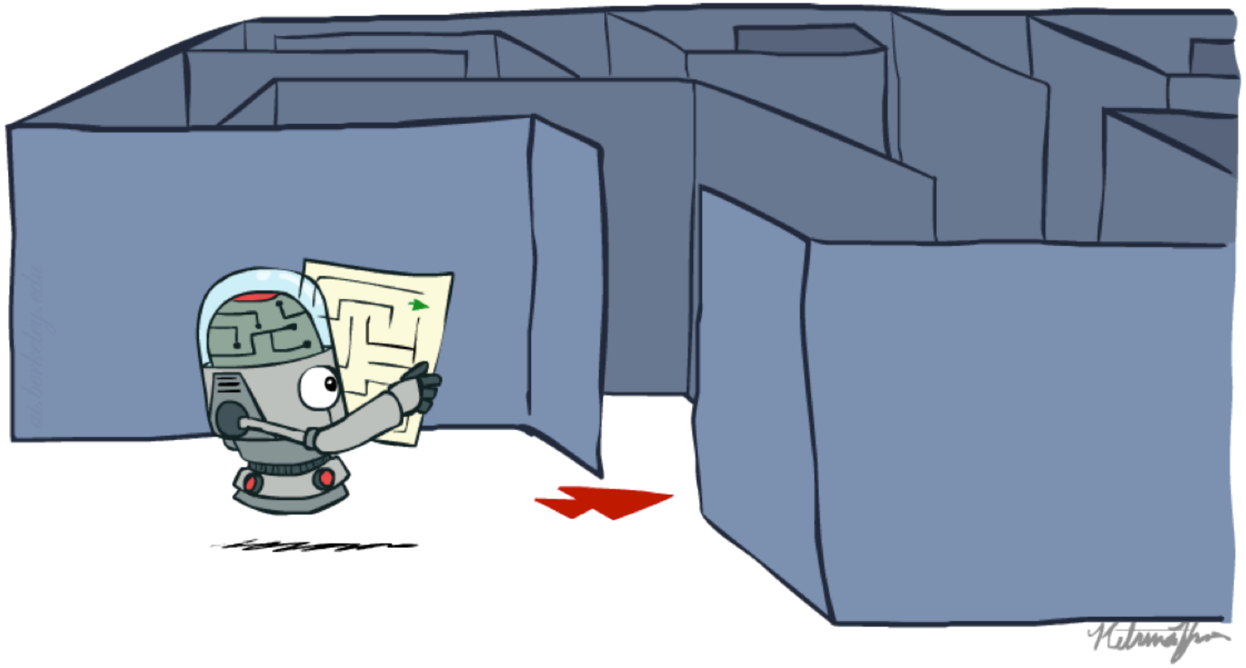
# CS 188: Artificial Intelligence

## Search



Instructor: Nikita Kitaev

University of California, Berkeley

[These slides adapted from Dan Klein and Pieter Abbeel]

# Announcements

- Exam Times
  - Midterm 1: July 13, 12pm-2pm (Alternative 12 hours later at 12am-2am)
  - Midterm 2: July 29, 12pm-2pm (Alternative 12 hours later at 12am-2am)
  - Final: August 13, 12pm-3pm (Alternative 12 hours later at 12am-3am)
- Sections
  - Start tomorrow, see Piazza for times
  - You can go to any section
- Office Hours
  - Start today
  - Ryan's OH are today at 3pm-5pm. Cathy's OH today at 11pm-12am. Nathan's OH tomorrow at 7am-9am
- Written Assessment 1 will be released tonight
  - due next Monday before start of lecture
- Lecture 1 slides and recording
  - See Piazza

# CS 188: Artificial Intelligence

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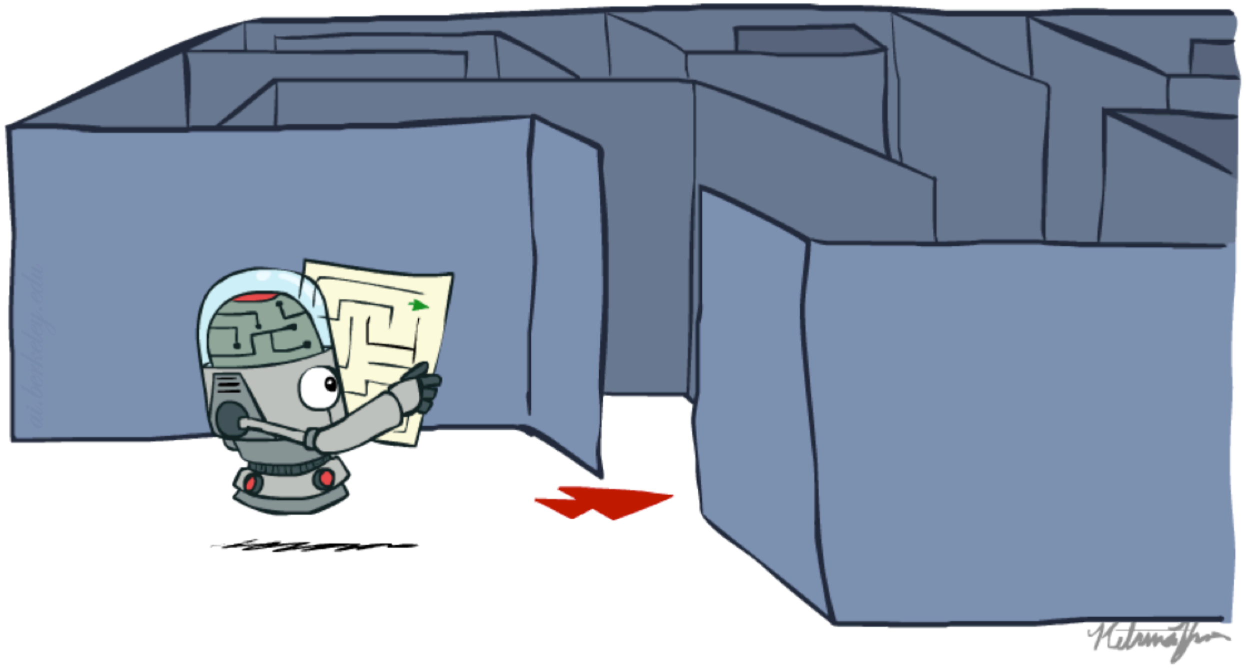

