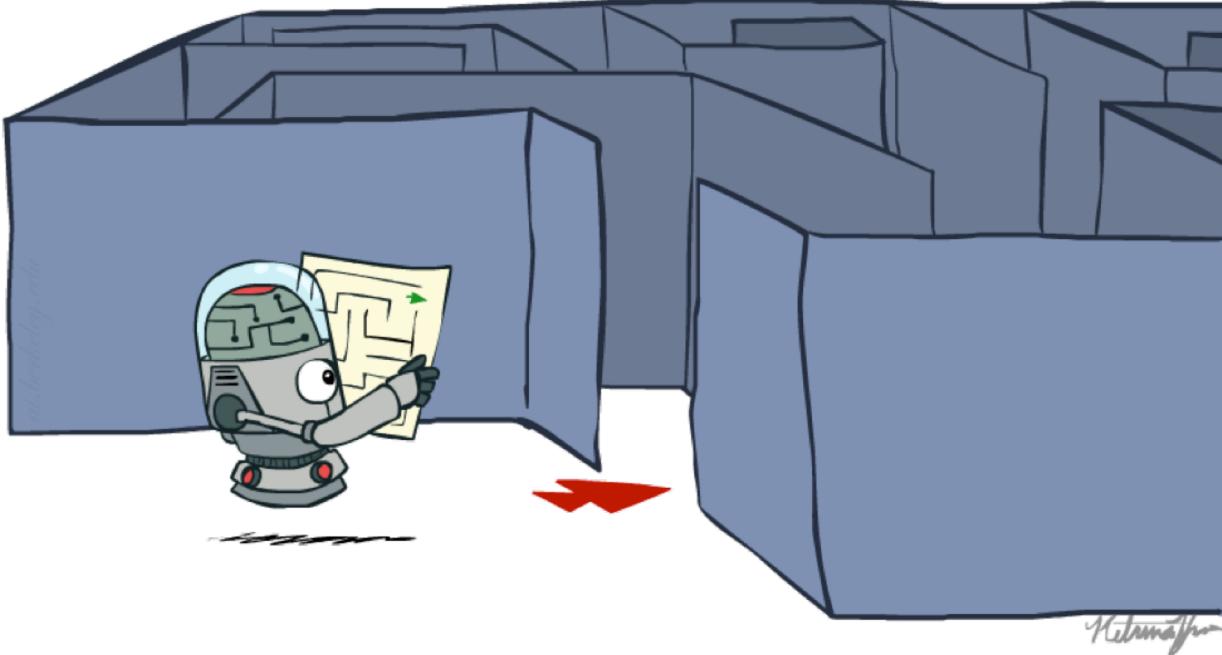


CS 188: Artificial Intelligence

Search

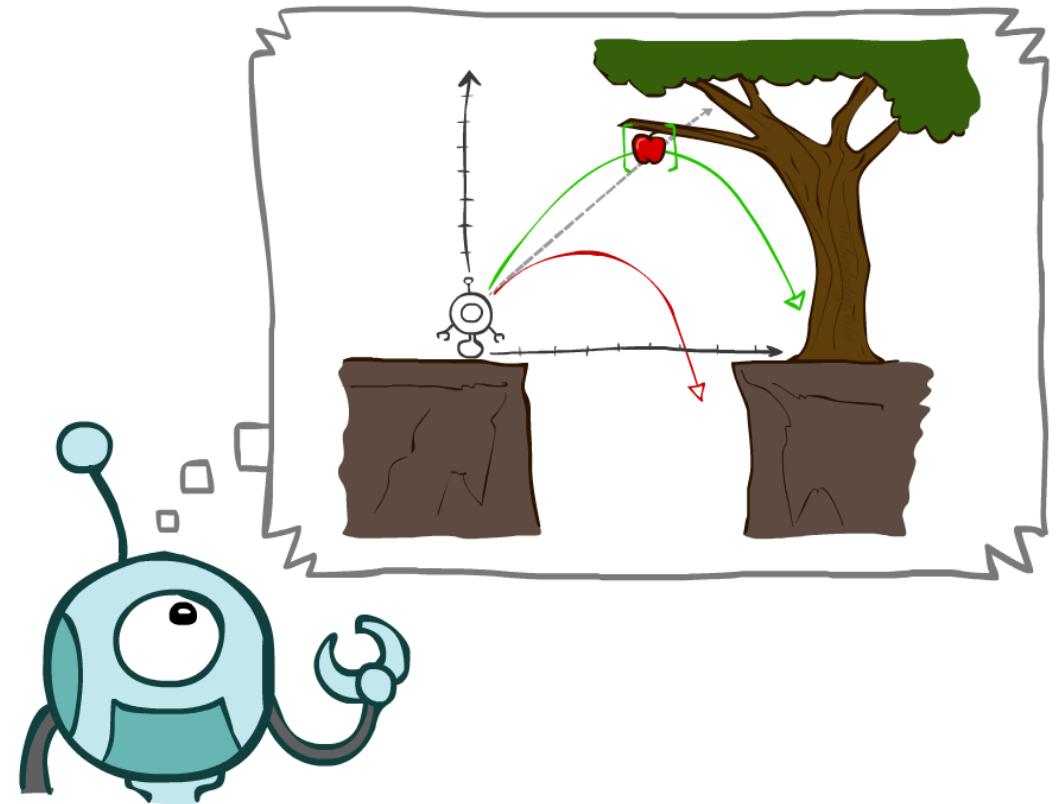


Instructors: Pieter Abbeel & Dan Klein

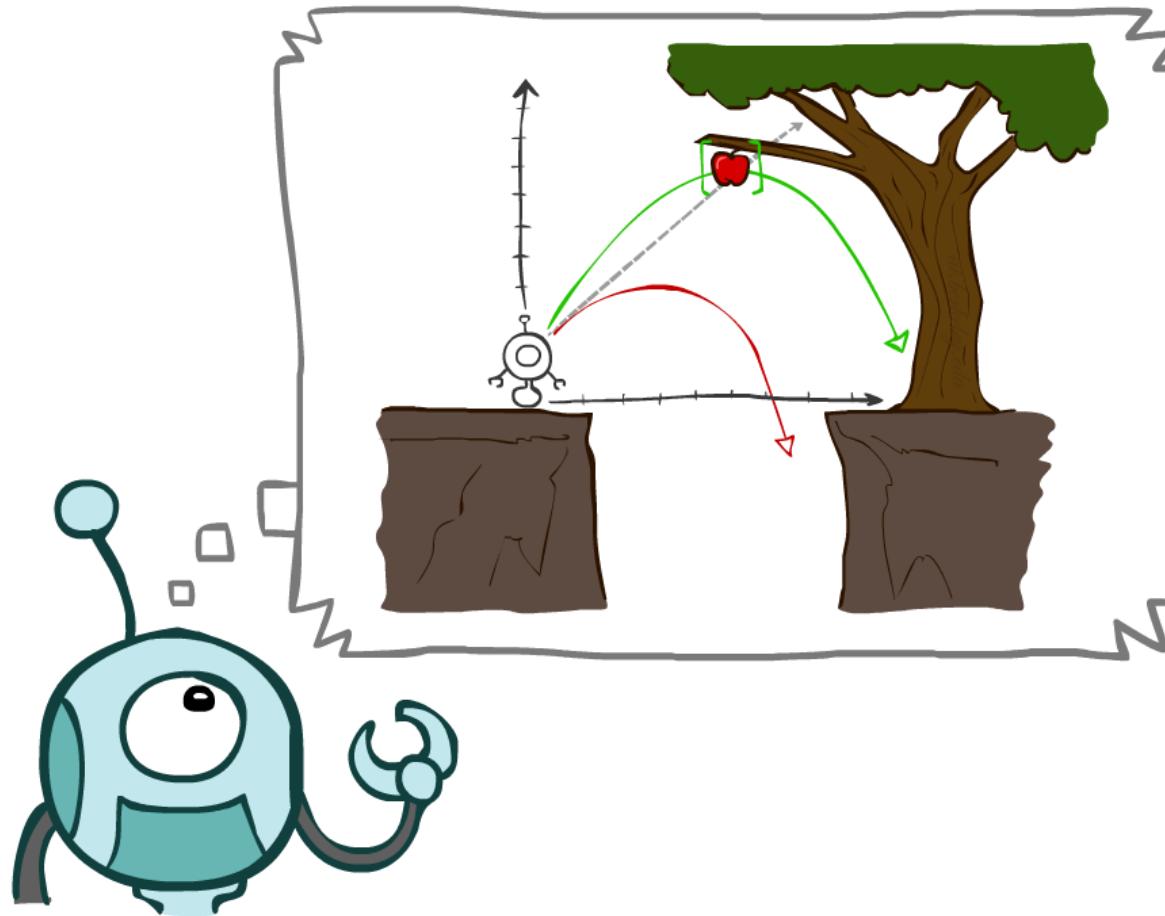
University of California, Berkeley

Today

- Agents that Plan Ahead
- Search Problems
- Uninformed Search Methods
 - Depth-First Search
 - Breadth-First Search
 - Uniform-Cost Search

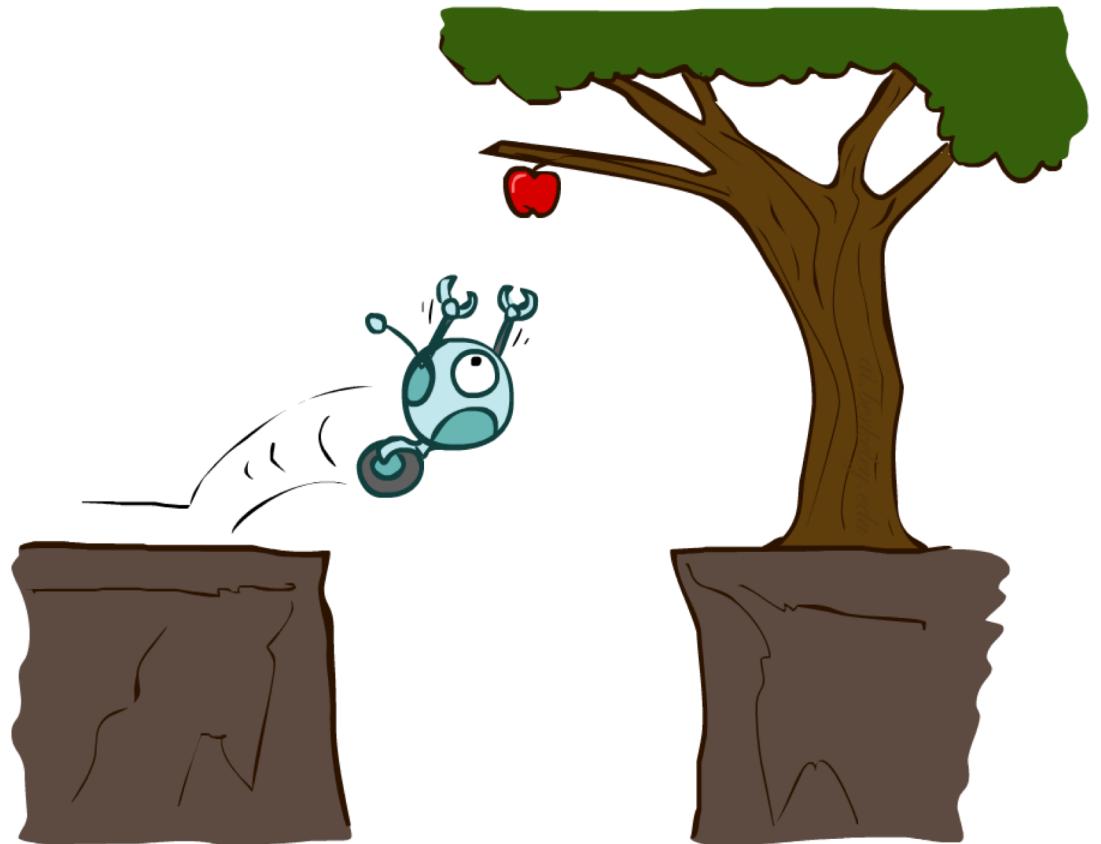


Agents that Plan



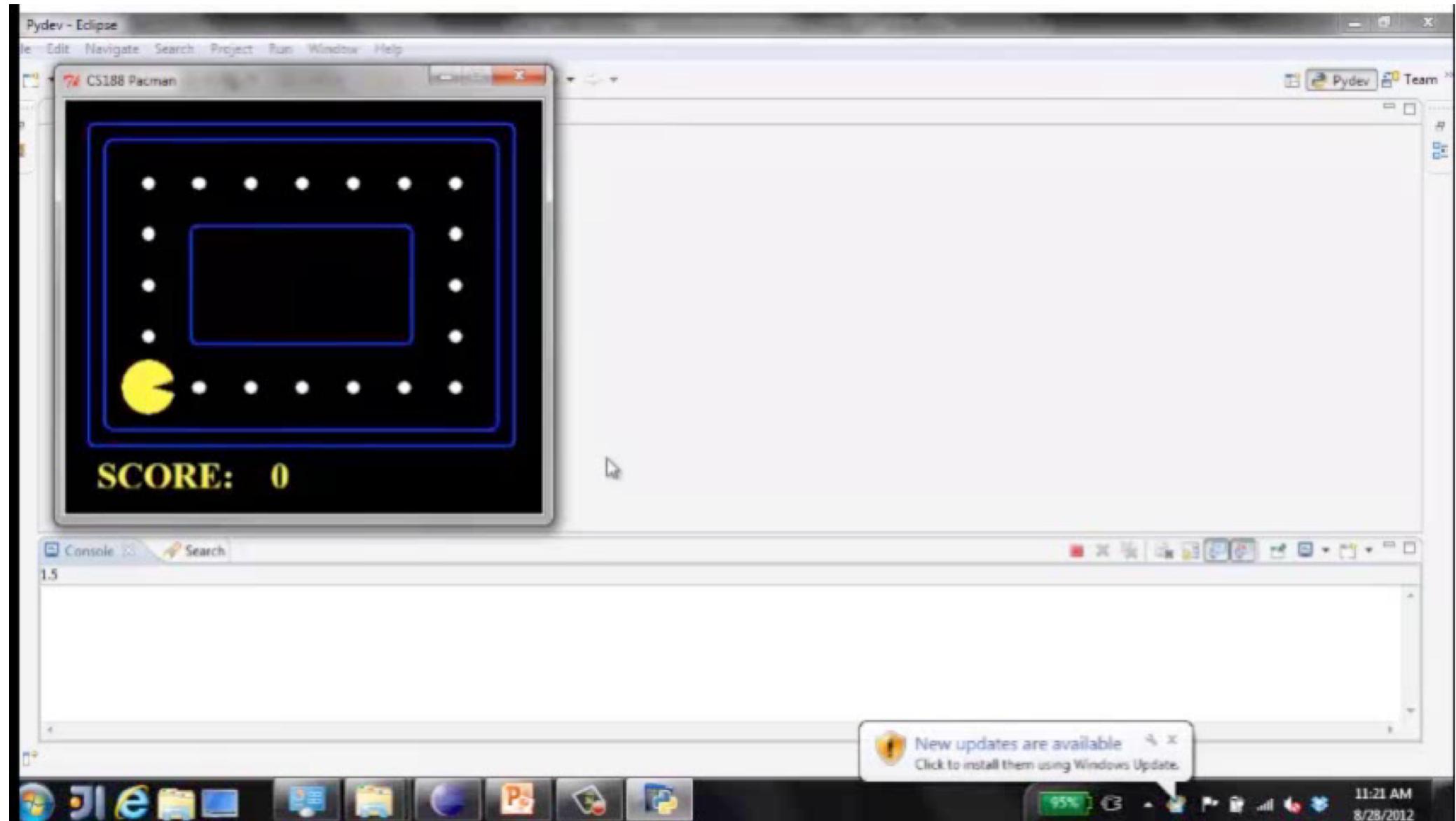
Reflex Agents

- Reflex agents:
 - Choose action based on current percept (and maybe memory)
 - May have memory or a model of the world's current state
 - Do not consider the future consequences of their actions
 - Consider how the world IS
- Can a reflex agent be rational?

