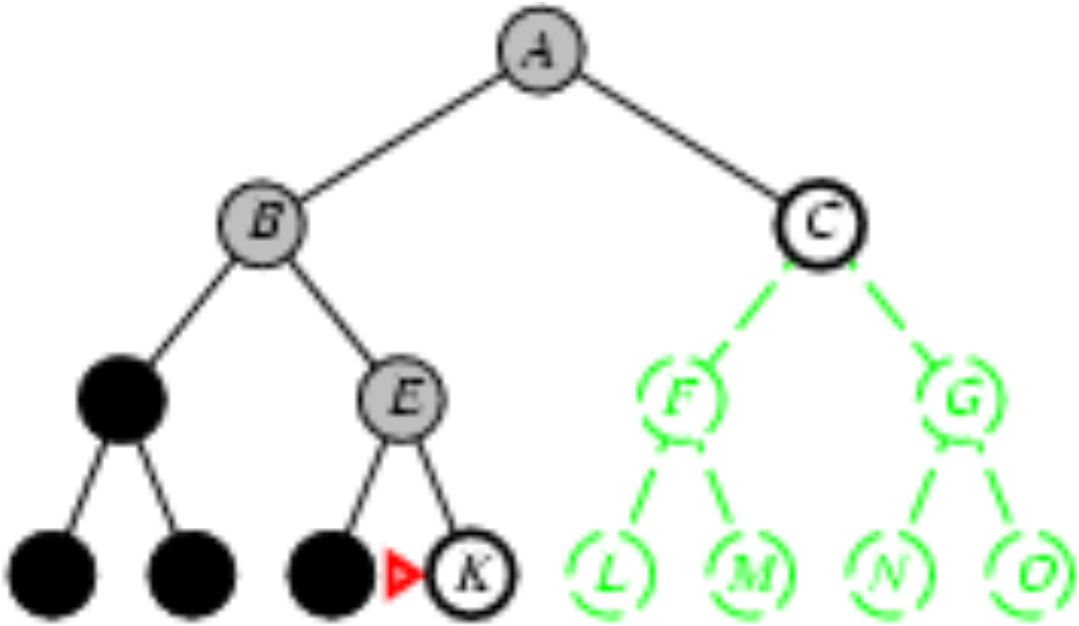

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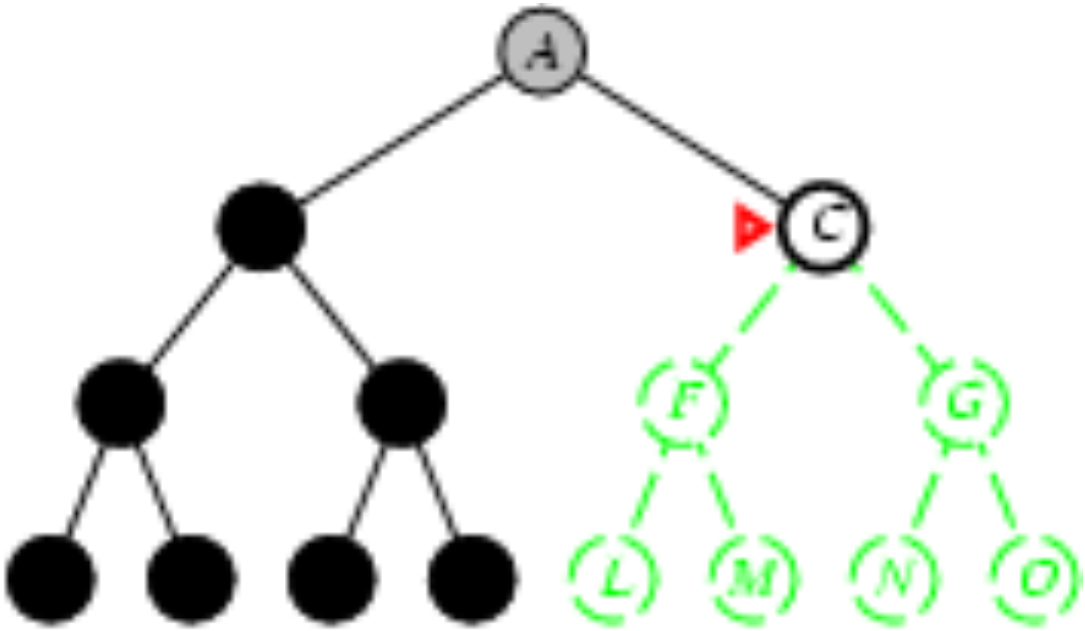