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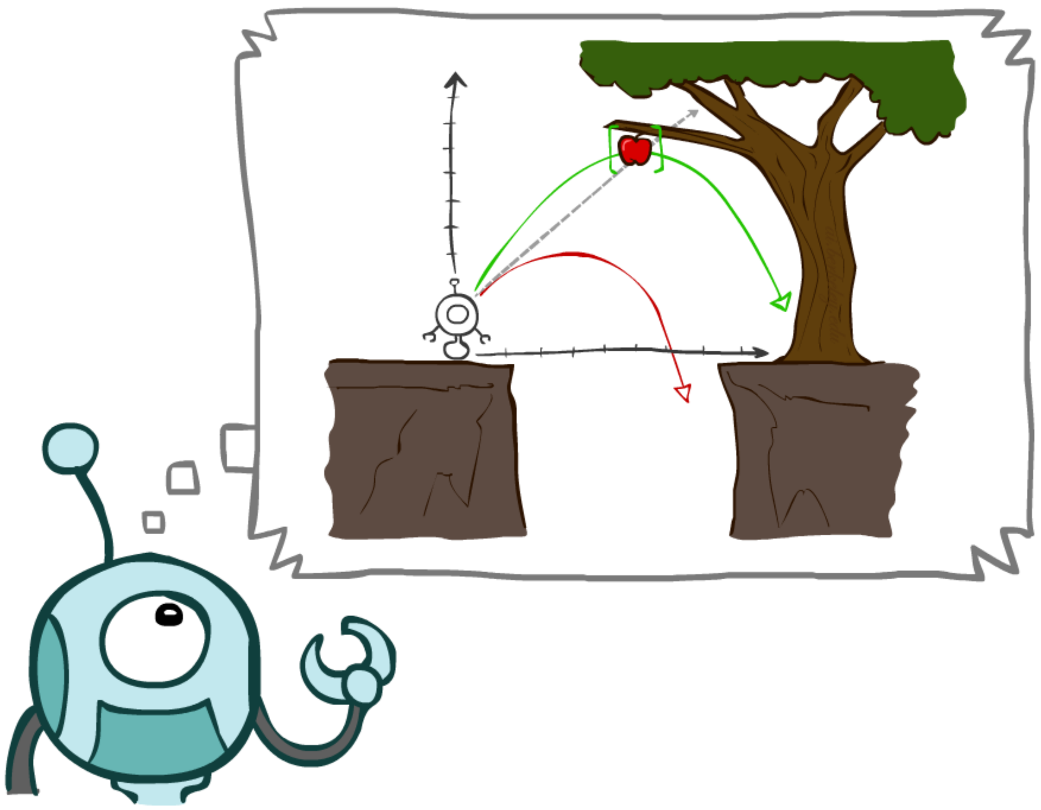
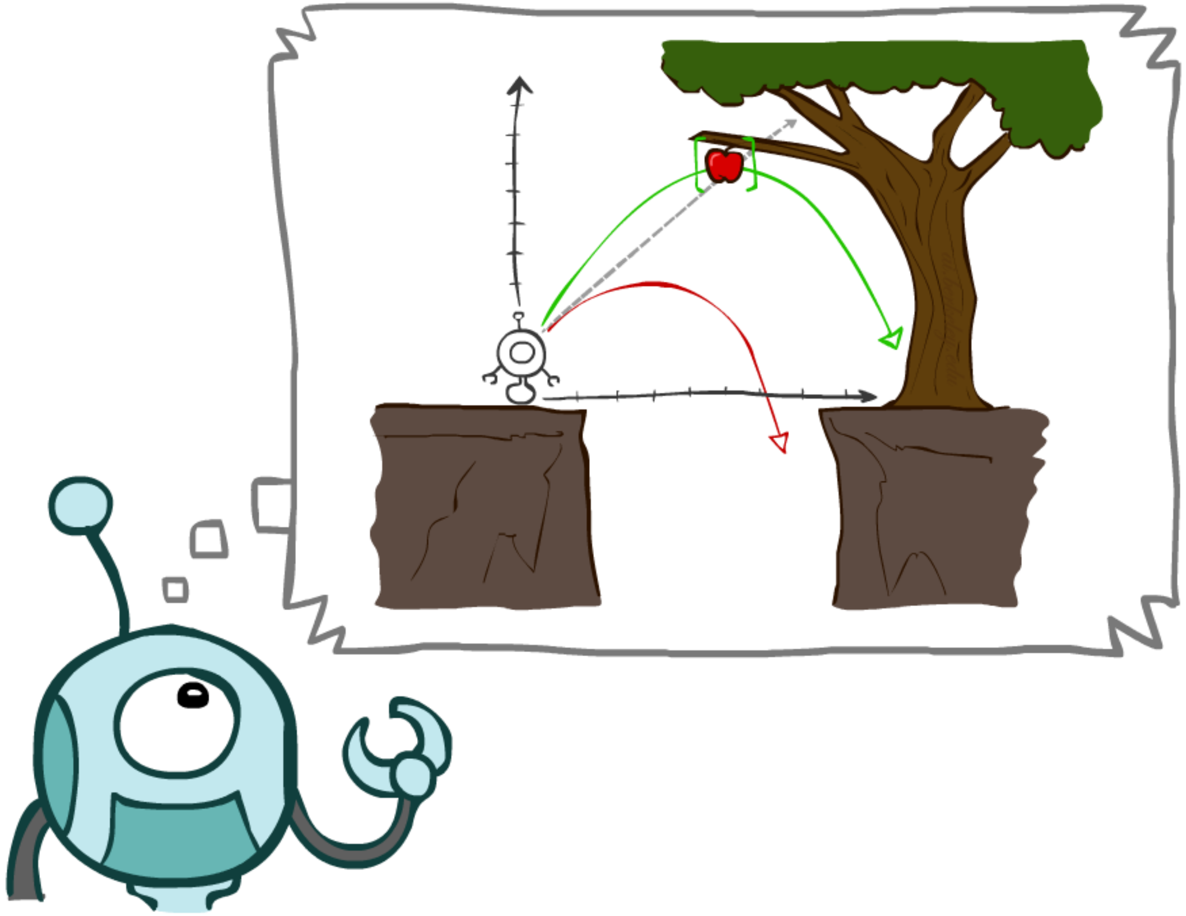
# Today