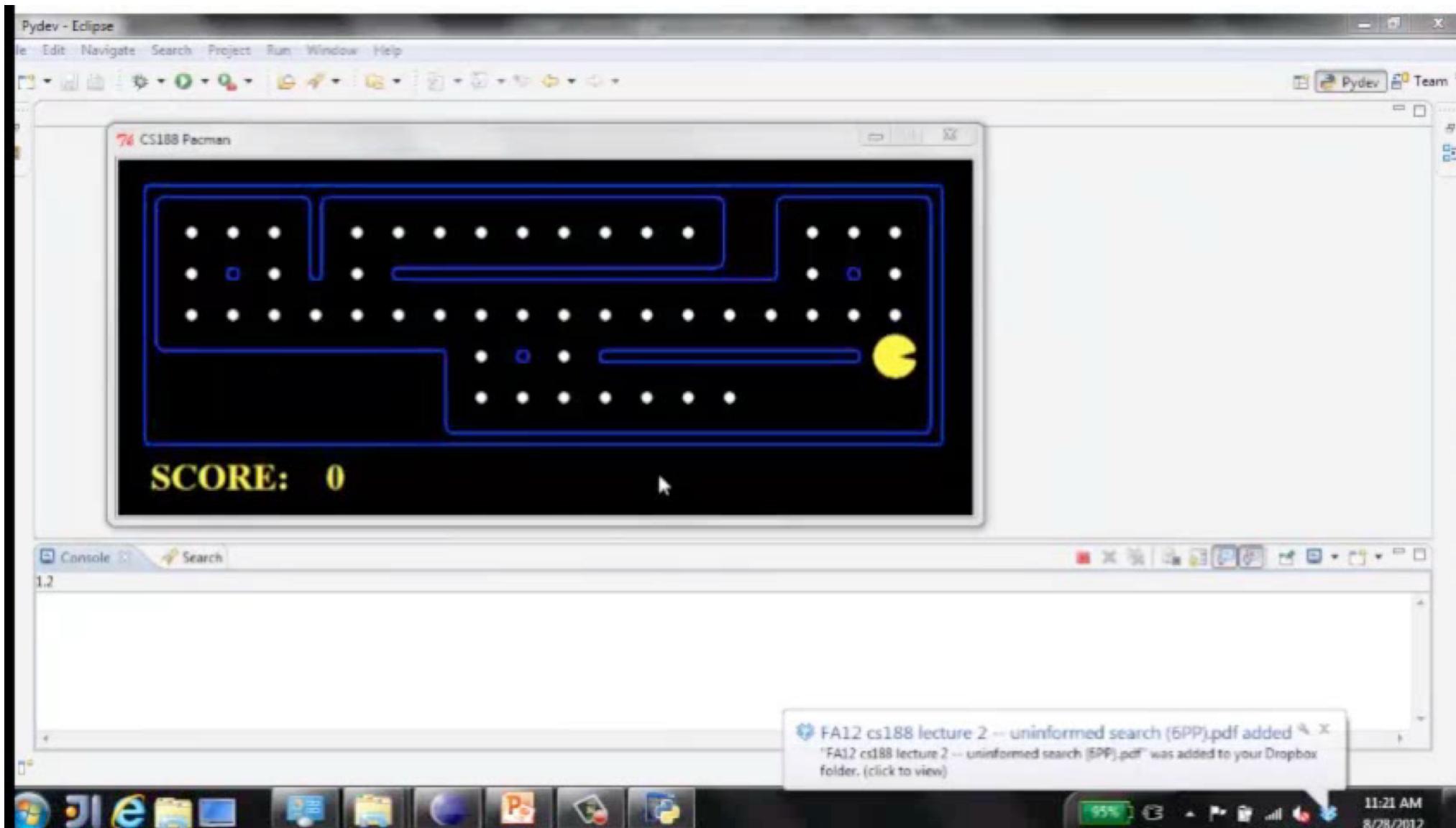


[Demo: reflex optimal (L2D1)]
[Demo: reflex optimal (L2D2)]

Video of Demo Reflex Optimal

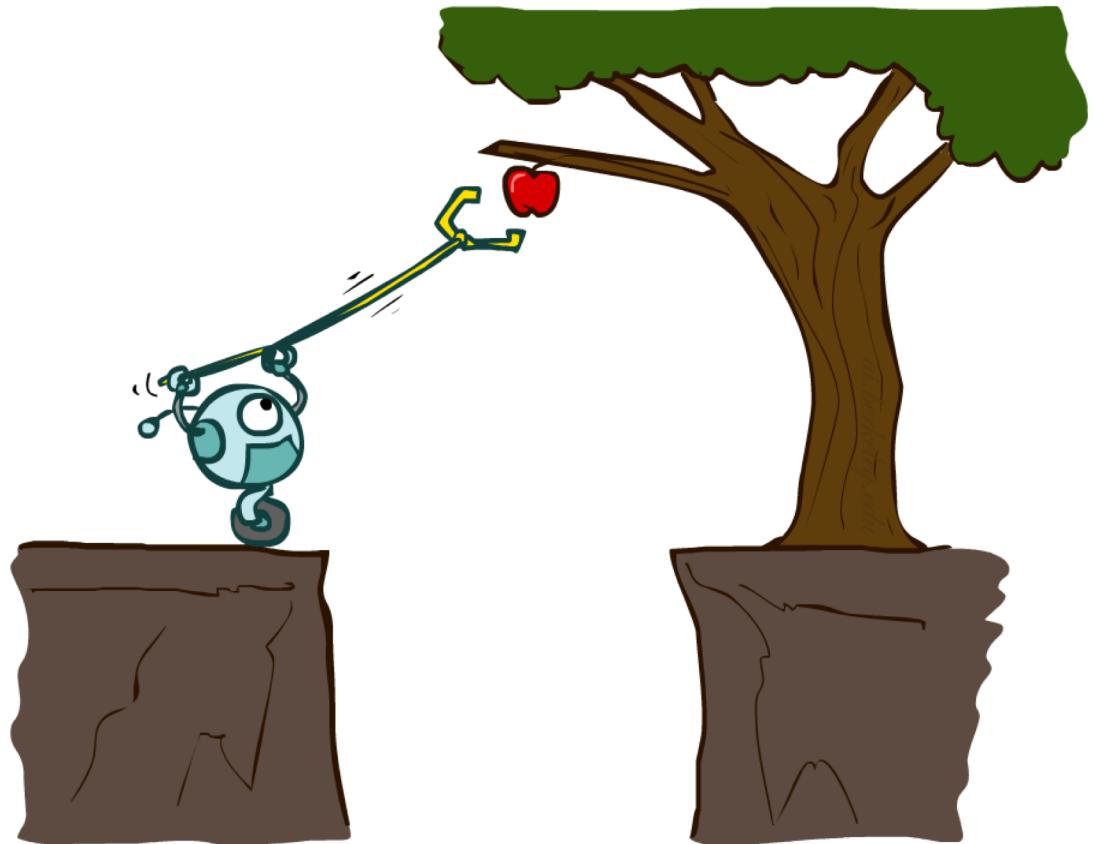


Video of Demo Reflex Odd



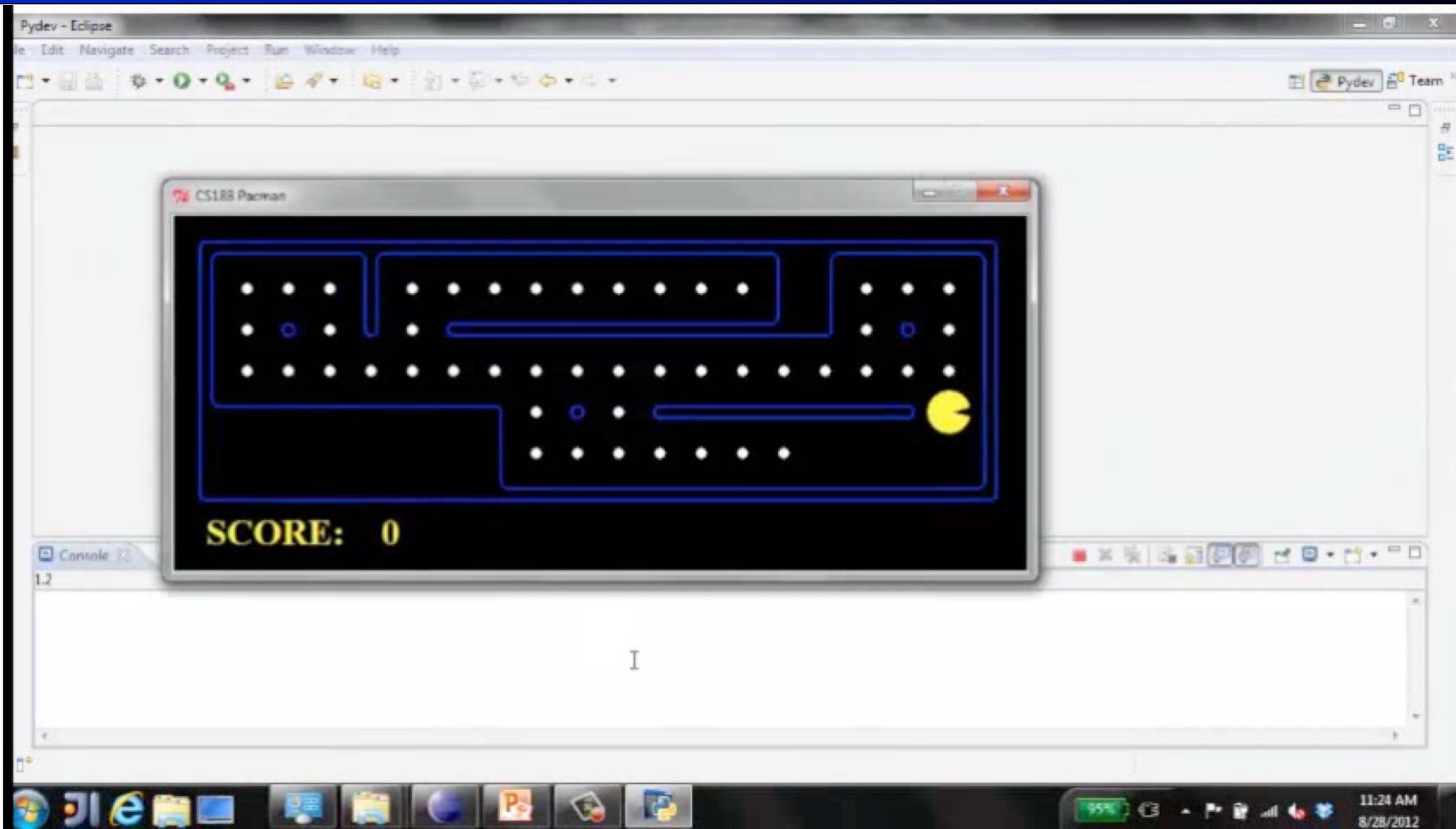
Planning Agents

- Planning agents:
 - Ask “what if”
 - Decisions based on (hypothesized) consequences of actions
 - Must have a model of how the world evolves in response to actions
 - Must formulate a goal (test)
 - Consider how the world **WOULD BE**
- Optimal vs. complete planning
- Planning vs. replanning

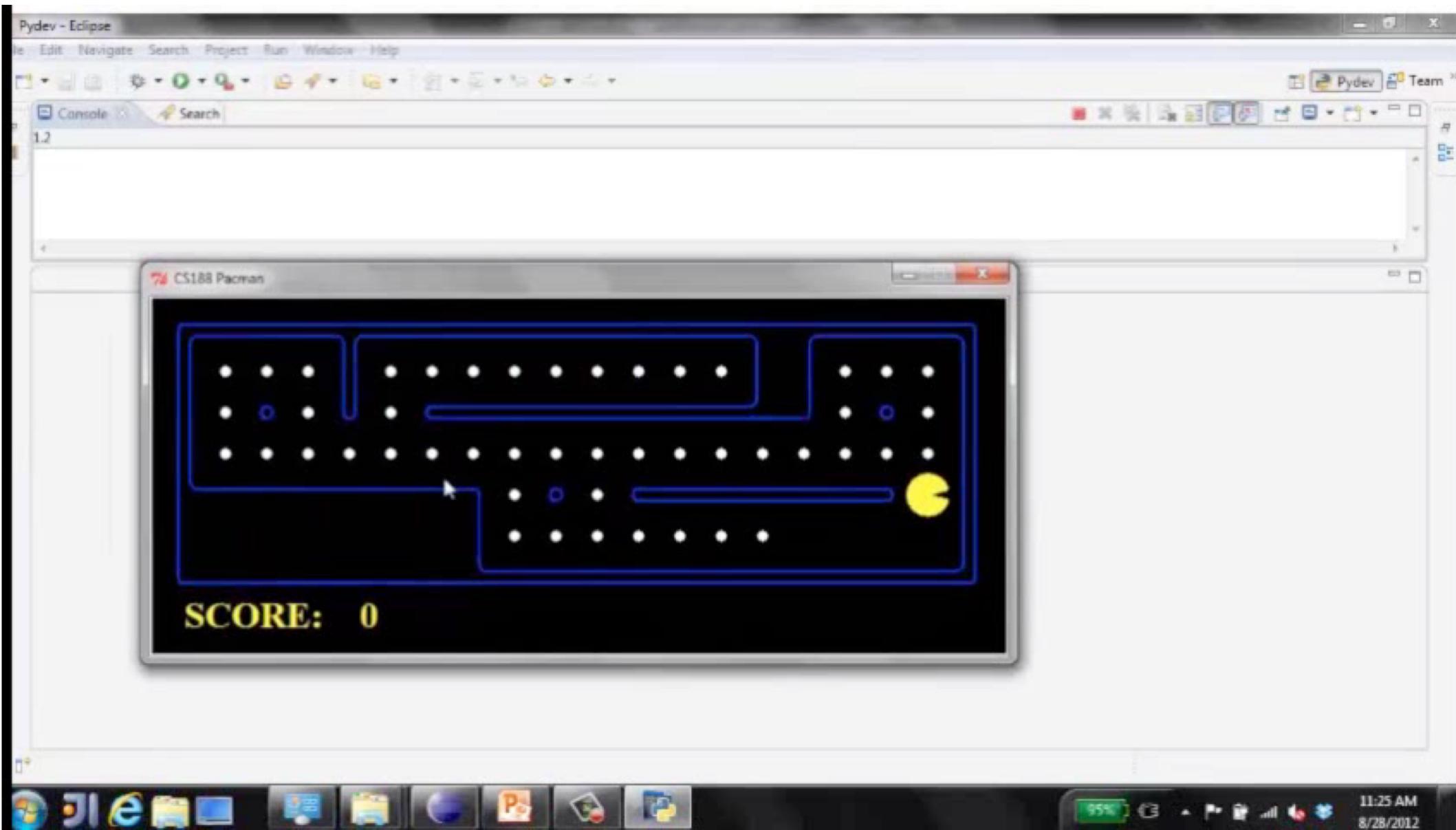


[Demo: re-planning (L2D3)]
[Demo: mastermind (L2D4)]

Video of Demo Replanning



Video of Demo Mastermind



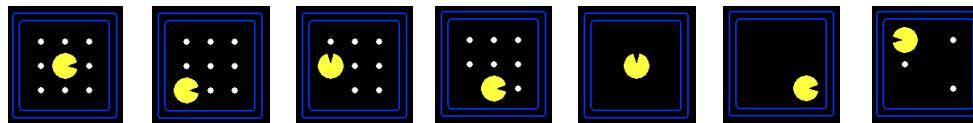
Search Problems



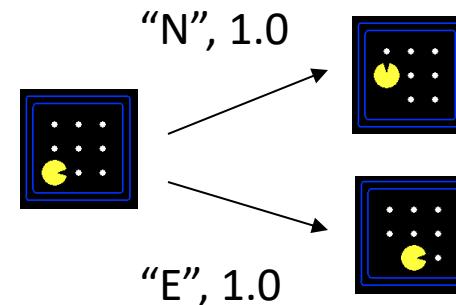
Search Problems

- A **search problem** consists of:

- A state space

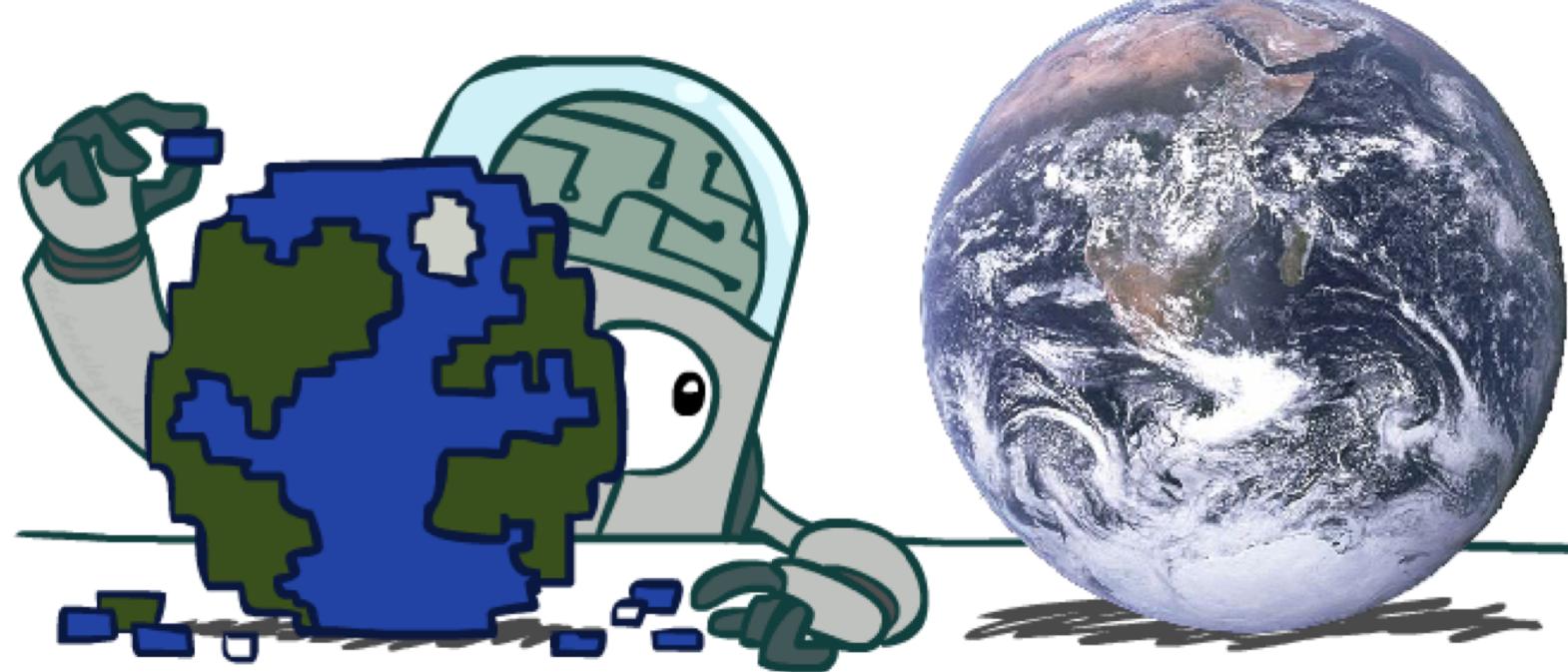


- A successor function
(with actions, costs)

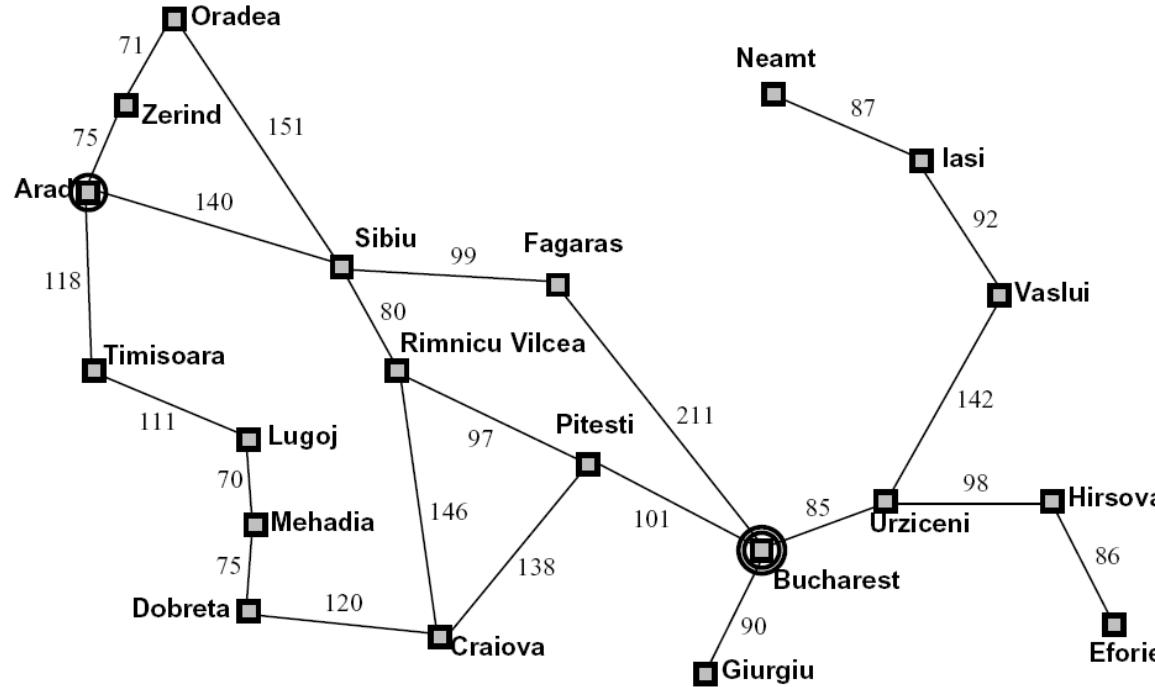


- A start state and a goal test
- A **solution** is a sequence of actions (a plan) which transforms the start state to a goal state

Search Problems Are Models



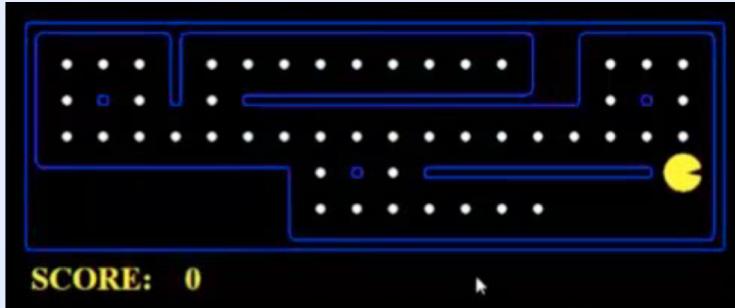
Example: Traveling in Romania



- State space:
 - Cities
- Successor function:
 - Roads: Go to adjacent city with cost = distance
- Start state:
 - Arad
- Goal test:
 - Is state == Bucharest?
- Solution?

What's in a State Space?

The **world state** includes every last detail of the environment



A **search state** keeps only the details needed for planning (abstraction)

- **Problem: Pathing**

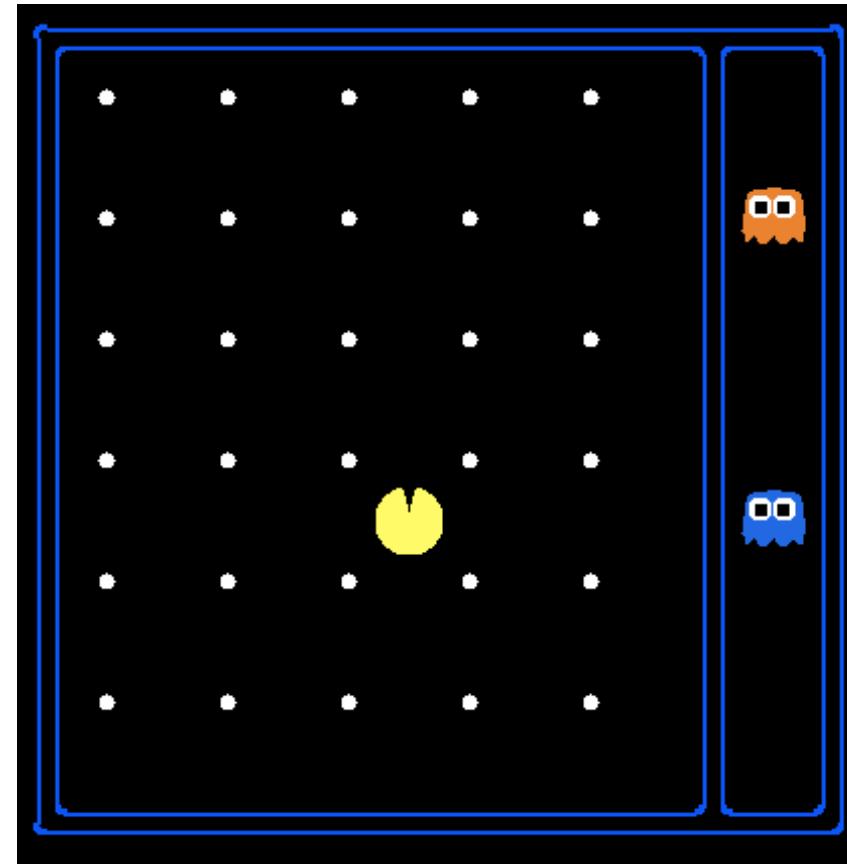
- States: (x,y) location
- Actions: NSEW
- Successor: update location only
- Goal test: is $(x,y)=\text{END}$

- **Problem: Eat-All-Dots**

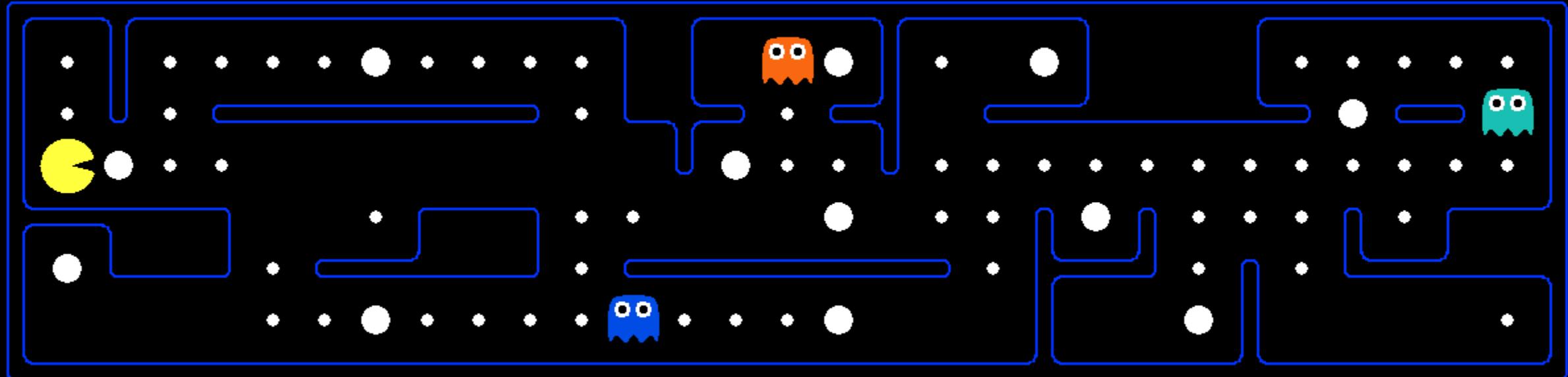
- States: $\{(x,y), \text{dot booleans}\}$
- Actions: NSEW
- Successor: update location and possibly a dot boolean
- Goal test: dots all false

State Space Sizes?

- World state:
 - Agent positions: 120
 - Food count: 30
 - Ghost positions: 12
 - Agent facing: NSEW
- How many
 - World states?
 $120 \times (2^{30}) \times (12^2) \times 4$
 - States for pathing?
120
 - States for eat-all-dots?
 $120 \times (2^{30})$

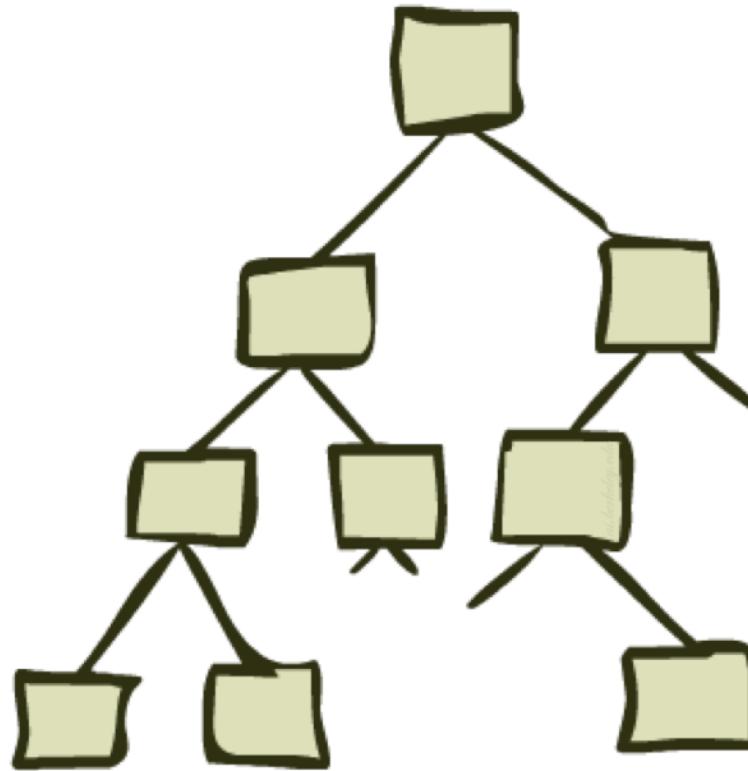


Quiz: Safe Passage



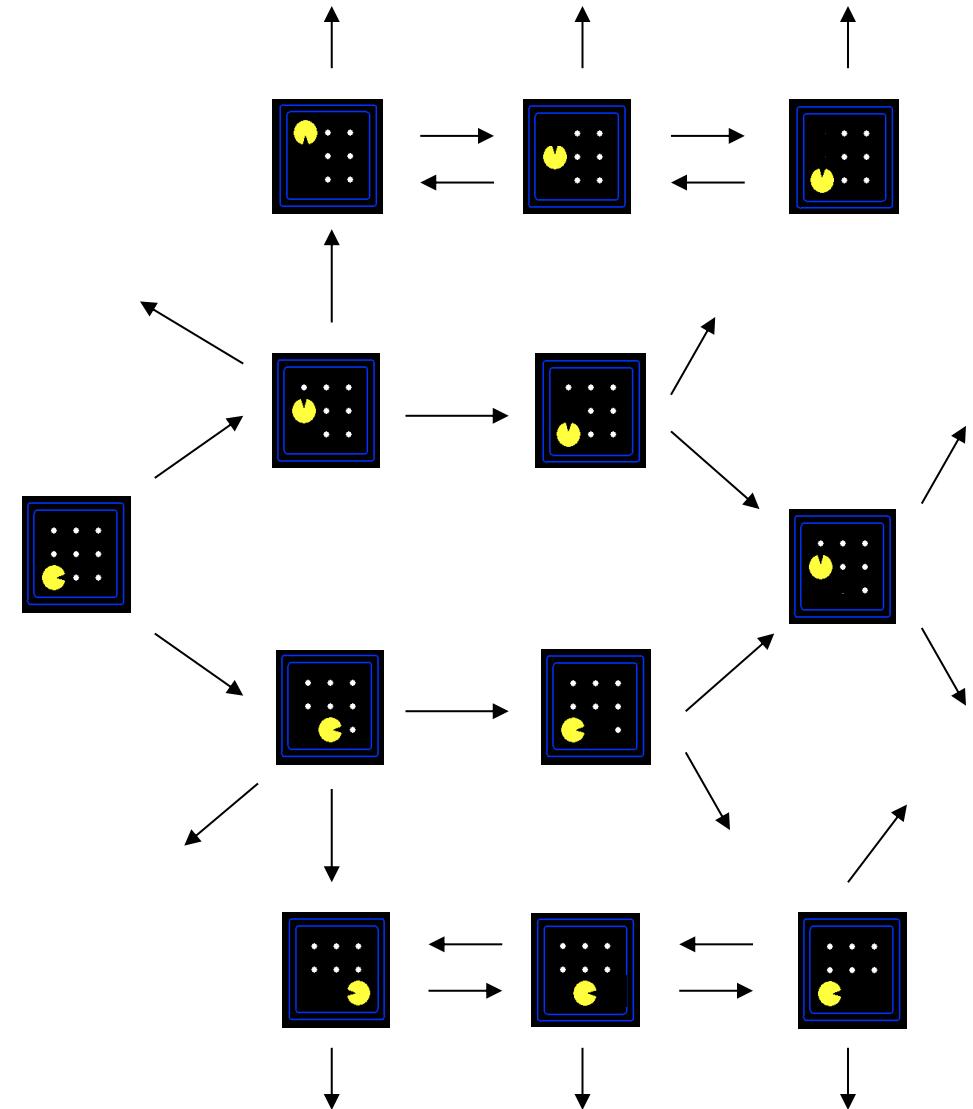
- Problem: eat all dots while keeping the ghosts perma-scared
- What does the state space have to specify?
 - (agent position, dot booleans, power pellet booleans, remaining scared time)