Depth-first search

- Expand deepest unexpanded node
- Implementation:
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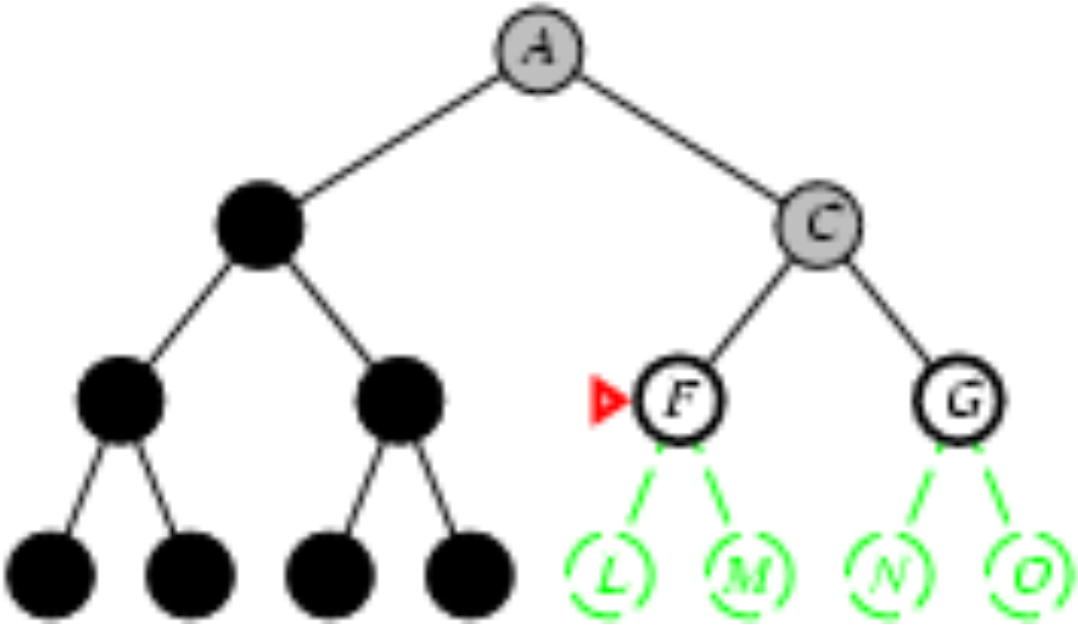

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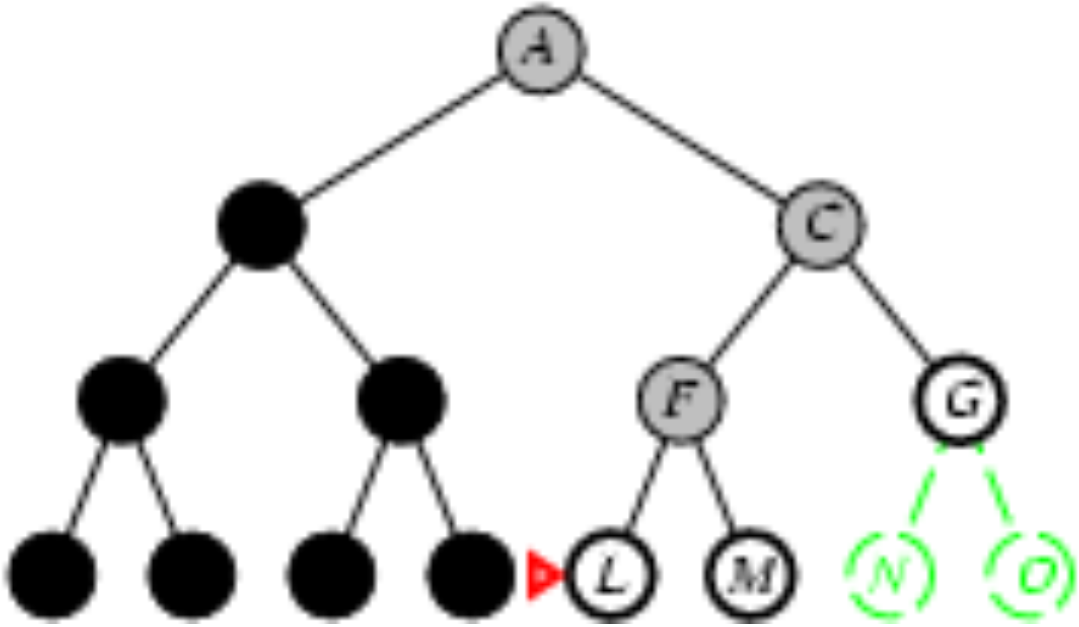

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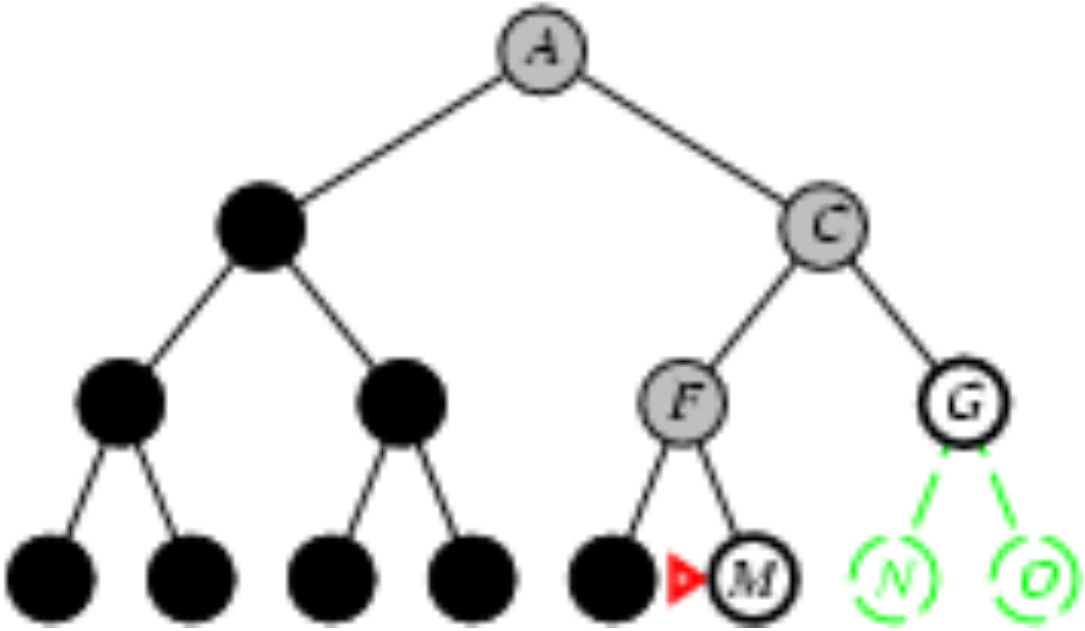