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



# Agents that Plan



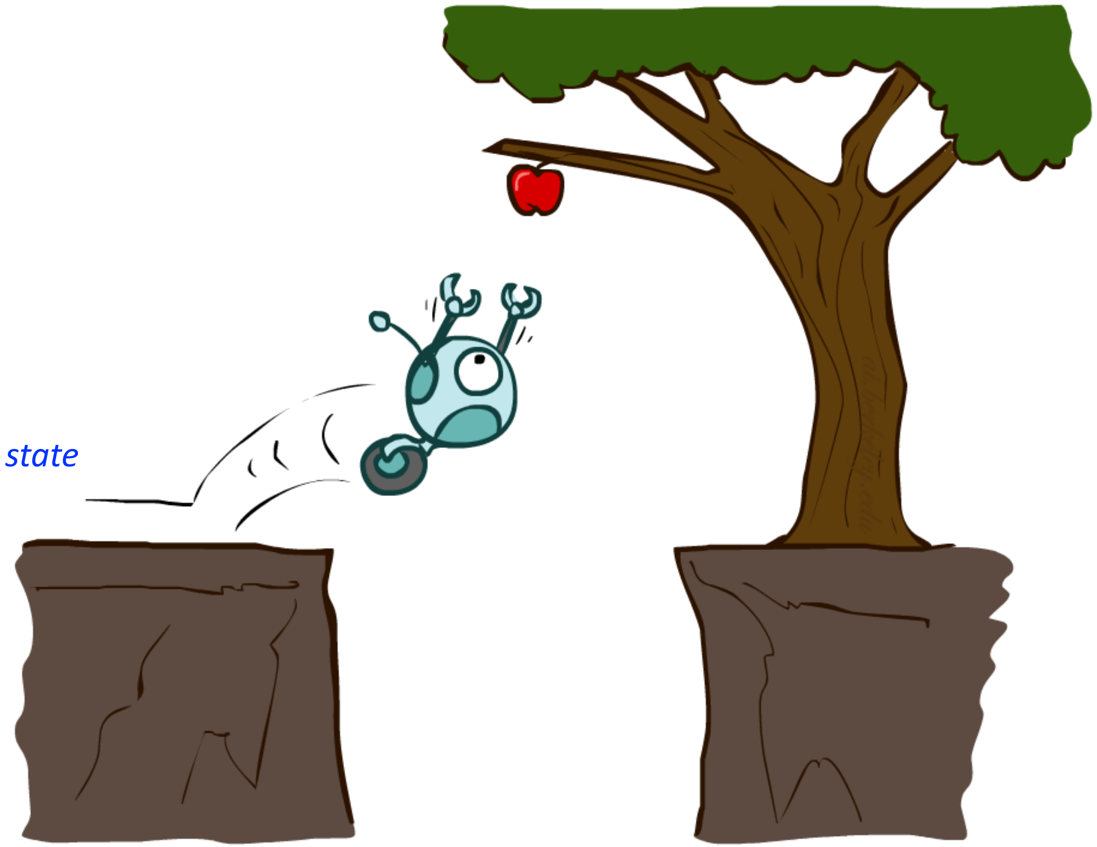
# Reflex Agents

- 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

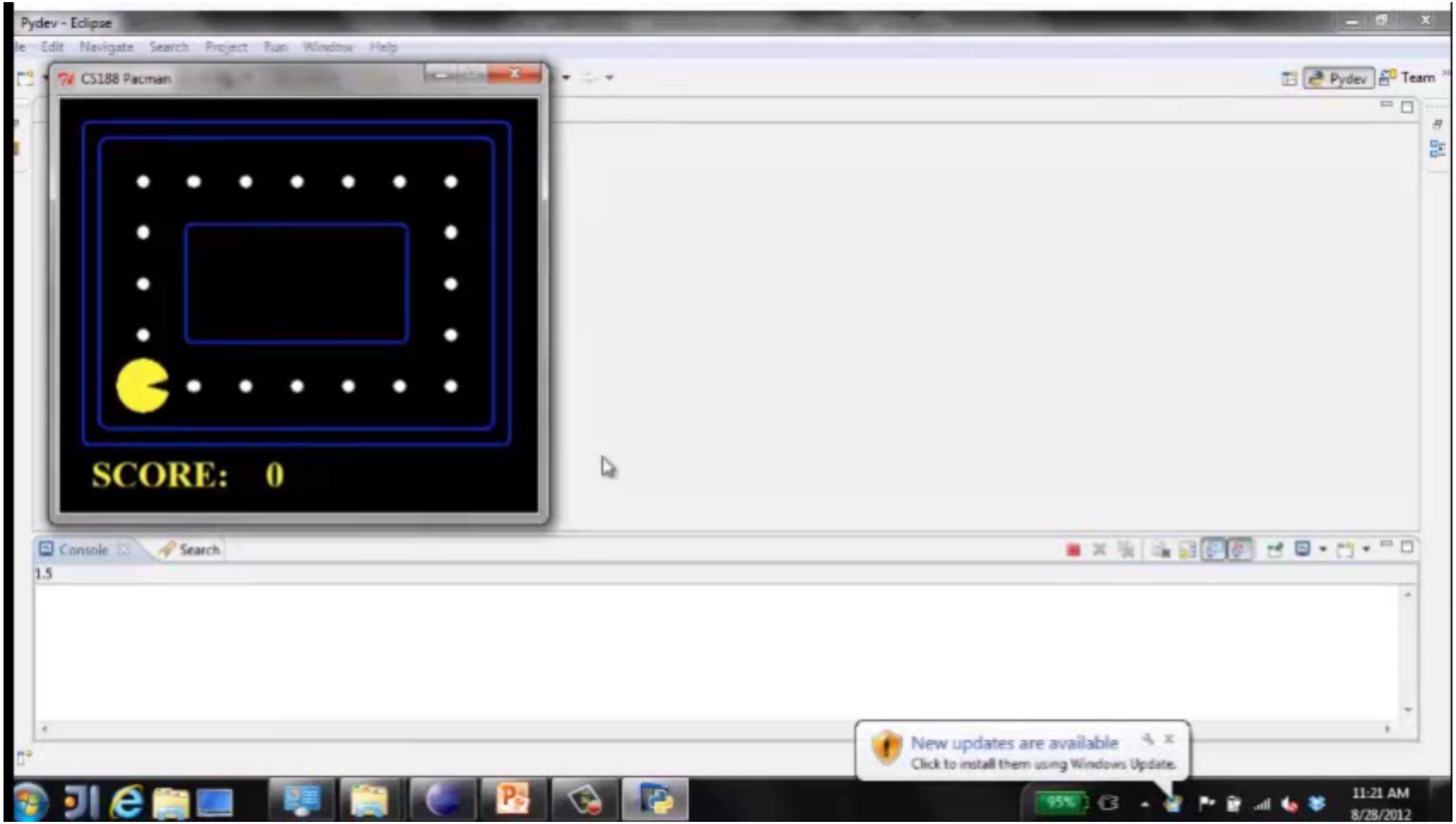
*is just how the world is in current state or any given state*

- Can a reflex agent be rational?