State Space Graphs and Search Trees



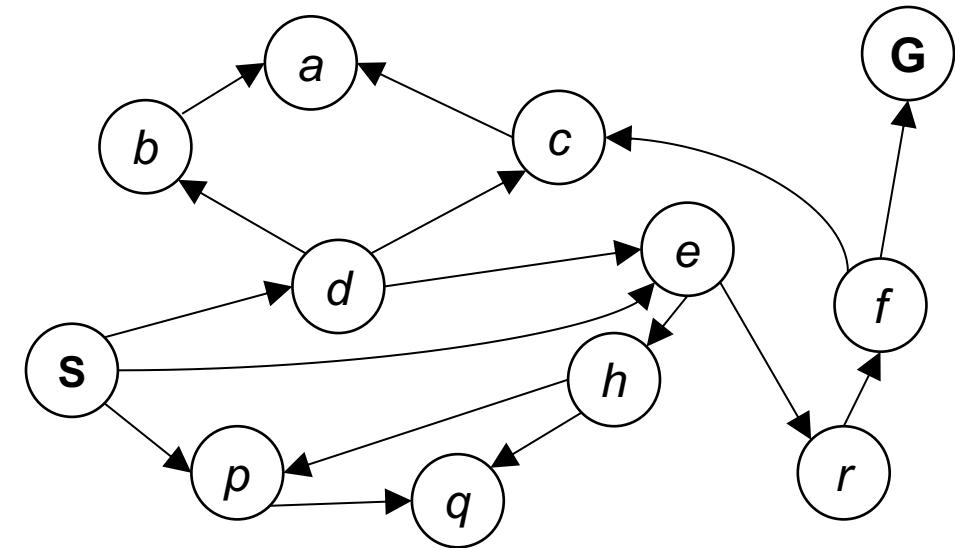
State Space Graphs

- State space graph: A mathematical representation of a search problem
 - Nodes are (abstracted) world configurations
 - Arcs represent successors (action results)
 - The goal test is a set of goal nodes (maybe only one)
- In a state space graph, each state occurs only once!
- We can rarely build this full graph in memory (it's too big), but it's a useful idea



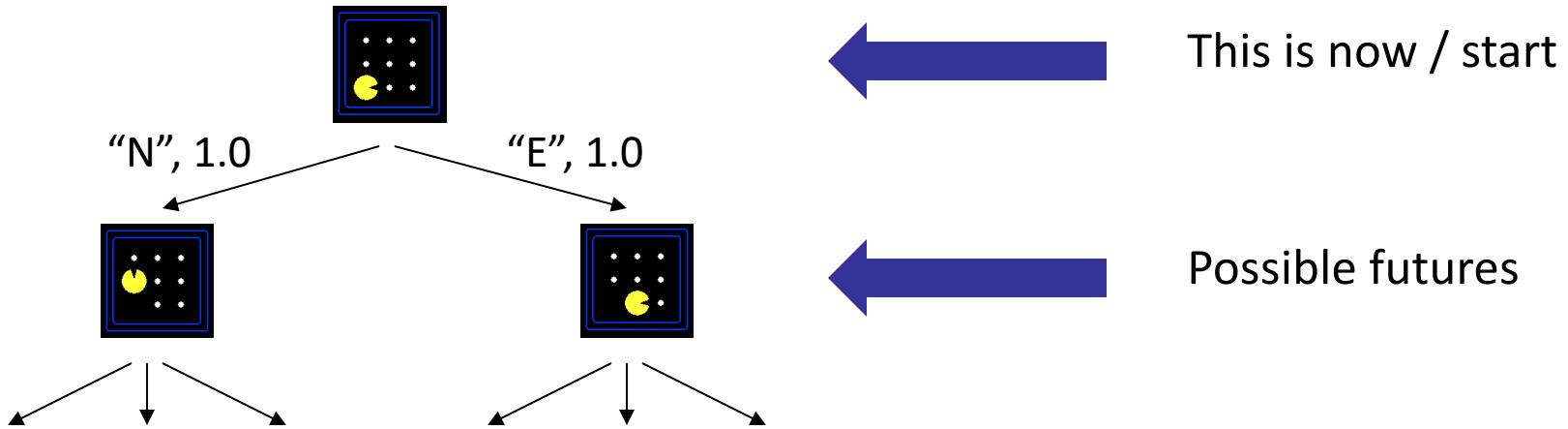
State Space Graphs

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Tiny state space graph for a tiny search problem

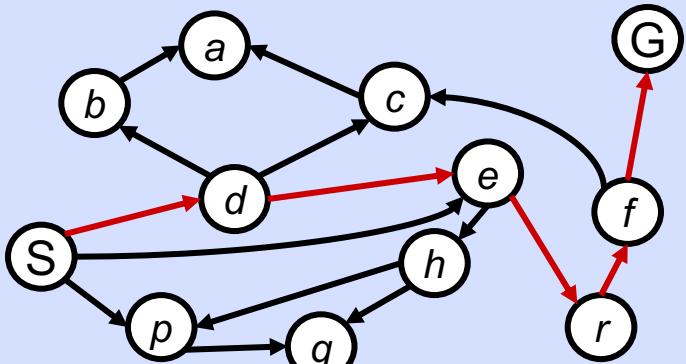
Search Trees



- A search tree:
 - A “what if” tree of plans and their outcomes
 - The start state is the root node
 - Children correspond to successors
 - Nodes show states, but correspond to PLANS that achieve those states
 - **For most problems, we can never actually build the whole tree**

State Space Graphs vs. Search Trees

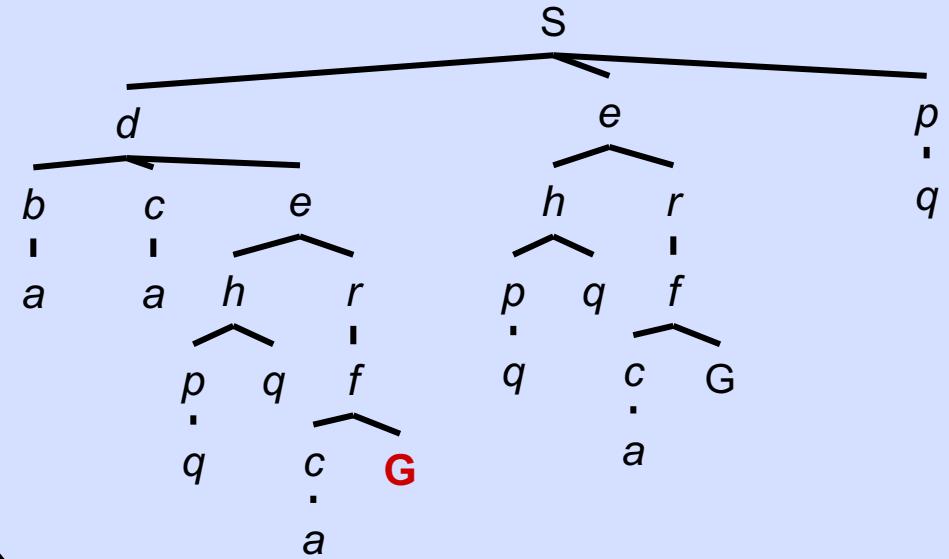
State Space Graph



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

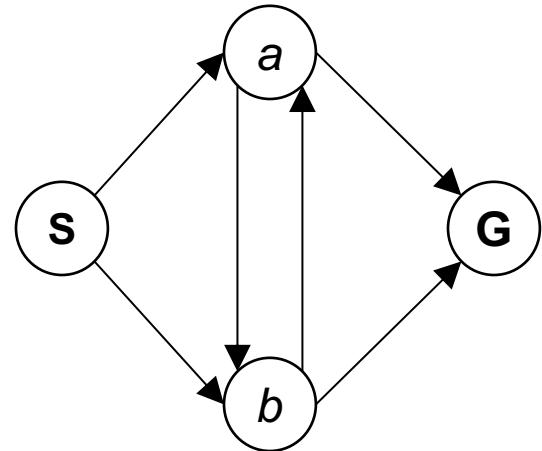
We construct both on demand – and we construct as little as possible.

Search Tree



Quiz: State Space Graphs vs. Search Trees

Consider this 4-state graph:

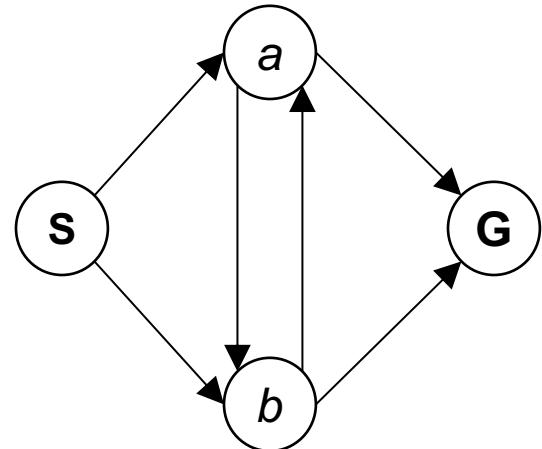


How big is its search tree (from S)?

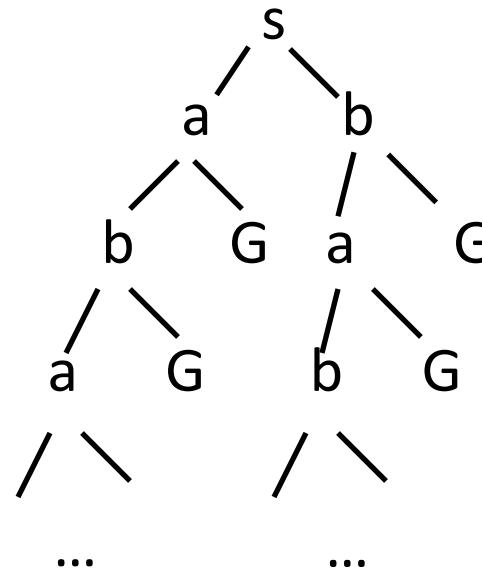


Quiz: State Space Graphs vs. Search Trees

Consider this 4-state graph:

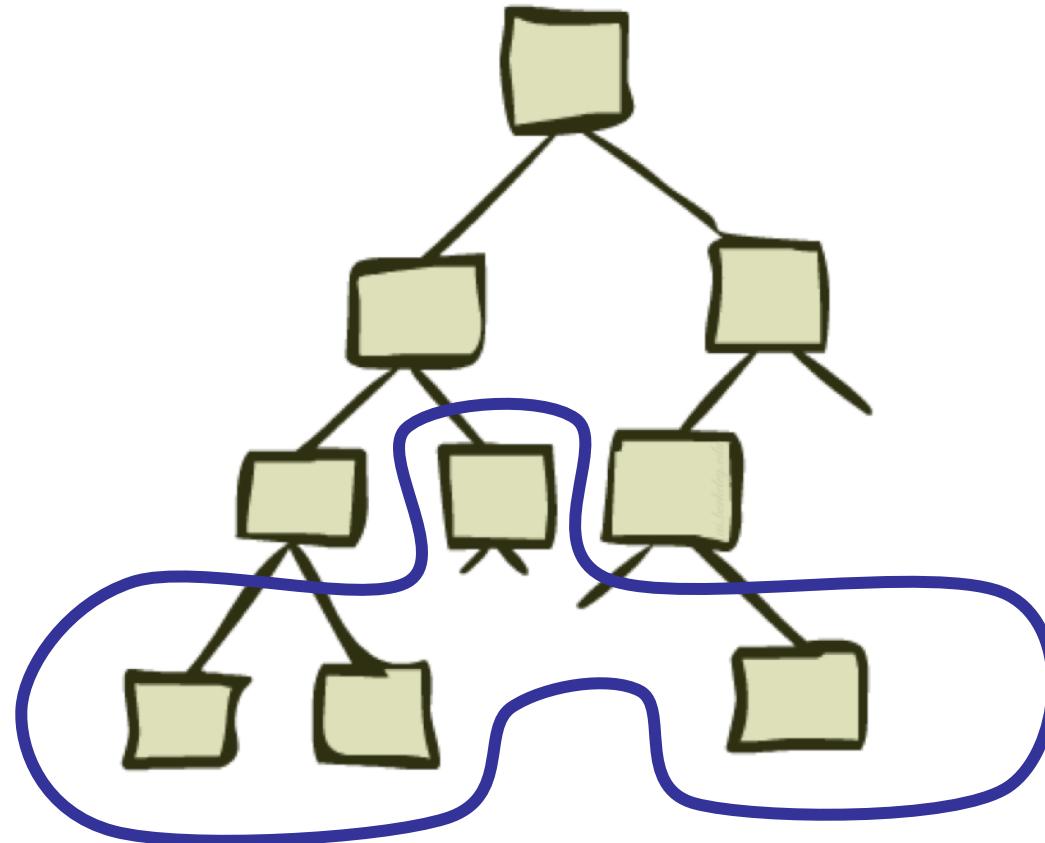


How big is its search tree (from S)?

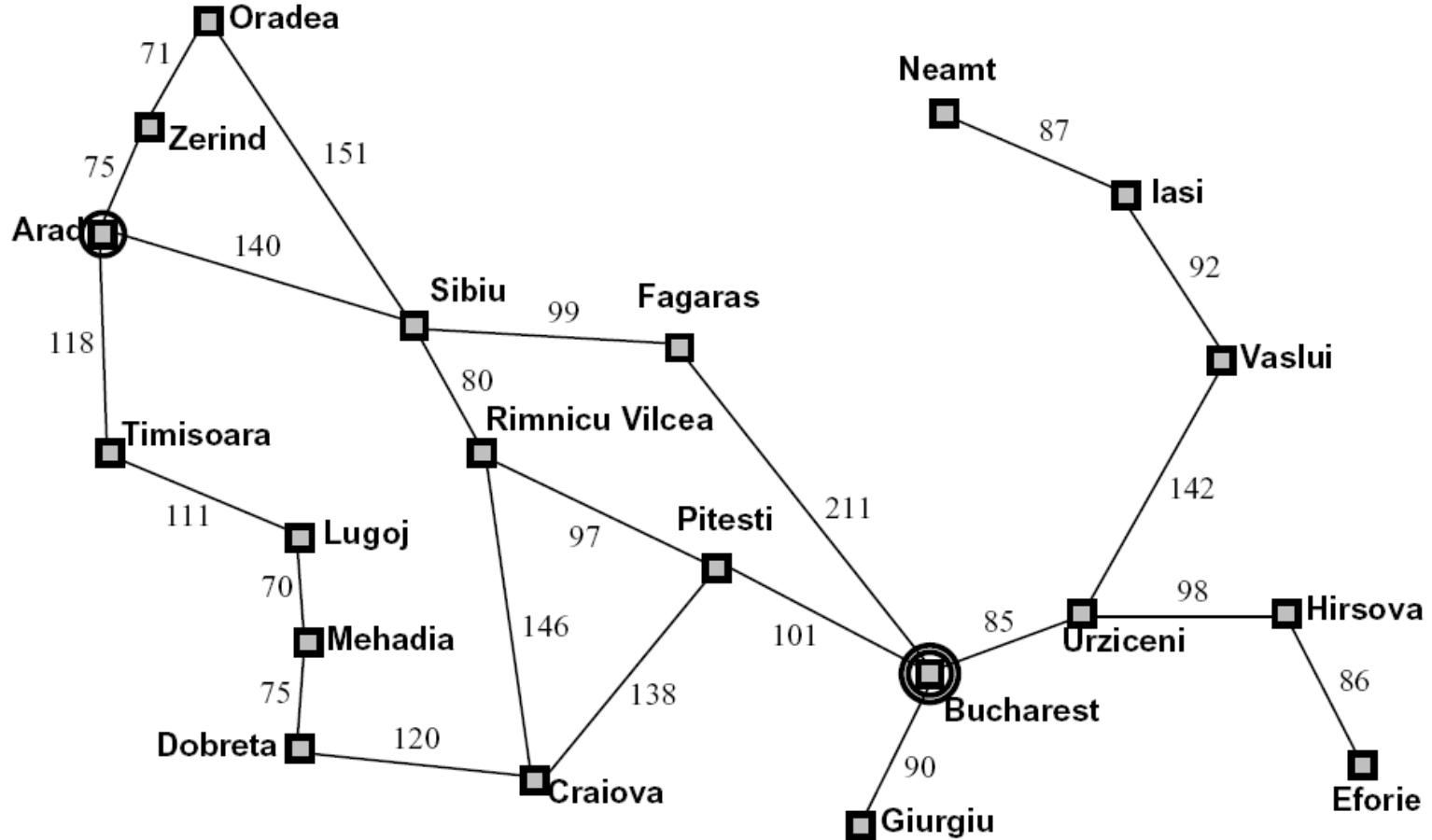


Important: Lots of repeated structure in the search tree!