Search algorithm properties

- Time (using Big-O)
  - approximate the number of nodes generated (not necessarily examined)
- Space (using Big-O)
  - the max # of nodes stored in memory at any time
- Complete
  - If a solution exists, will we find it?
- Optimal
  - If we return a solution, will it be the best/optimal (really just shallowest) solution

Activity

- Analyze DFS and BFS according to the criteria time, space, completeness and optimality

  (for time and space, analyze in terms of *b*, *d*, and *m* (max depth)*;* for complete and optimal - simply YES or NO)

  – Which strategy would you use and why?

- Brainstorm improvements to DFS and BFS

BFS

- Time: $O(b^{d+1})$
- Space: $O(b^{d+1})$
- Complete = YES
- Optimal = YES

Time and Memory requirements for BFS

Depth	Nodes	Time	Memory
2	1100	.11 sec	1 MB
4	111,100	11 sec	106 MB
6	10^7	19 min	10 GB
8	10^9	31 hours	1 terabyte
10	10^{11}	129 days	101 terabytes
12	10^{13}	35 years	10 petabytes
14	10^{15}	3,523 years	1 exabyte

BFS with b=10, 10,000 nodes/sec; 10 bytes/node

DFS

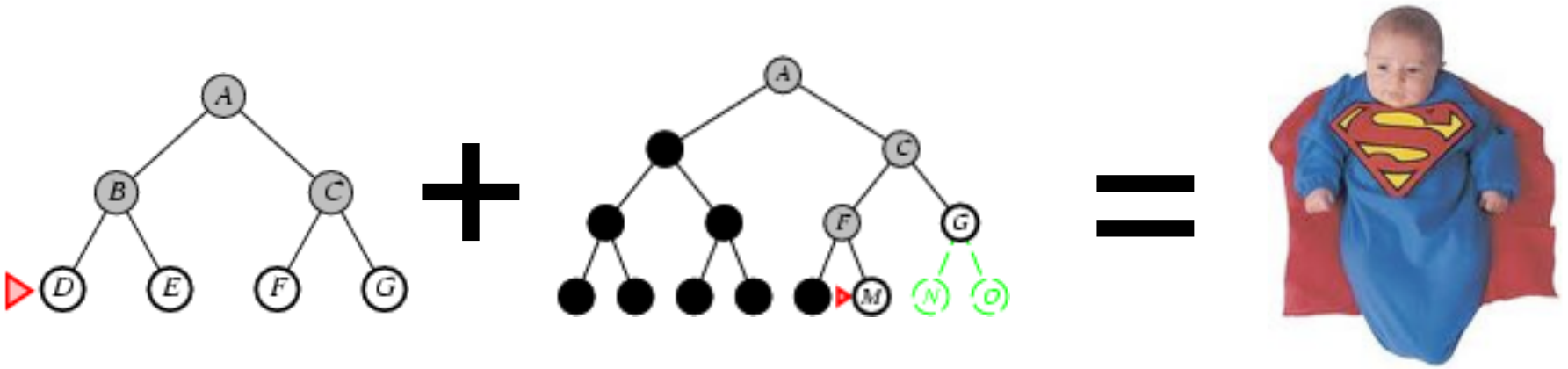
- Time: $O(b^m)$
- Space: O(bm)
- Complete = NO (YES, if space is finite and no circular paths)
- Optimal = NO

Problems with BFS and DFS

- BFS
  - memory! ☹
- DFS
  - Not optimal
  - And not even necessarily complete!

Ideas?

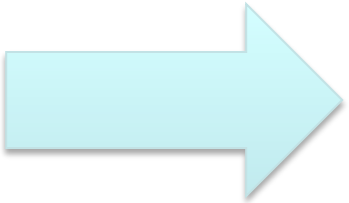
Can we combined the optimality and completeness of BFS with the memory of DFS?



Depth limited DFS

- DFS, but with a depth limit **L** specified
  - nodes at depth **L** are treated as if they have no successors
  - we only search down to depth **L**
- Time?
  - O(b^L)
- Space?
  - O(bL)
- Complete?
  - No, if solution is longer than L
- Optimal
  - No, for same reasons DFS isn't

Ideas?



Iterative deepening search

For depth 0, 1, …., ∞
    run depth limited DFS
    if solution found, return result