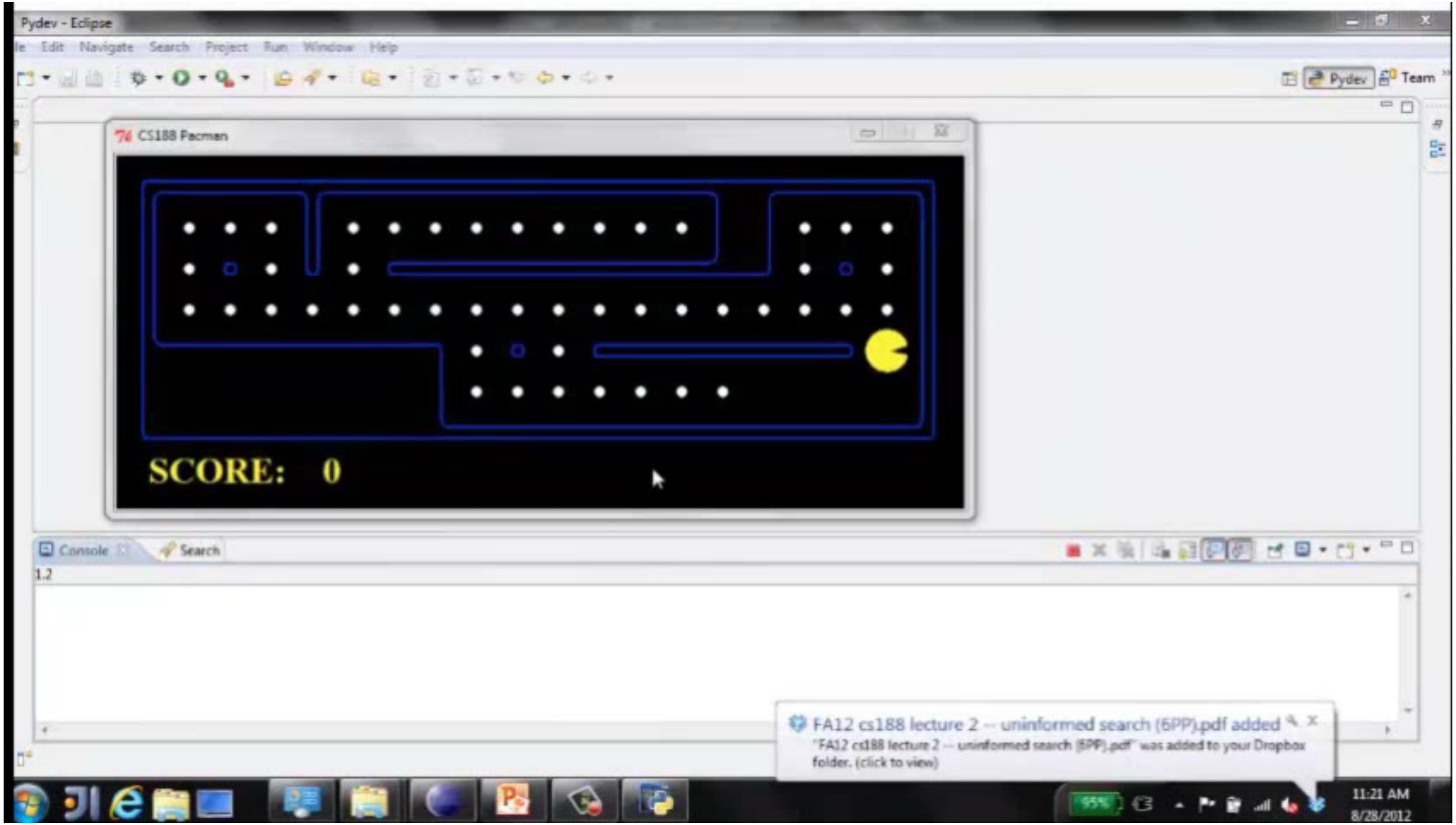
*Rationality means do whatever actions to reach whatever goals…*