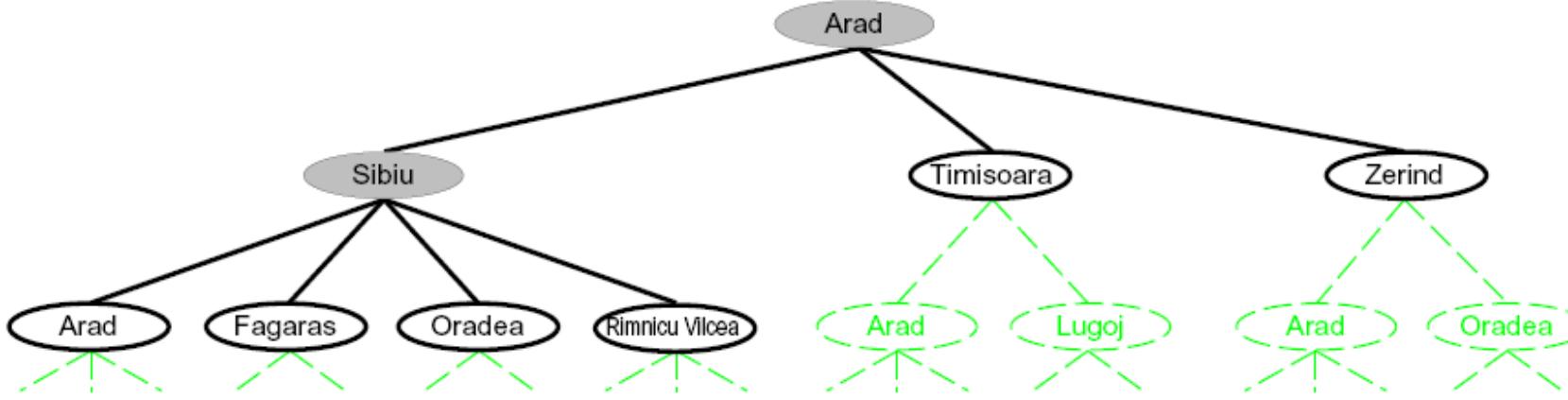
Tree Search



Search Example: Romania



Searching with a Search Tree



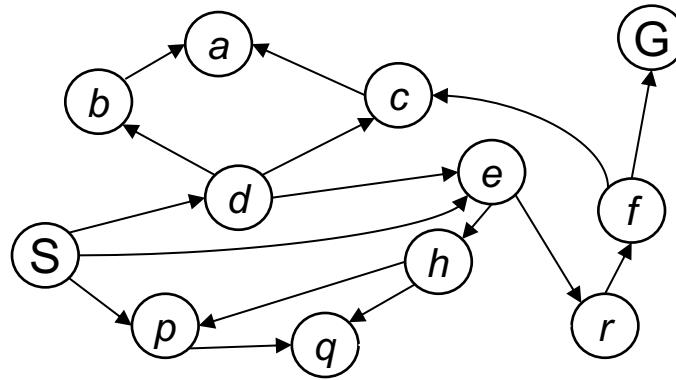
- Search:
 - Expand out potential plans (tree nodes)
 - Maintain a **fringe** of partial plans under consideration
 - Try to expand as few tree nodes as possible