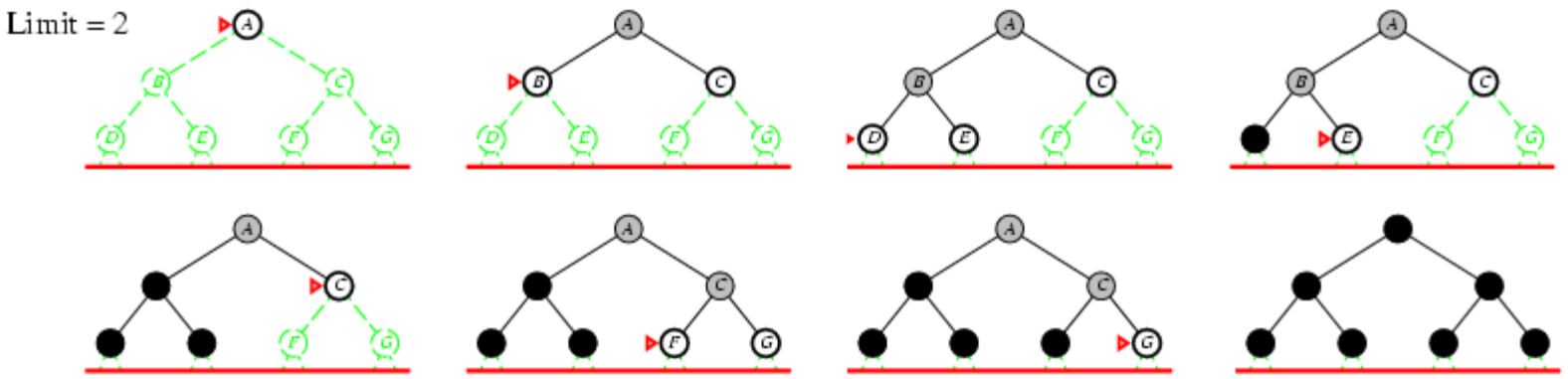
- Blends the benefits of BFS and DFS
  - searches in a similar order to BFS
  - but has the memory requirements of DFS
- Will find the solution when **L** is the depth of the shallowest goal