# Video of Demo Reflex Optimal



# Video of Demo Reflex Odd

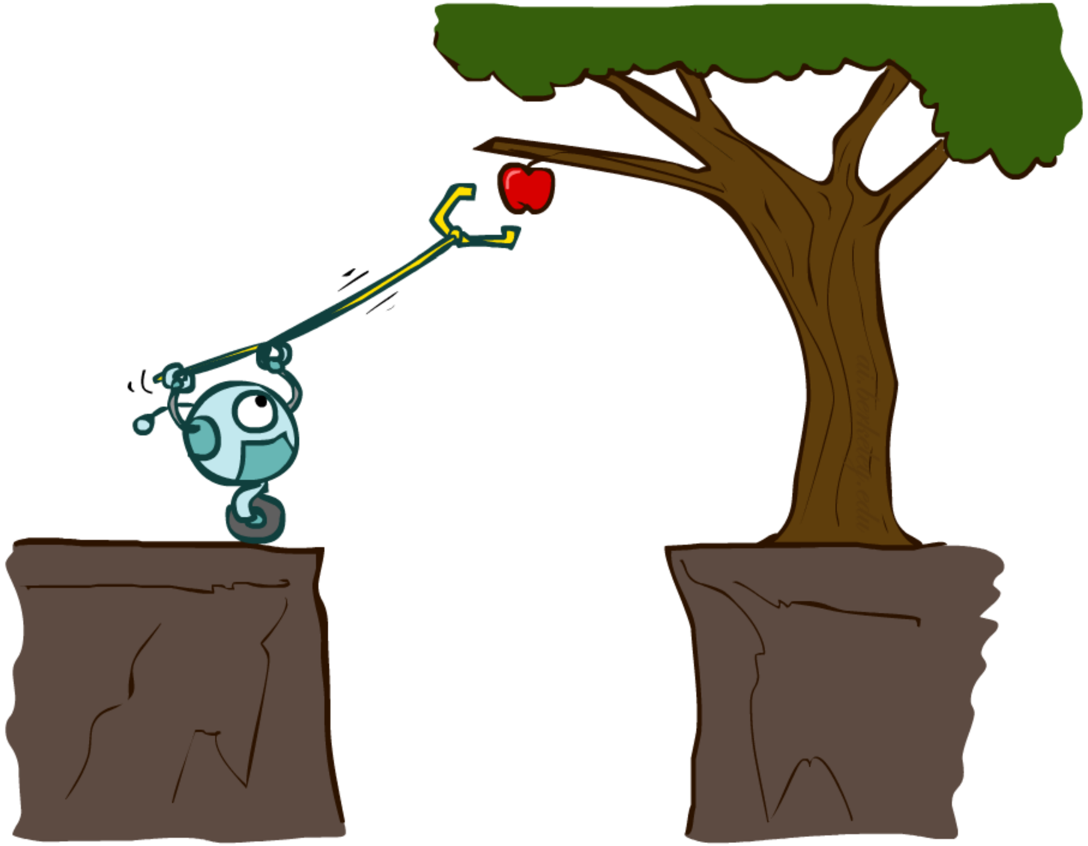


# Planning Agents

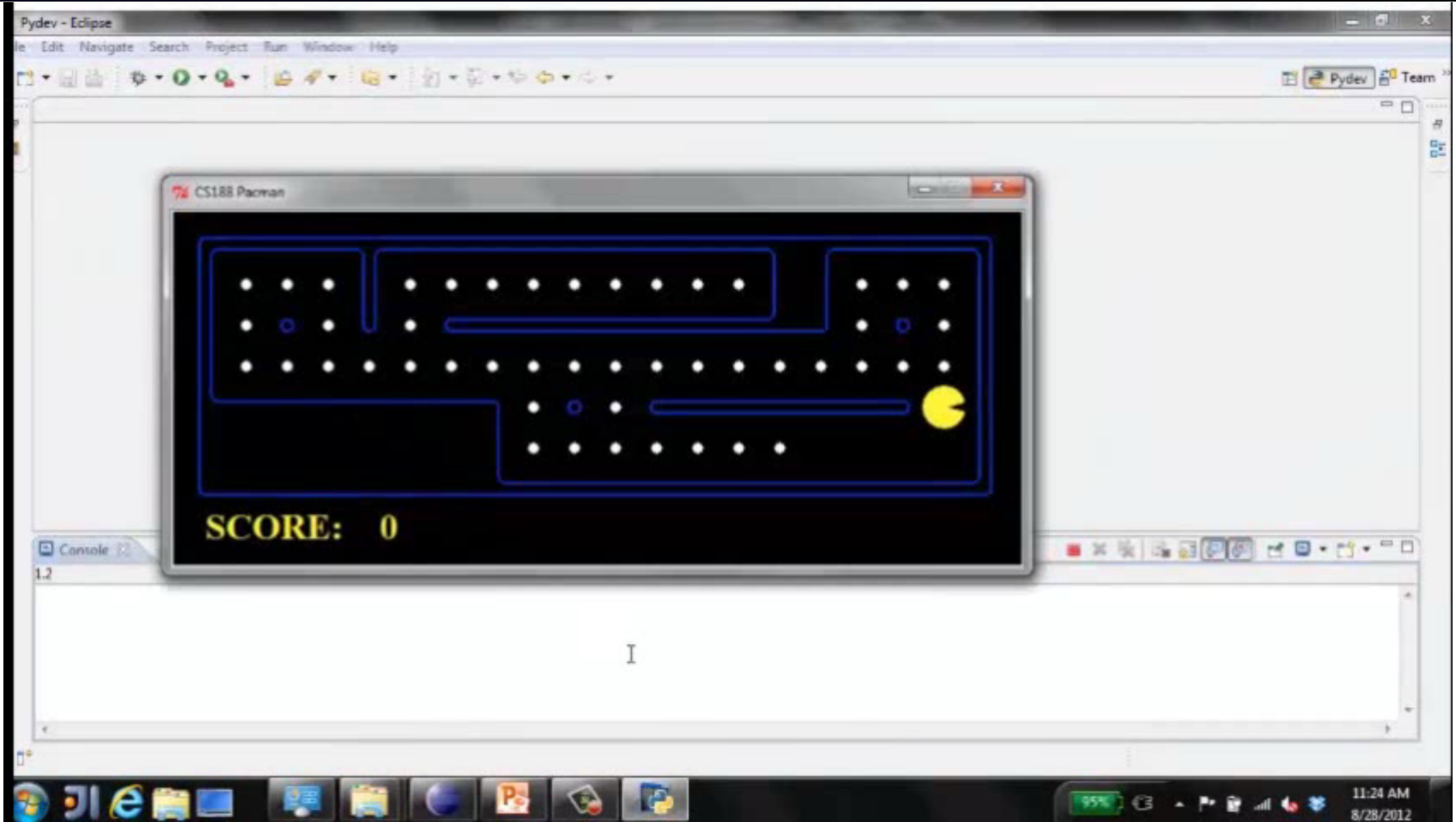
- Planning agents:
  - Ask “what if”
  - Decisions based on (hypothesized) consequences of actions
  - Must have a model of how the world evolves in response to actions
  - Must formulate a goal (test)
  - Consider how the world WOULD BE