General Tree Search

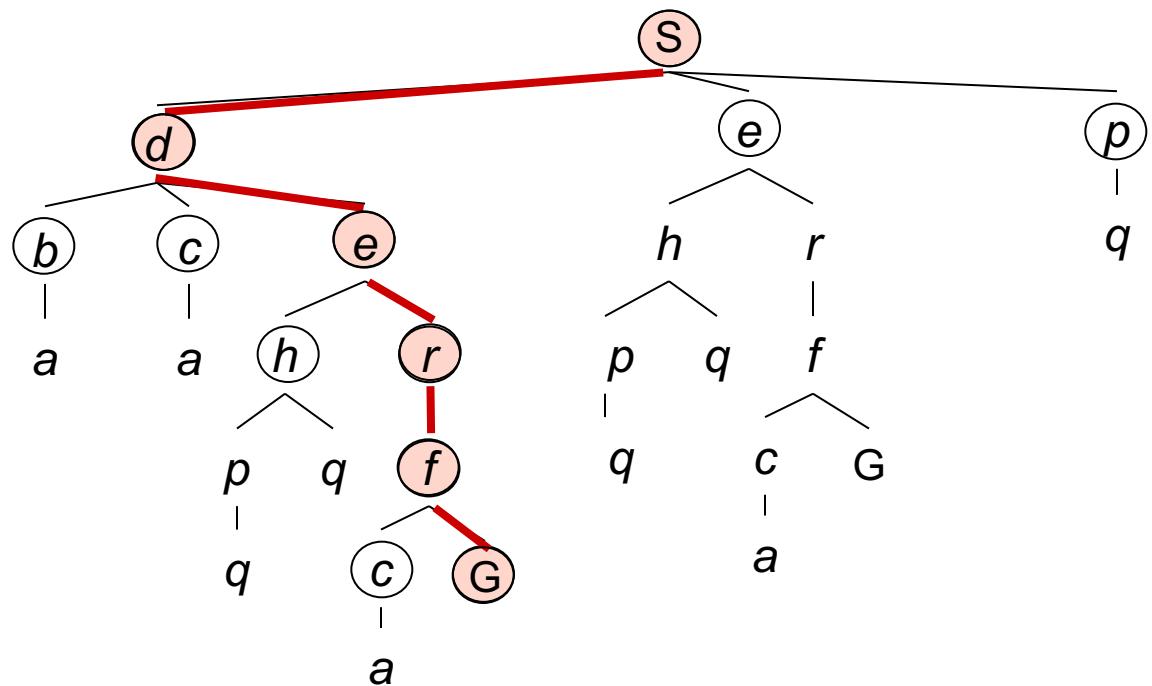
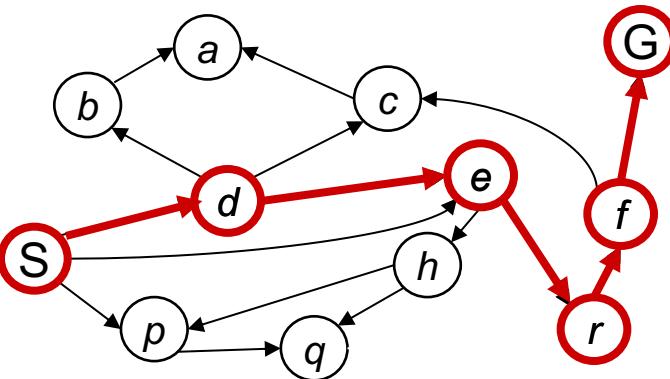
```
function TREE-SEARCH(problem, strategy) returns a solution, or failure
    initialize the search tree using the initial state of problem
    loop do
        if there are no candidates for expansion then return failure
        choose a leaf node for expansion according to strategy
        if the node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

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

Example: Tree Search



Example: Tree Search



~~s~~
~~s → d~~
s → e
s → p
s → d → b
s → d → c
~~s → d → e~~
s → d → e → h
~~s → d → e → r~~
~~s → d → e → r → f~~
s → d → e → r → f → c
~~s → d → e → r → f → G~~

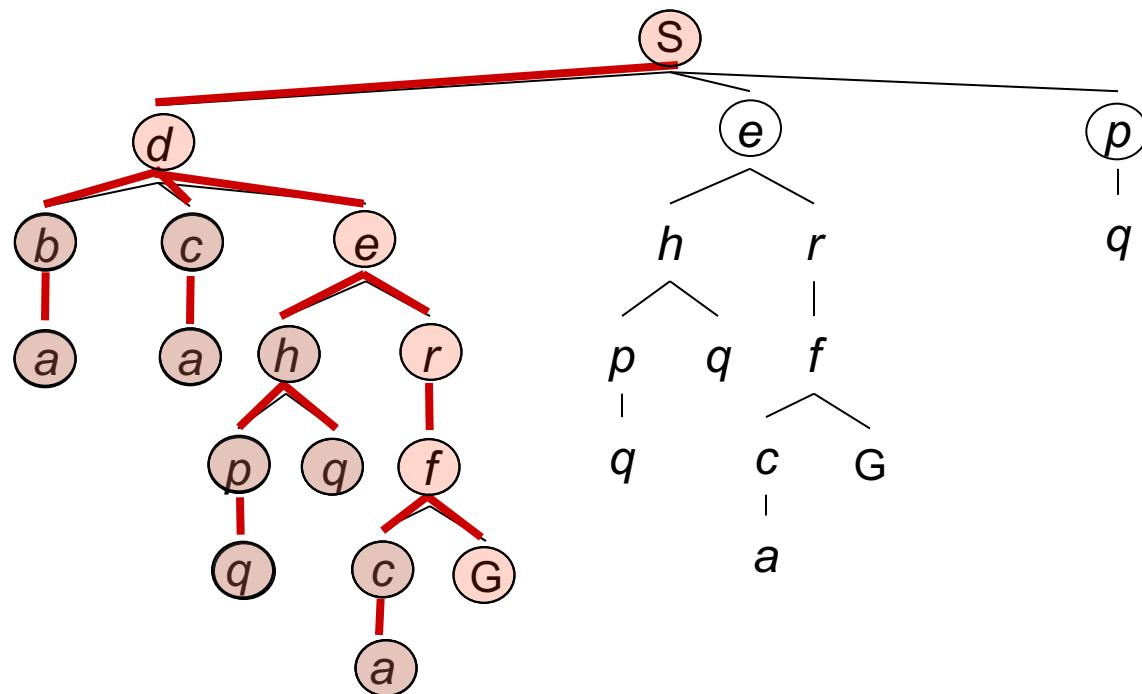
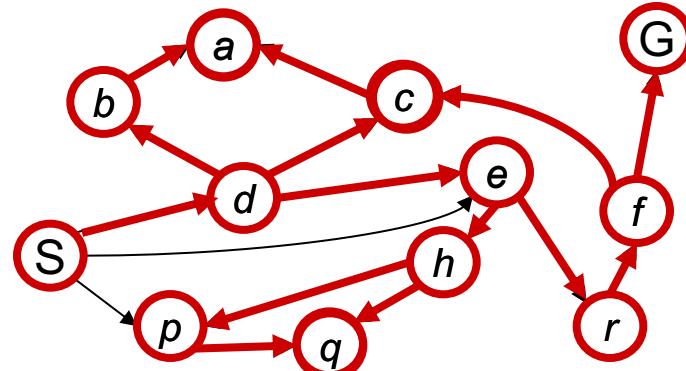
Depth-First Search



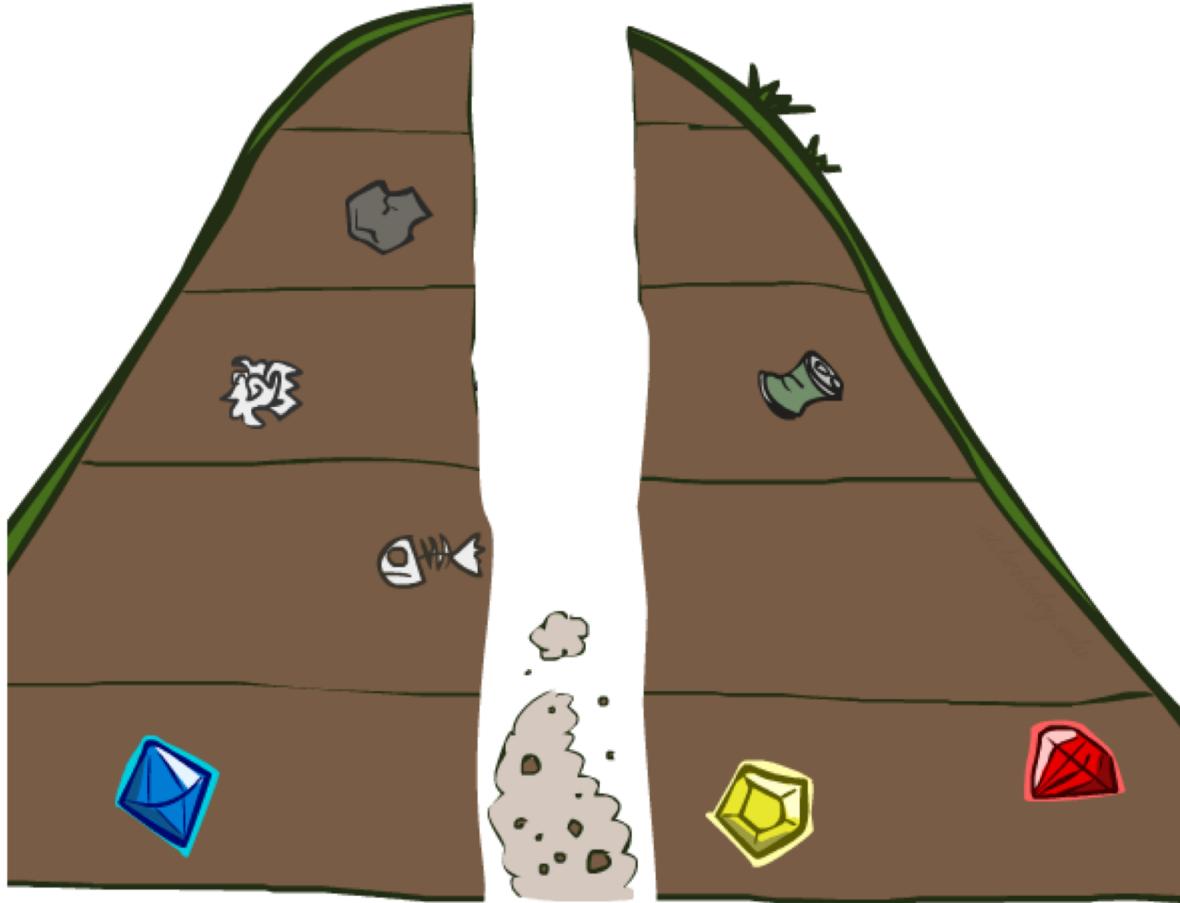
Depth-First Search

Strategy: expand a deepest node first

*Implementation:
Fringe is a LIFO stack*

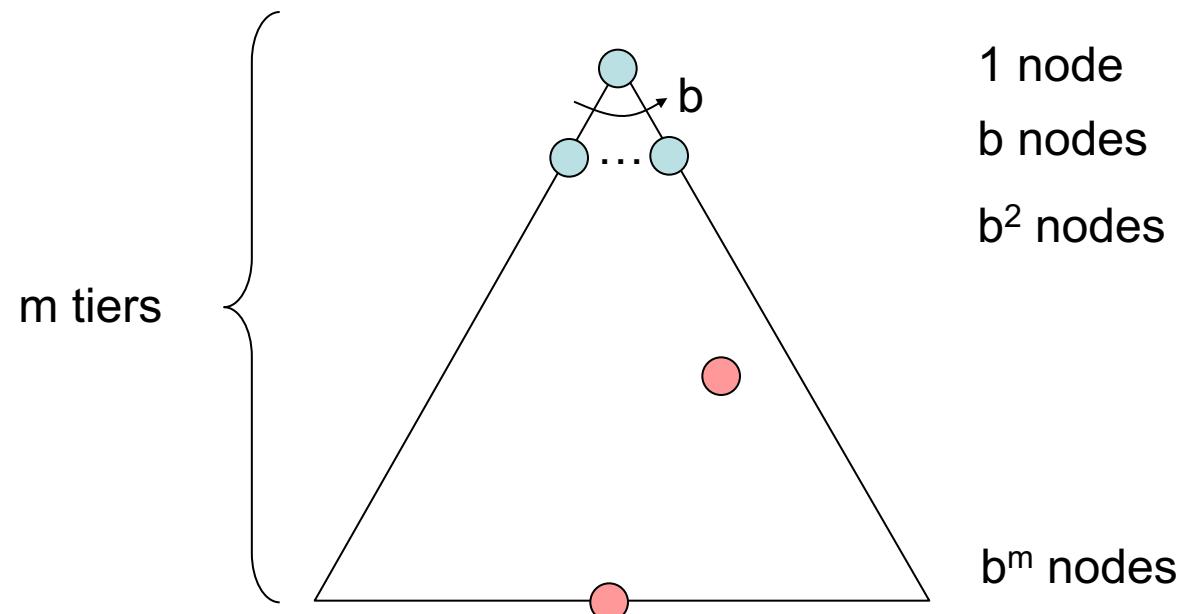


Search Algorithm Properties



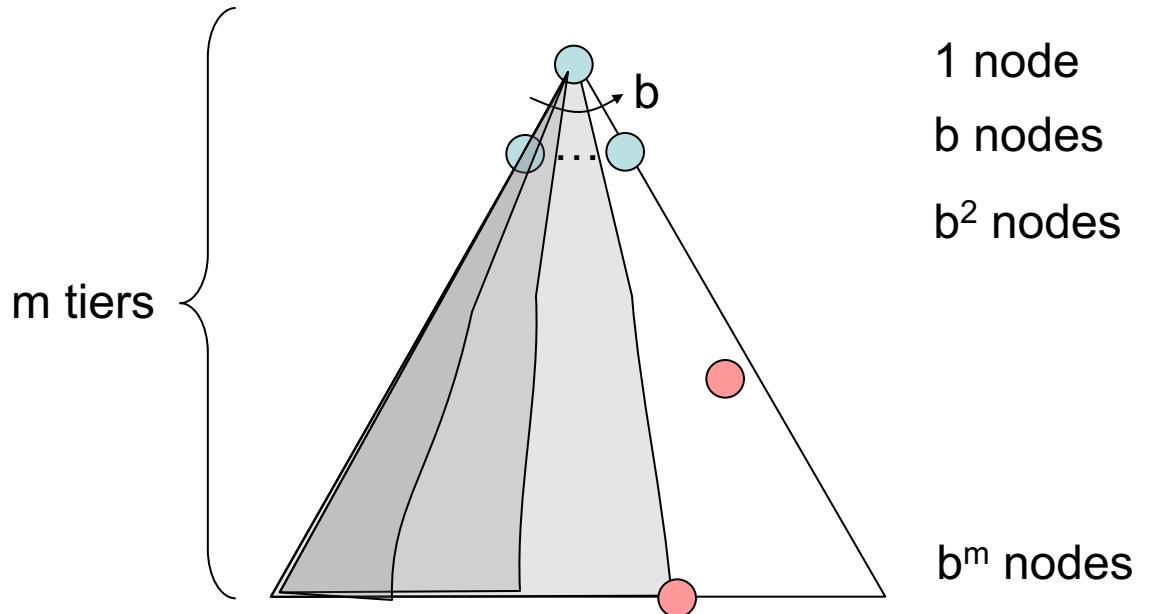
Search Algorithm Properties

- Complete: Guaranteed to find a solution if one exists?
- Optimal: Guaranteed to find the least cost path?
- Time complexity?
- Space complexity?
- Cartoon of search tree:
 - b is the branching factor
 - m is the maximum depth
 - solutions at various depths
- Number of nodes in entire tree?
 - $1 + b + b^2 + \dots + b^m = O(b^m)$

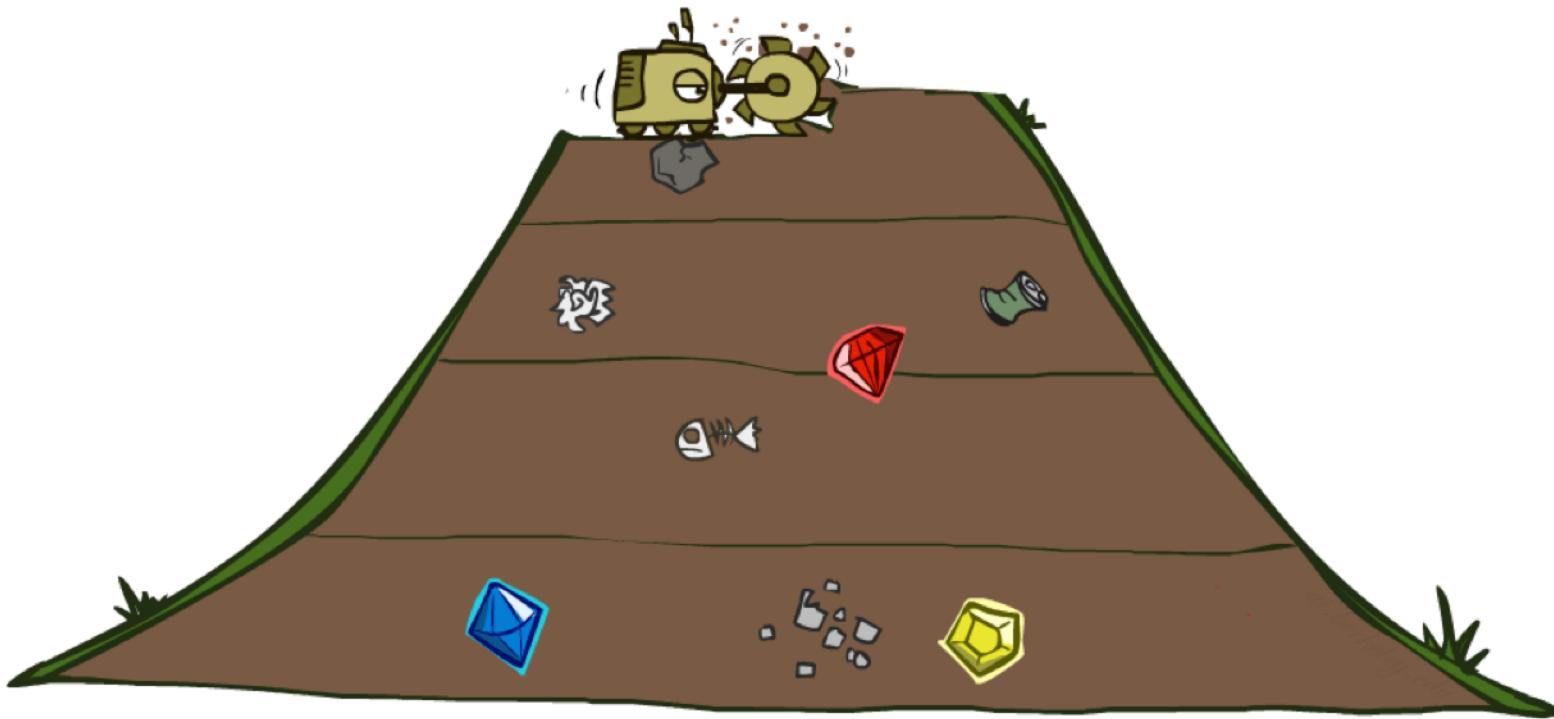


Depth-First Search (DFS) Properties

- What nodes DFS expand?
 - Some left prefix of the tree.
 - Could process the whole tree!
 - If m is finite, takes time $O(b^m)$
- How much space does the fringe take?
 - Only has siblings on path to root, so $O(bm)$
- Is it complete?
 - m could be infinite, so only if we prevent cycles (more later)
- Is it optimal?
 - No, it finds the “leftmost” solution, regardless of depth or cost



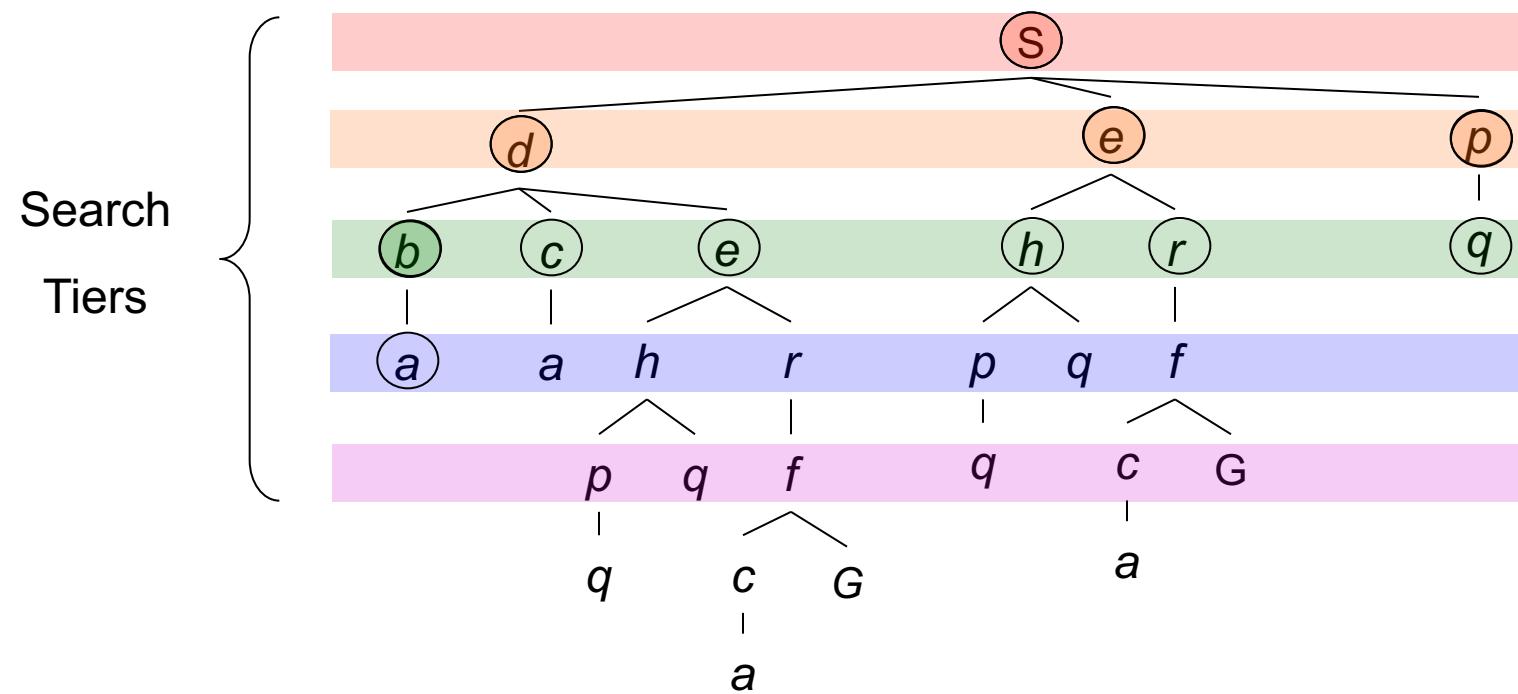
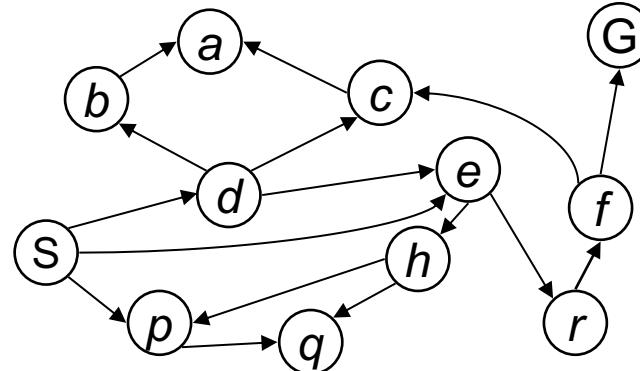