Iterative deepening search *L* =0

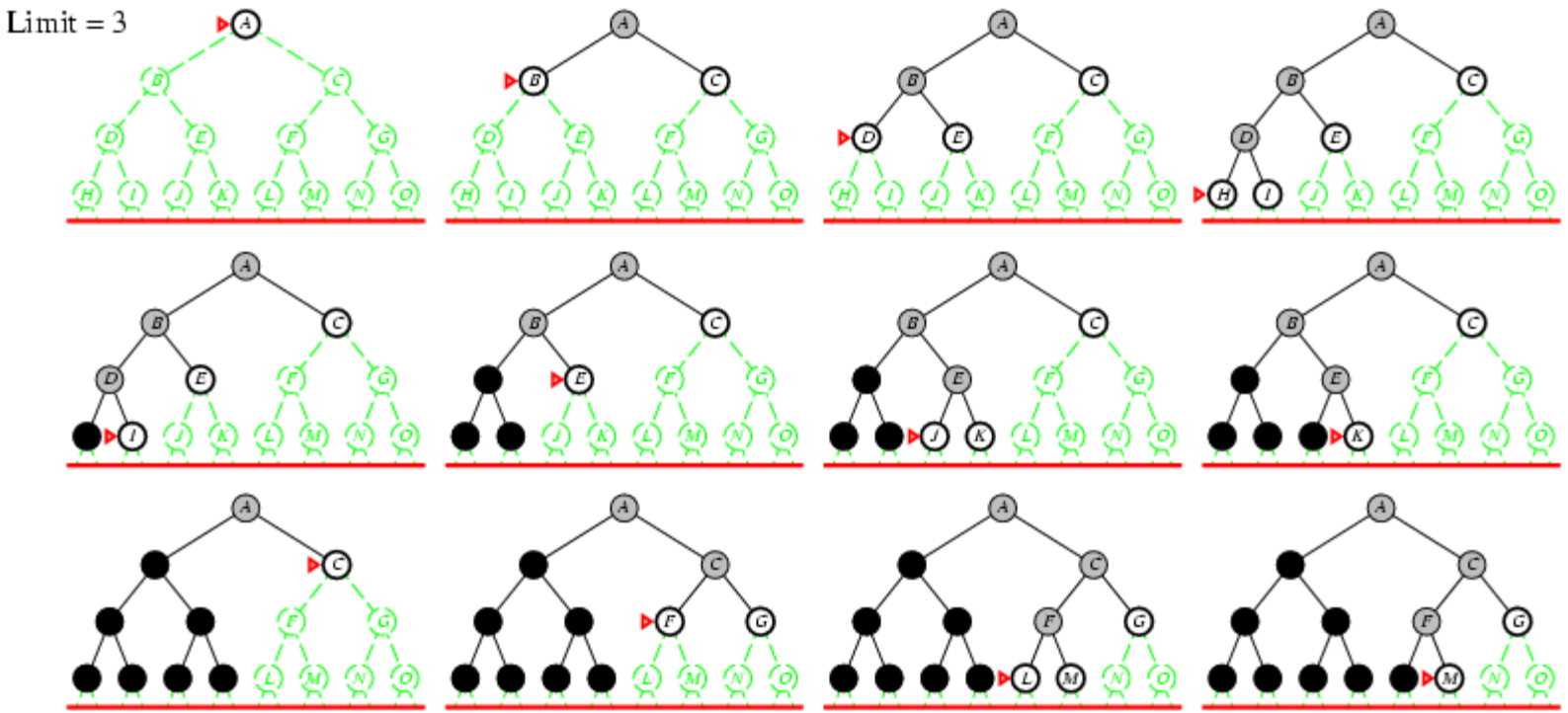
Limit = 0

Iterative deepening search *L* =1

Iterative deepening search *L* =2



Iterative deepening search *L* =3



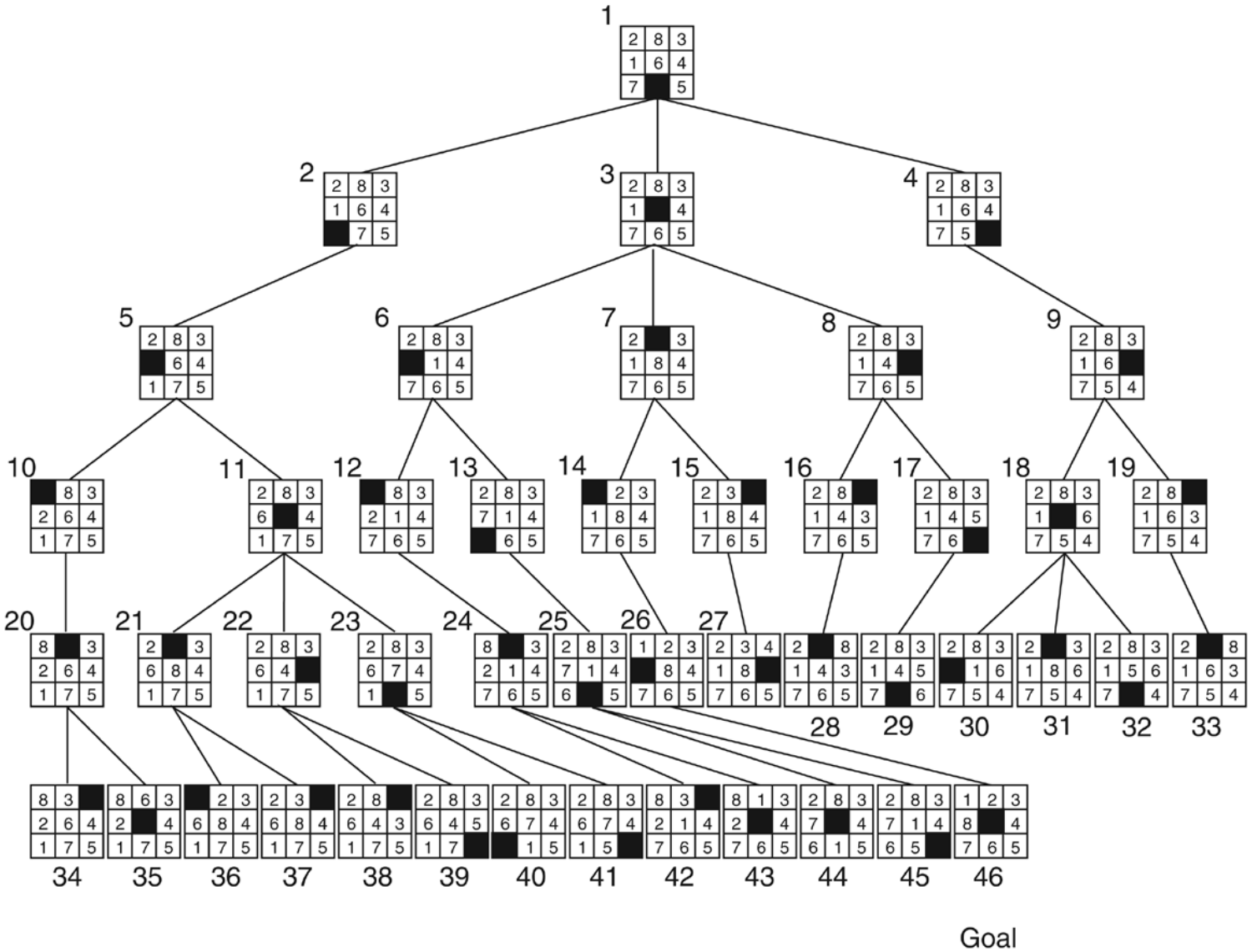
Time?

- L = 0: 1
- L = 1: $1 + b$
- L = 2: $1 + b + b^2$
- L = 3: $1 + b + b^2 + b^3$
- …
- L = d: $1 + b + b^2 + b^3 + \ldots + b^d$
- Overall:
  - $d(1) + (d-1)b + (d-2)b^2 + (d-3)b^3 + \ldots + b^d$
  - $O(b^d)$
  - the cost of the repeat of the lower levels is subsumed by the cost at the highest level