- Optimal vs. complete planning

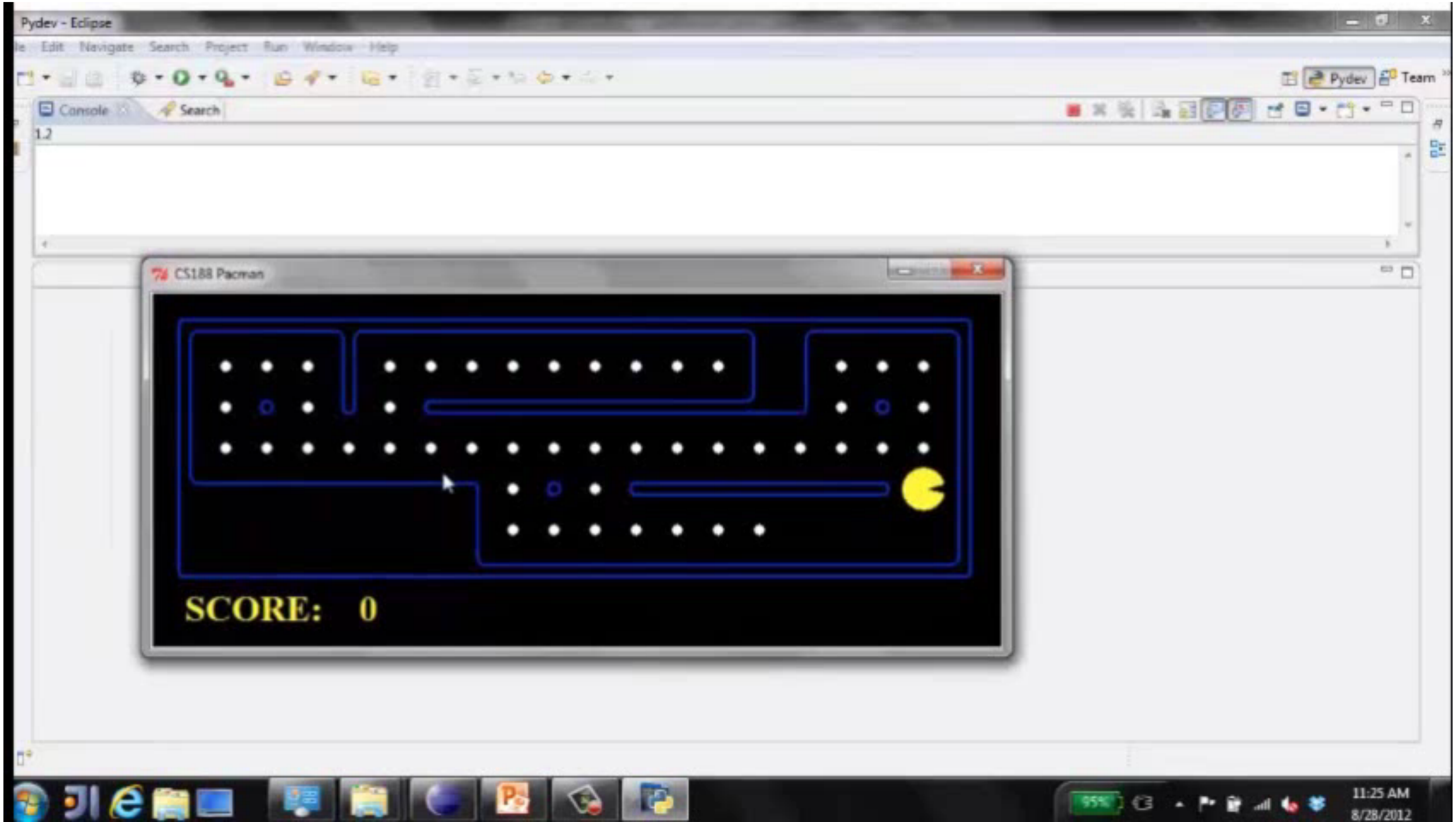
- Planning vs. replanning



# Video of Demo Replanning



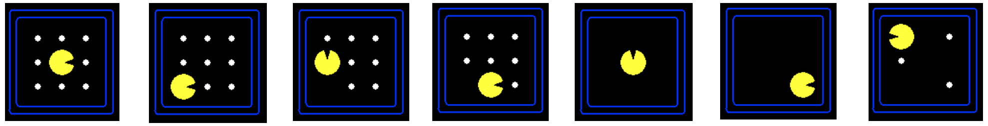
# Video of Demo Mastermind



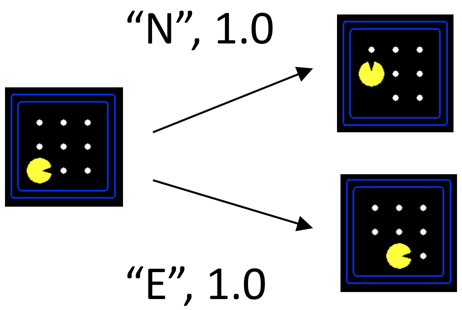
# Search Problems

# Search Problems

- A search problem consists of:
  - A state space



  - A successor function (with actions, costs)