Breadth-First Search



Breadth-First Search

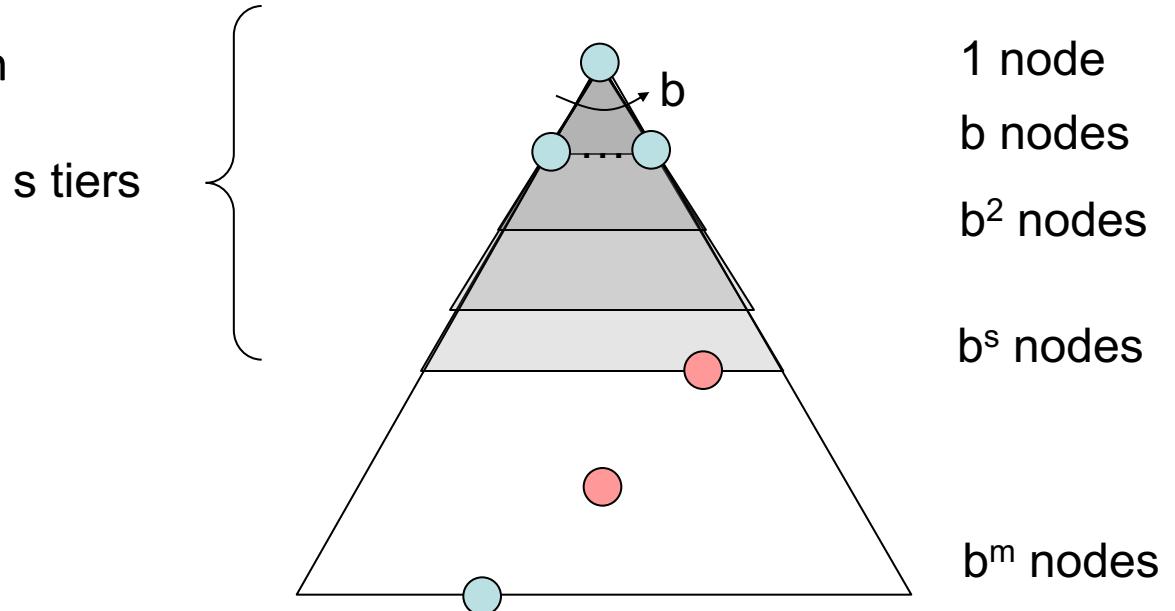
Strategy: expand a shallowest node first

Implementation: Fringe is a FIFO queue

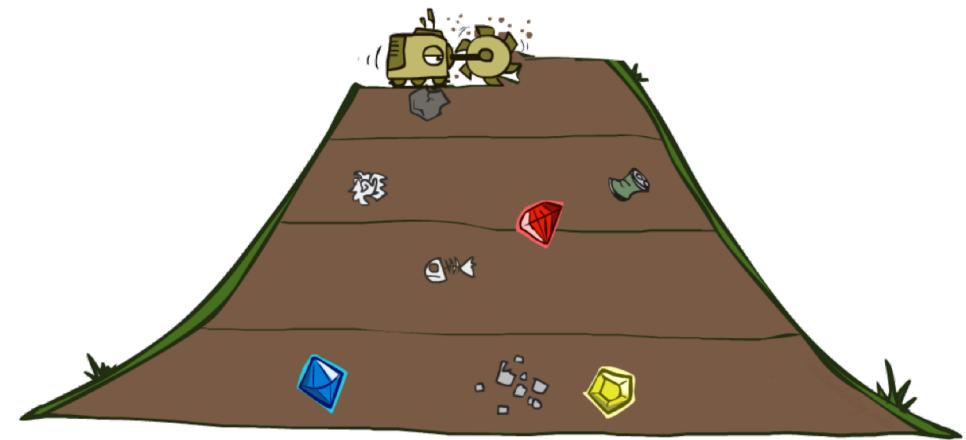
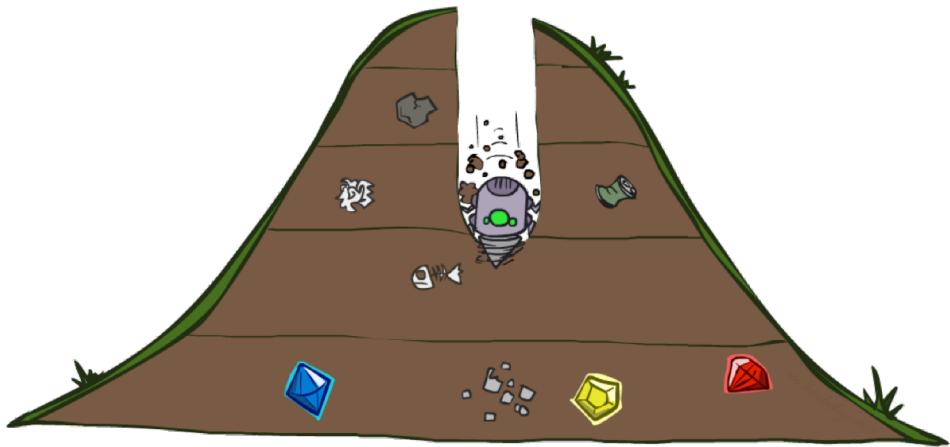


Breadth-First Search (BFS) Properties

- What nodes does BFS expand?
 - Processes all nodes above shallowest solution
 - Let depth of shallowest solution be s
 - Search takes time $O(b^s)$
- How much space does the fringe take?
 - Has roughly the last tier, so $O(b^s)$
- Is it complete?
 - s must be finite if a solution exists, so yes!
- Is it optimal?
 - Only if costs are all 1 (more on costs later)



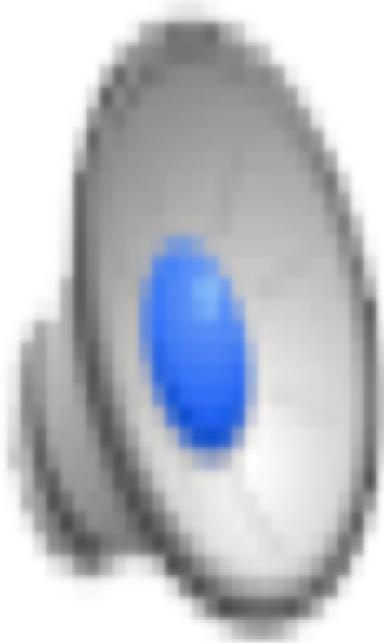
Quiz: DFS vs BFS



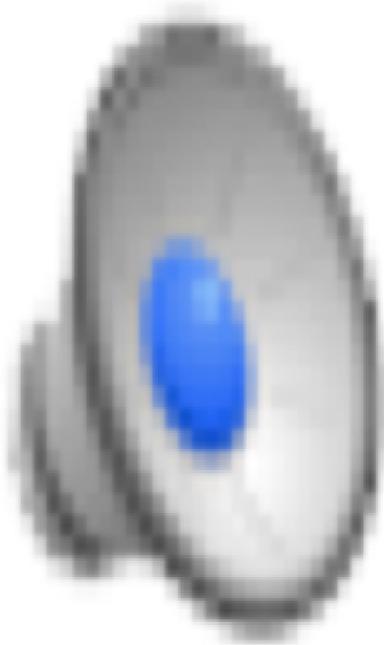
Quiz: DFS vs BFS

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

Video of Demo Maze Water DFS/BFS (part 1)

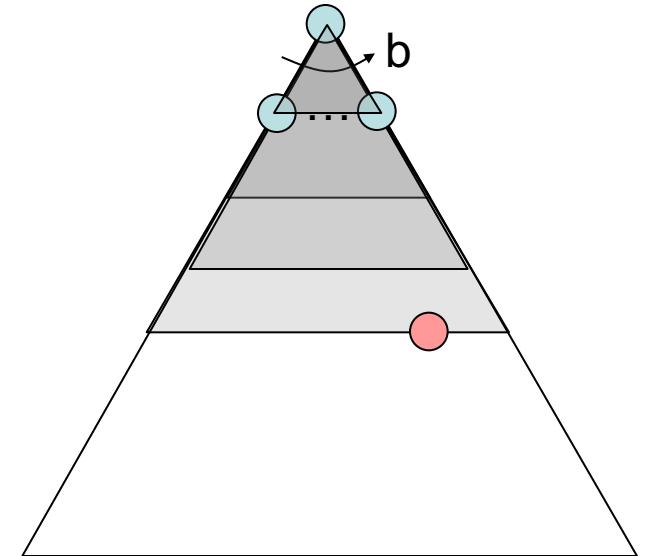


Video of Demo Maze Water DFS/BFS (part 2)

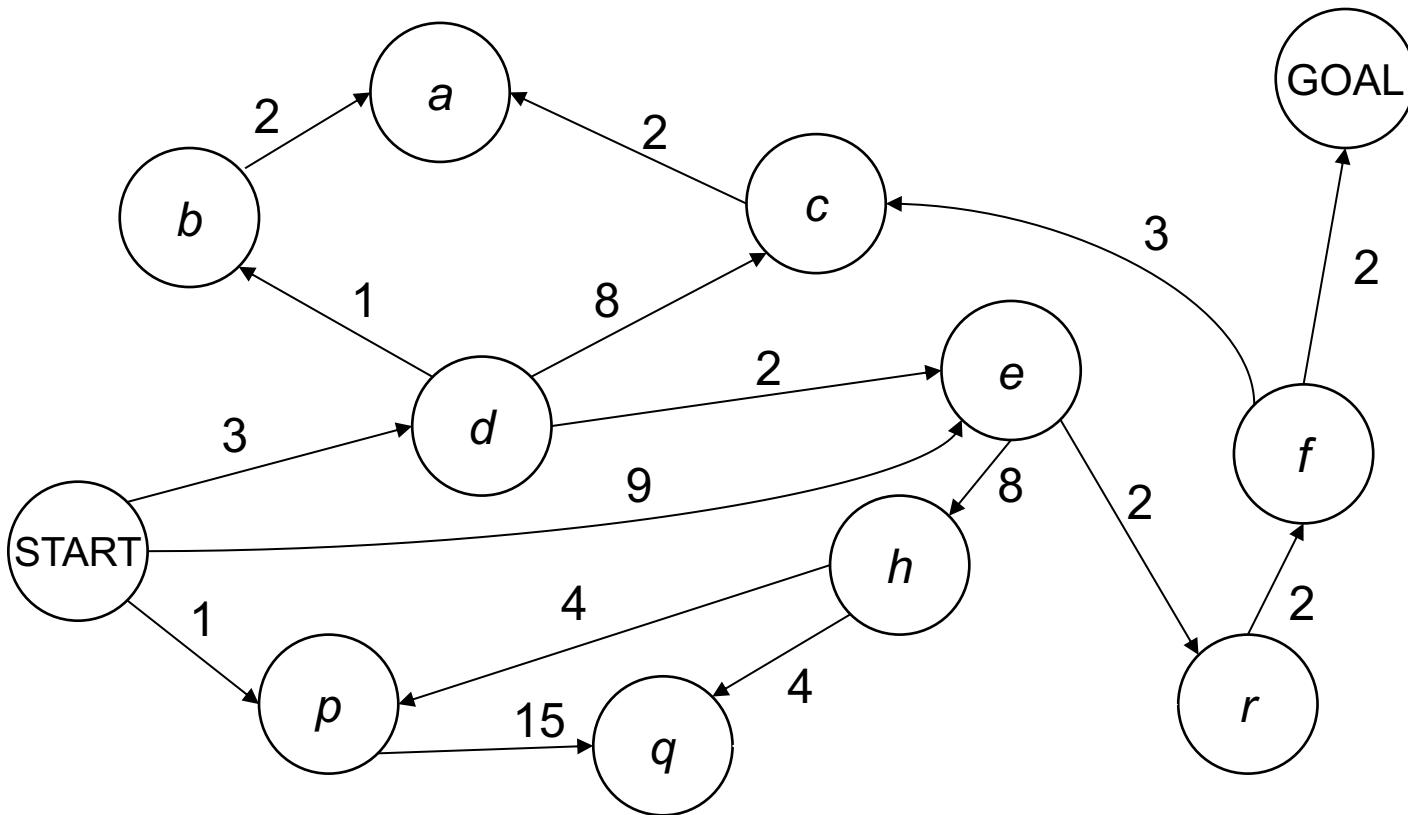


Iterative Deepening

- Idea: get DFS's space advantage with BFS's time / shallow-solution advantages
 - Run a DFS with depth limit 1. If no solution...
 - Run a DFS with depth limit 2. If no solution...
 - Run a DFS with depth limit 3.
- Isn't that wastefully redundant?
 - Generally most work happens in the lowest level searched, so not so bad!

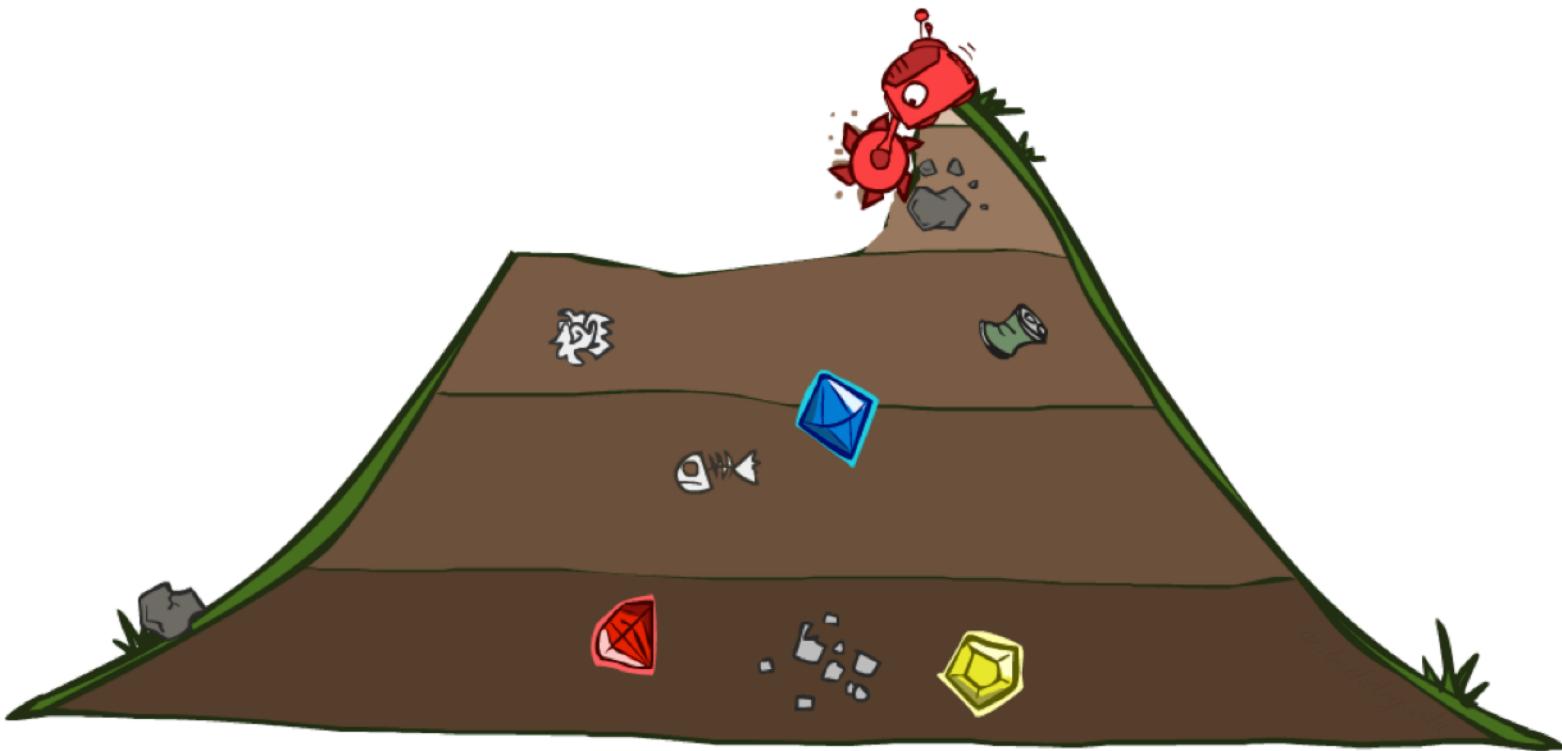


Cost-Sensitive Search



BFS finds the shortest path in terms of number of actions.
It does not find the least-cost path. We will now cover
a similar algorithm which does find the least-cost path.

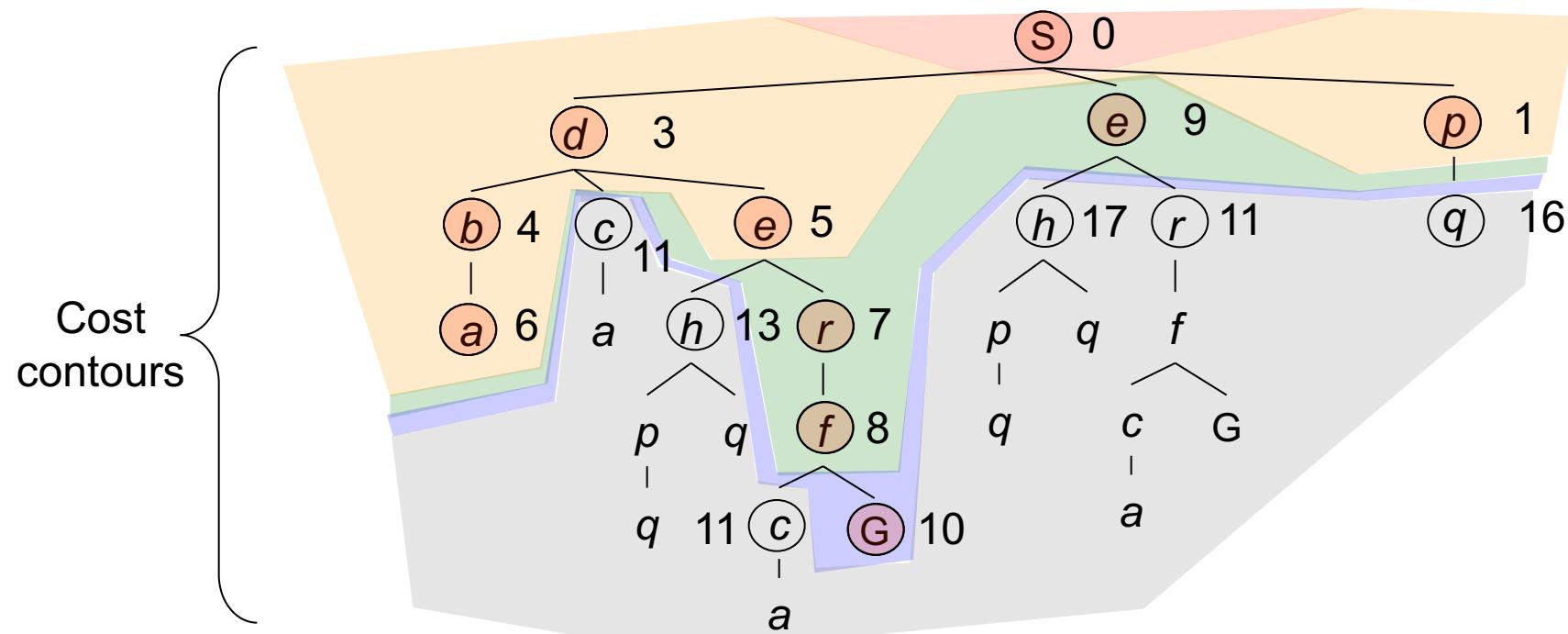
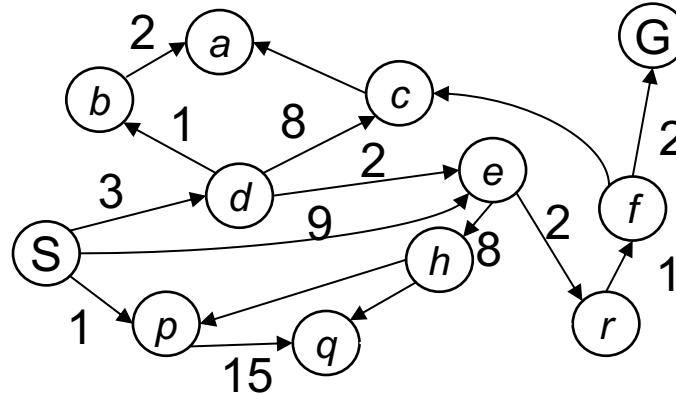
Uniform Cost Search



Uniform Cost Search

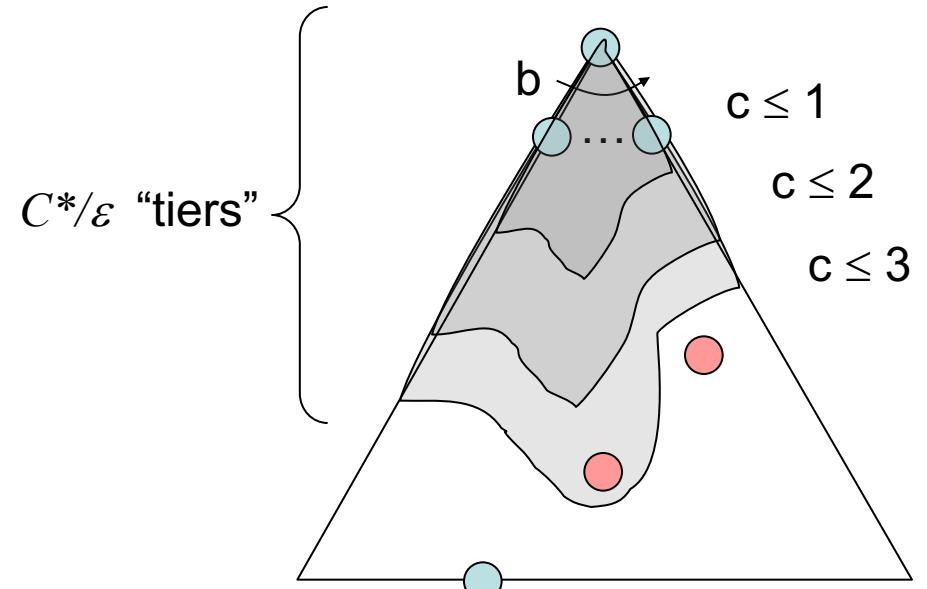
Strategy: expand a cheapest node first:

Fringe is a priority queue
(priority: cumulative cost)



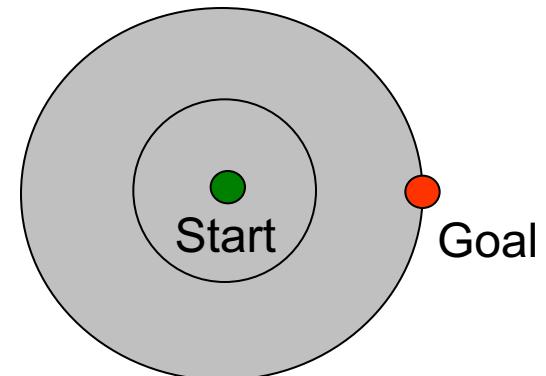
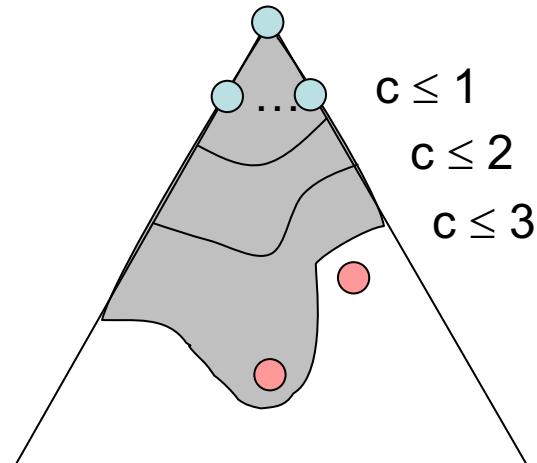
Uniform Cost Search (UCS) Properties