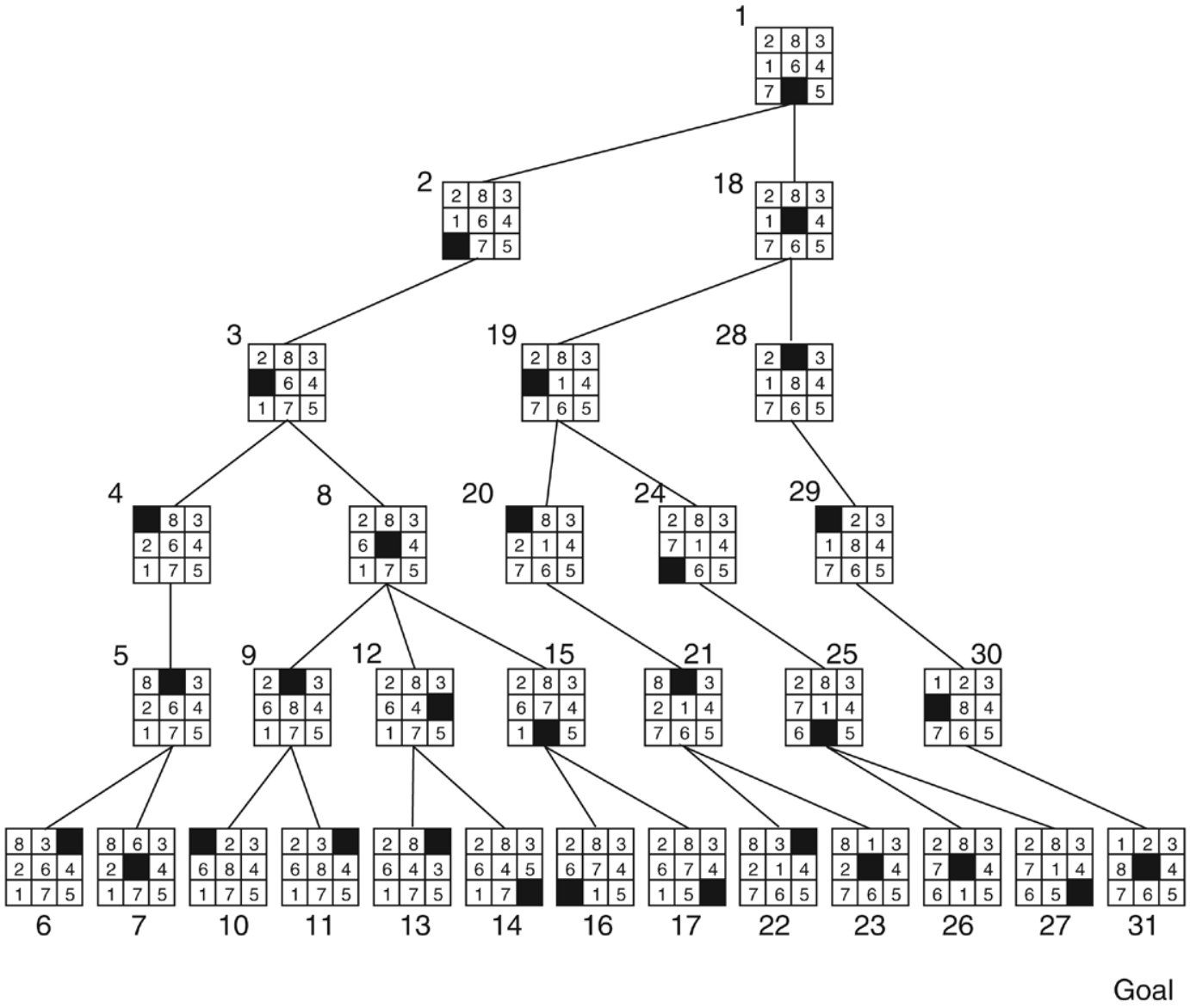
Properties of iterative deepening search

- Space?
  - *O(bd)*
- Complete?
  - Yes
- Optimal?
  - Yes

Breadth-first search of the 8-puzzle - # of node denotes order in which the nodes are visited.



Depth-first search of the 8-puzzle with a depth bound of 5 (order on node denotes the order in which the nodes are examined - this pic is missing some nodes that were added but not examined).

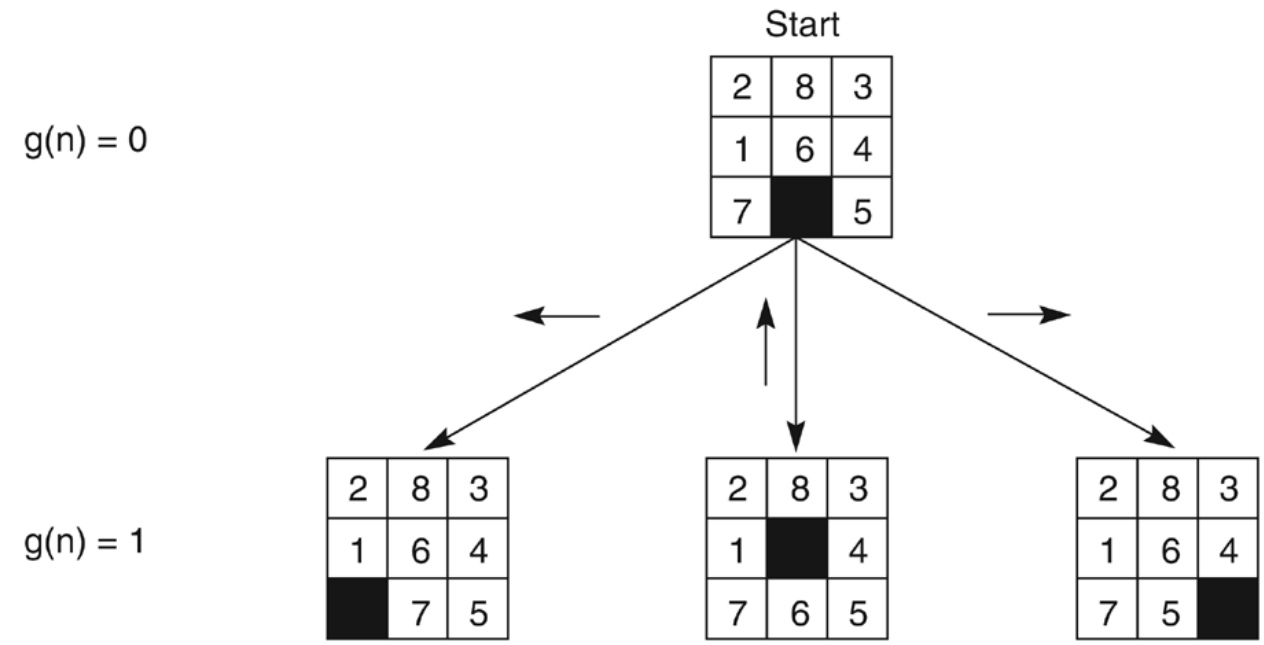


Two heuristics applied to states in the 8-puzzle.

	Tiles out of place	Sum of distances out of place
2 8 3 1 6 4 ■ 7 5	**5**	**6**
2 8 3 1 ■ 4 7 6 5	**3**	**4**
2 8 3 1 6 4 7 5 ■	**5**	**6**

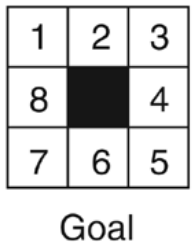
Goal

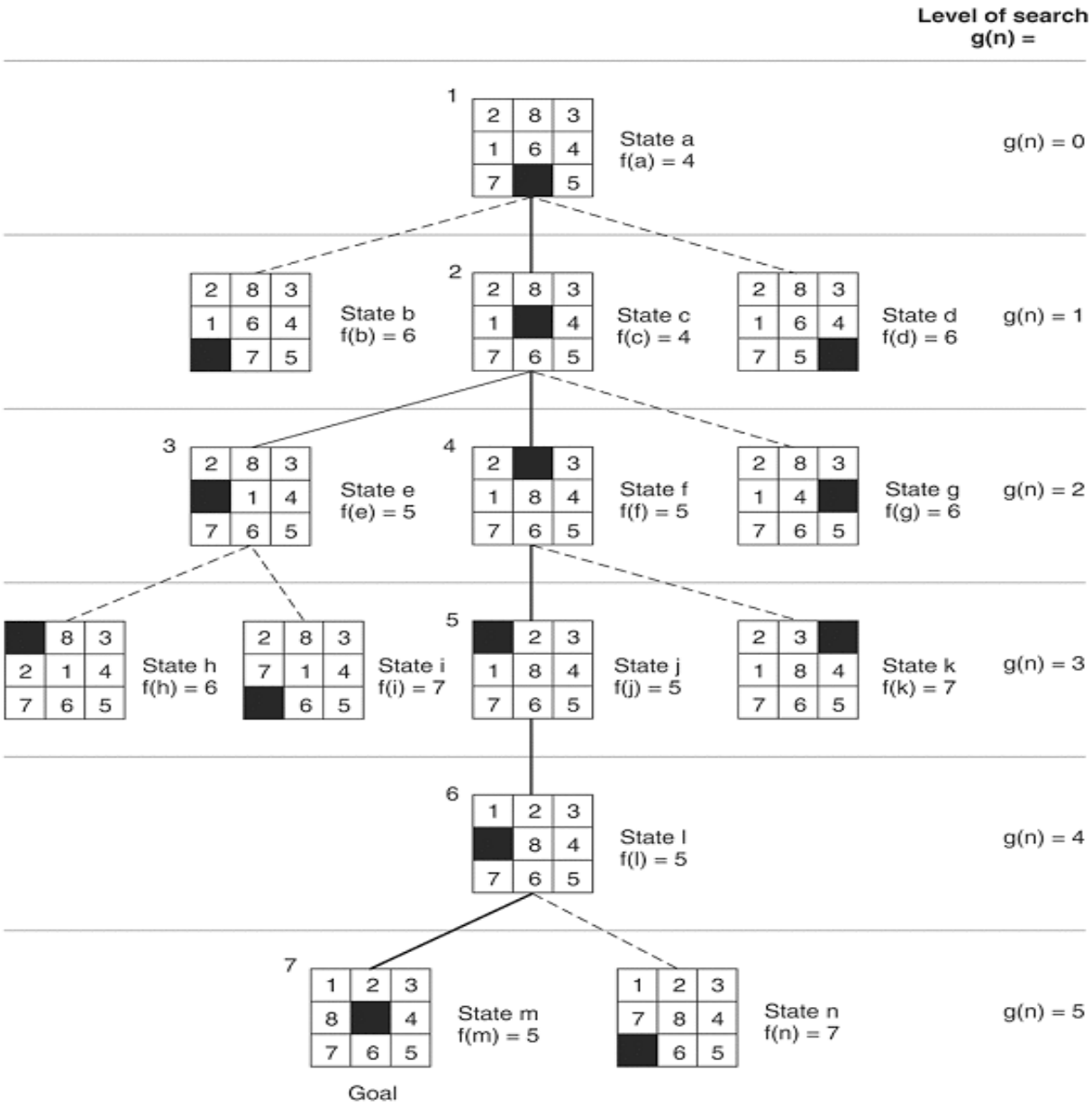
The heuristic **f** applied to states in the 8-puzzle.



Values of f(n) for each state,

where:
f(n) = g(n) + h(n),
g(n) = actual distance from n to the start state, and
h(n) = number of tiles out of place.



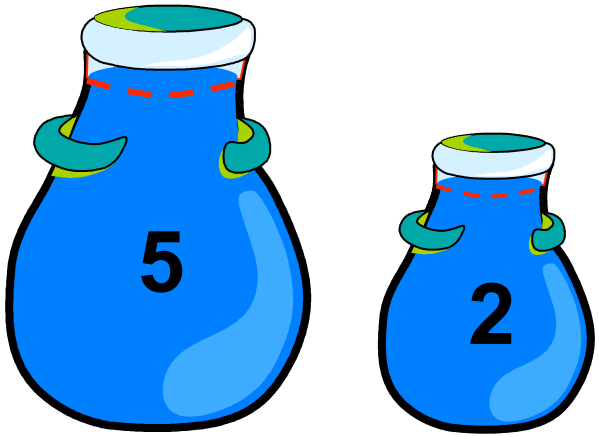


State space generated in heuristic search of the 8-puzzle graph.