- What nodes does UCS expand?
 - Processes all nodes with cost less than cheapest solution!
 - If that solution costs C^* and arcs cost at least ε , then the “effective depth” is roughly C^*/ε
 - Takes time $O(b^{C^*/\varepsilon})$ (exponential in effective depth)
- How much space does the fringe take?
 - Has roughly the last tier, so $O(b^{C^*/\varepsilon})$
- Is it complete?
 - Assuming best solution has a finite cost and minimum arc cost is positive, yes!
- Is it optimal?
 - Yes! (Proof next lecture via A*)



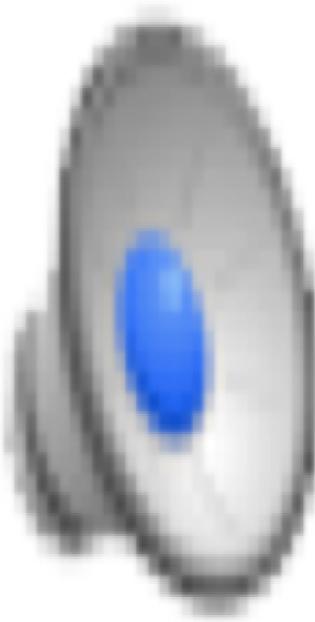
Uniform Cost Issues

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

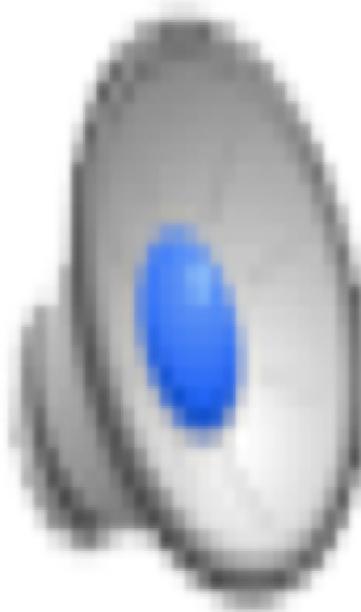


[Demo: empty grid UCS (L2D5)]
[Demo: maze with deep/shallow water DFS/BFS/UCS (L2D7)]

Video of Demo Empty UCS



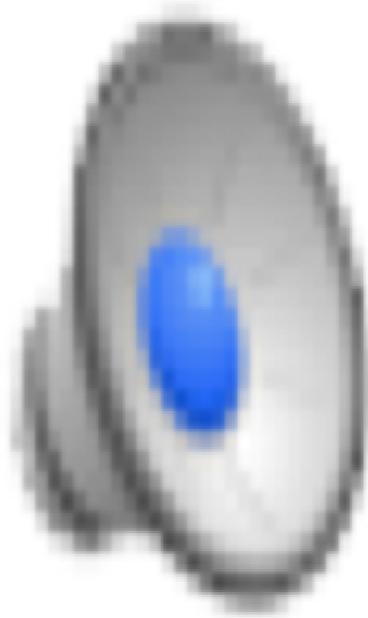
Video of Demo Maze with Deep/Shallow Water --- DFS, BFS, or UCS? (part 1)



Video of Demo Maze with Deep/Shallow Water --- DFS, BFS, or UCS? (part 2)

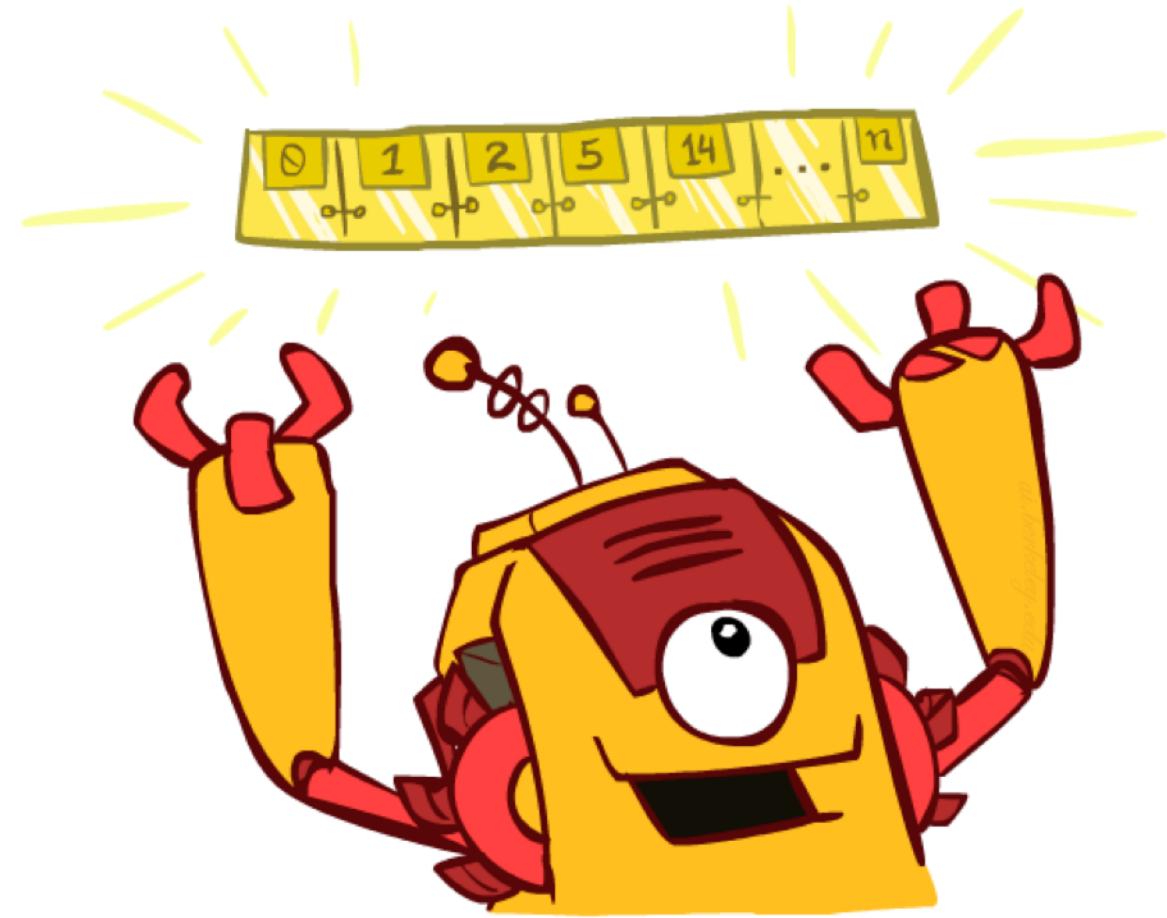


Video of Demo Maze with Deep/Shallow Water --- DFS, BFS, or UCS? (part 3)



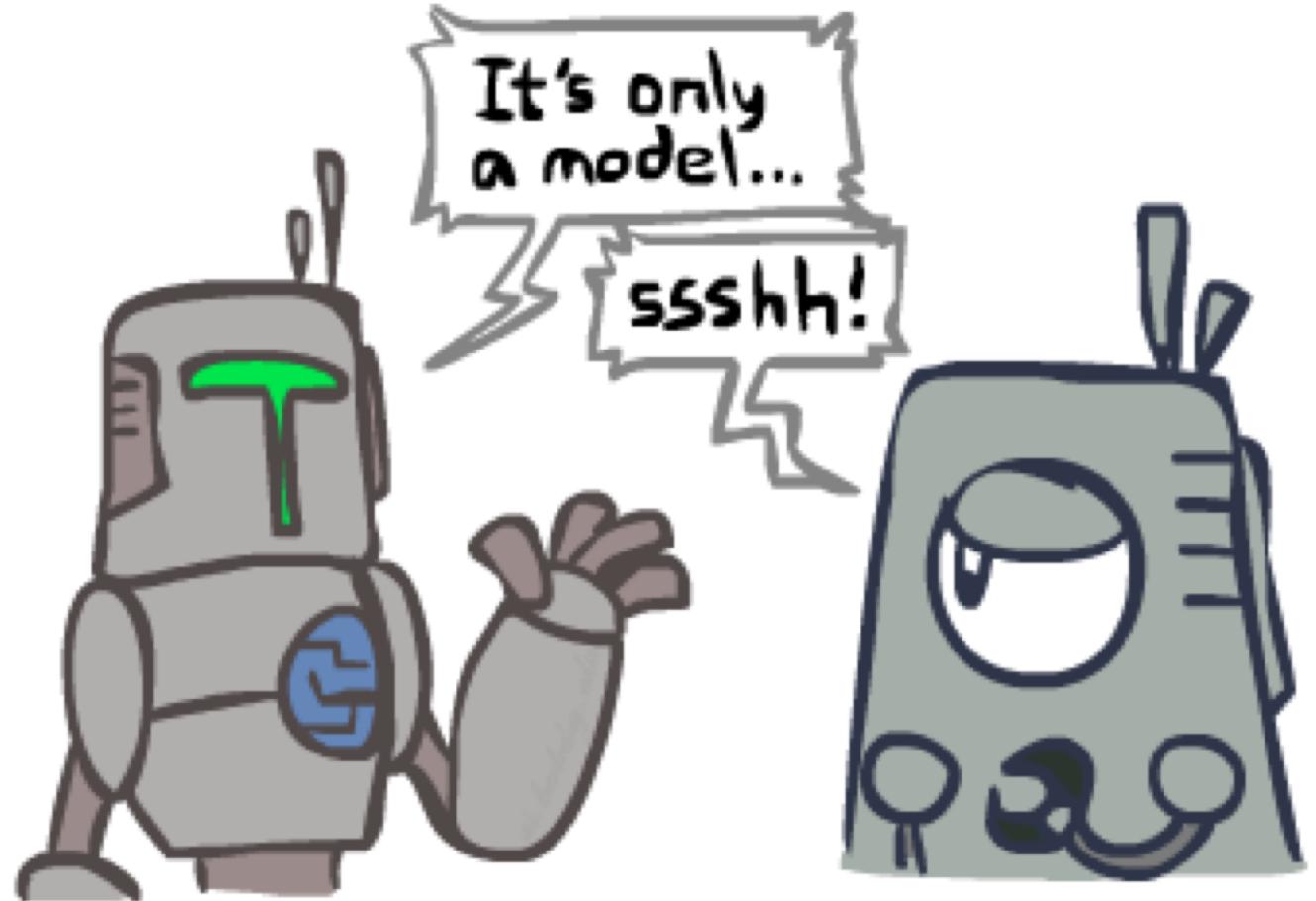
The One Queue

- All these search algorithms are the same except for fringe strategies
 - Conceptually, all fringes are priority queues (i.e. collections of nodes with attached priorities)
 - Practically, for DFS and BFS, you can avoid the $\log(n)$ overhead from an actual priority queue, by using stacks and queues
 - Can even code one implementation that takes a variable queuing object

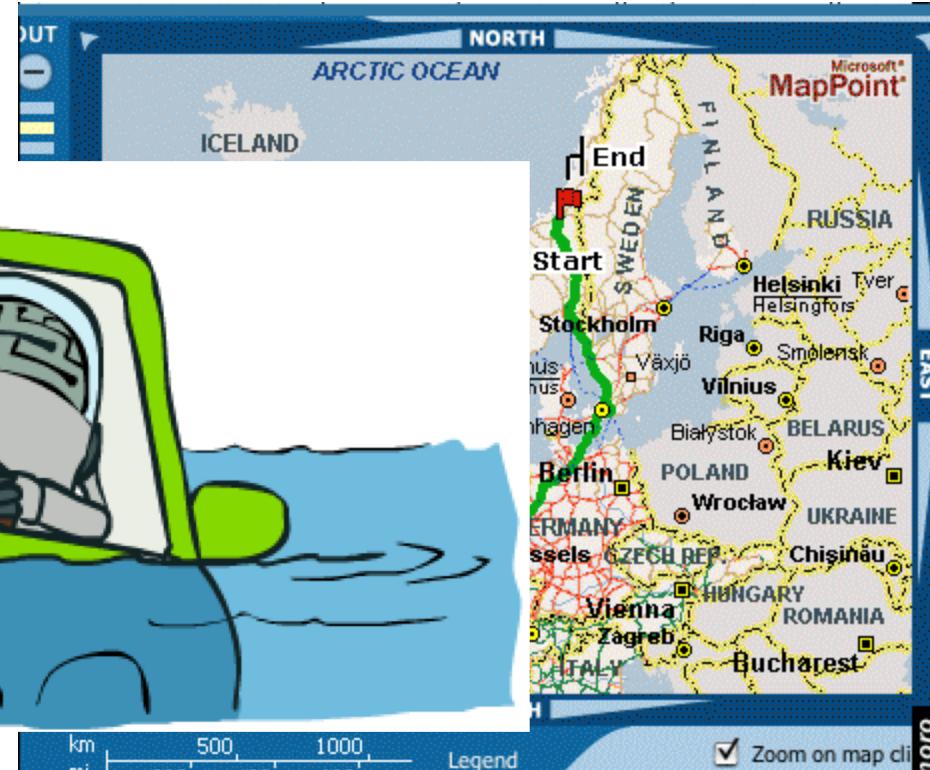
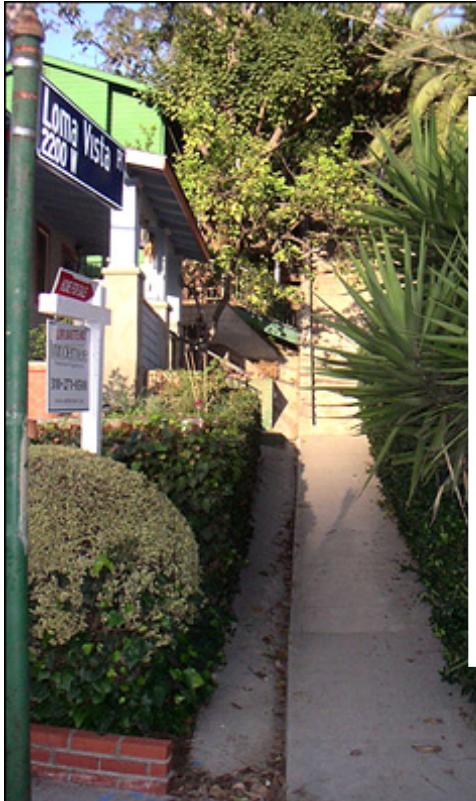


Search and Models

- Search operates over models of the world
 - The agent doesn't actually try all the plans out in the real world!
 - Planning is all “in simulation”
 - Your search is only as good as your models...



Search Gone Wrong?



Start: Haugesund, Rogaland, Norway

End: Trondheim, Sør-Trøndelag, Norway

Total Distance: 2713.2 Kilometers

Estimated Total Time: 47 hours, 31 minutes