Missionaries and Cannibals Solution

	Near side		***Far side***	
0 Initial setup:	MMMCCC	B		-
1 Two cannibals cross over:	MMMC		B	CC
2 One comes back:	MMMCC	B		C
3 Two cannibals go over again:	MMM		B	CCC
4 One comes back:	MMMC	B		CC
5 Two missionaries cross:	MC		B	MMCC
6 A missionary & cannibal return:	MMCC	B		MC
7 Two missionaries cross again:	CC		B	MMMC
8 A cannibal returns:	CCC	B		MMM
9 Two cannibals cross:	C		B	MMMCC
10 One returns:	CC	B		MMMC
11 And brings over the third:	-		B	MMMCCC

Water Jug Problem



- State = (x,y), where x is the number of gallons of water in the 5-gallon jug and y is # of gallons in the 2-gallon jug
- Initial State = (5,2)
- Goal State = (*,1), where * means any amount

Operator table

Name	Cond.	Transition	Effect
Empty5	–	(x,y)→(0,y)	Empty 5-gal. jug
Empty2	–	(x,y)→(x,0)	Empty 2-gal. jug
2to5	$x \leq 3$	(x,2)→(x+2,0)	Pour 2-gal. into 5-gal.
5to2	$x \geq 2$	(x,0)→(x-2,2)	Pour 5-gal. into 2-gal.
5to2part	$y < 2$	(1,y)→(0,y+1)	Pour partial 5-gal. into 2-gal.

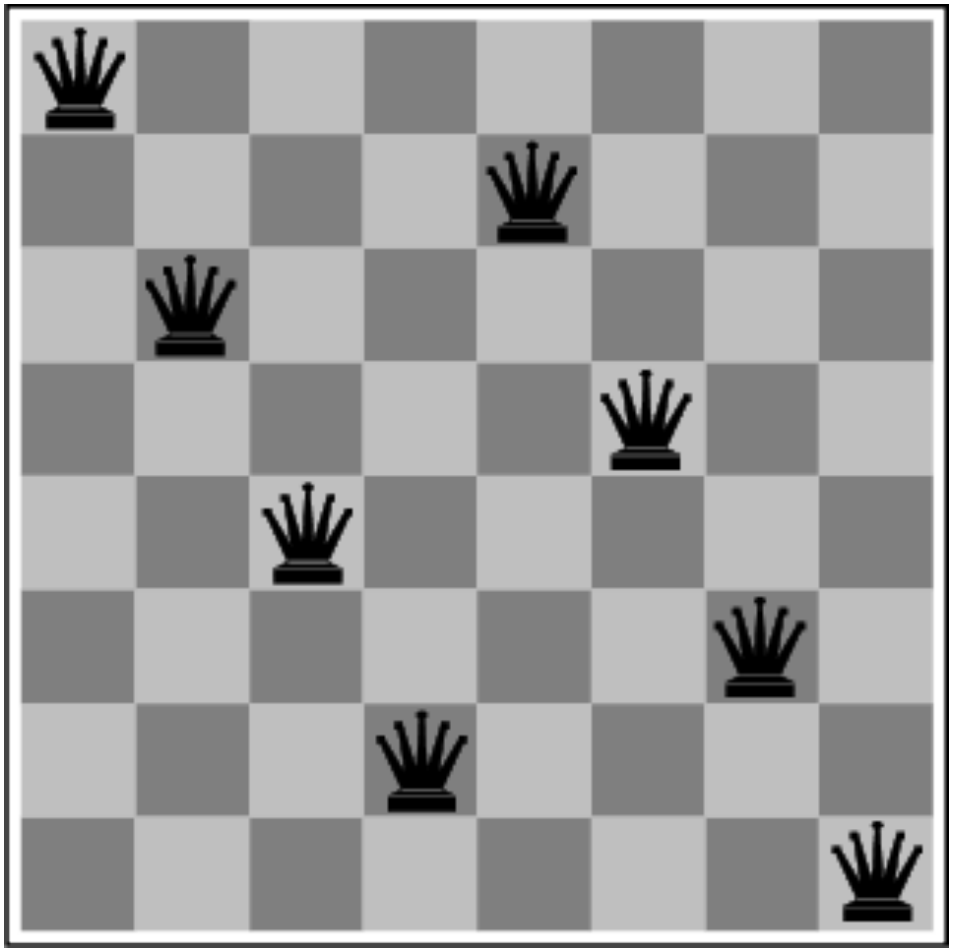
The 8-Queens Problem

State transition: ?

Initial State: ?

Actions: ?

Goal: Place eight queens on a chessboard such that no queen attacks any other!



Roomers: Baker, Cooper, Fletcher, Miller, and Smith live on different floors of an apartment house that contains only five floors. Baker does not live on the top floor. Cooper does not live on the bottom floor. Fletcher does not live on either the top or the bottom floor. Miller lives on a higher floor than does Cooper. Smith does not live on a floor adjacent to Fletcher's. Fletcher does not live on a floor adjacent to Cooper's. Where does everyone live?

[Taken verbatim from Abelson and Sussman, Structure and Interpretation of Computer Programs, second edition, M.I.T. Press, 1996. The authors attribute the puzzle to Dinesman, Superior Mathematical Puzzles, Simon and Schuster, 1968.]