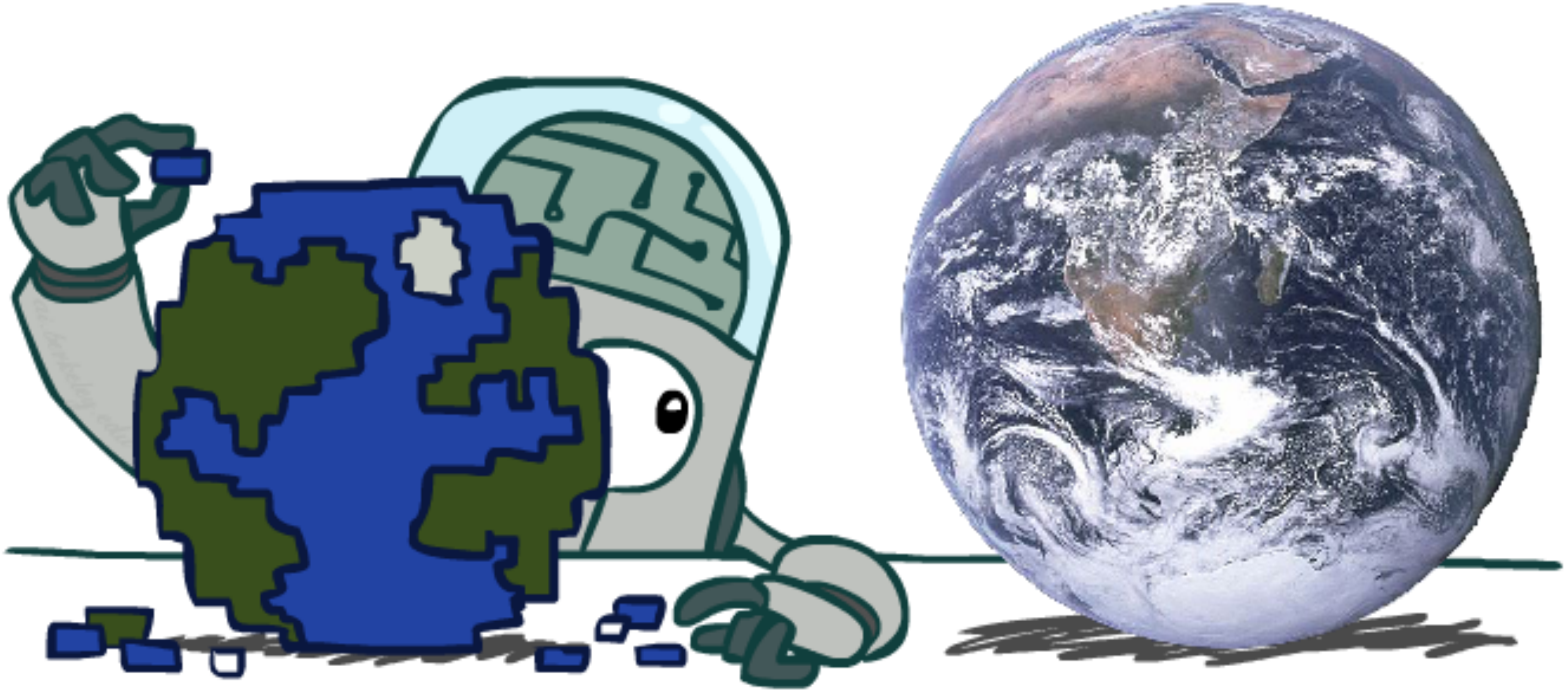



  - A start state and a goal test

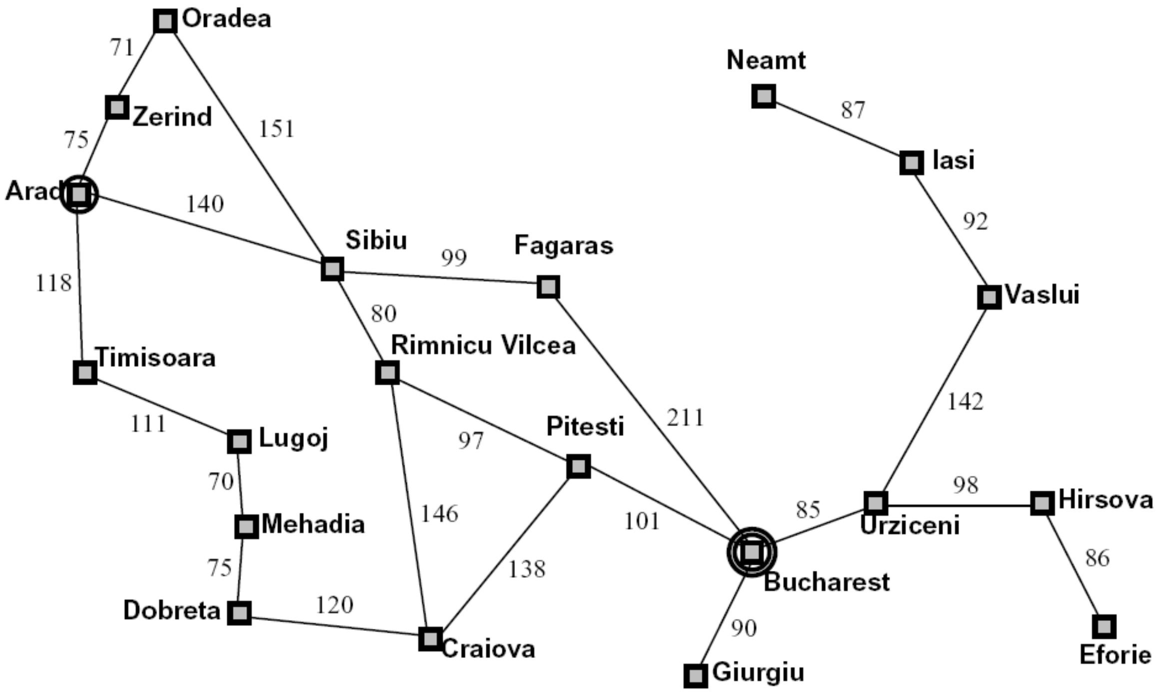
*That we have more than one state to accomplish the goal..*

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

# Search Problems Are Models



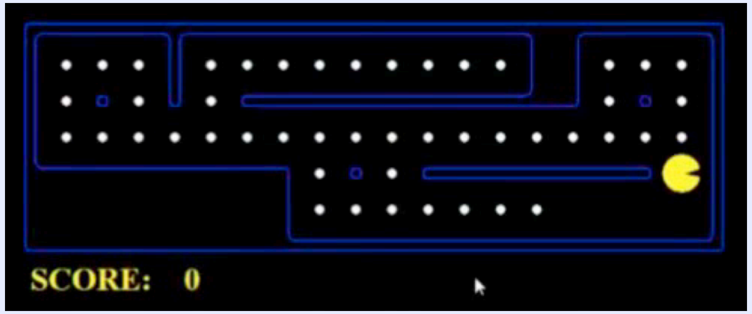
# Example: Traveling in Romania




- 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



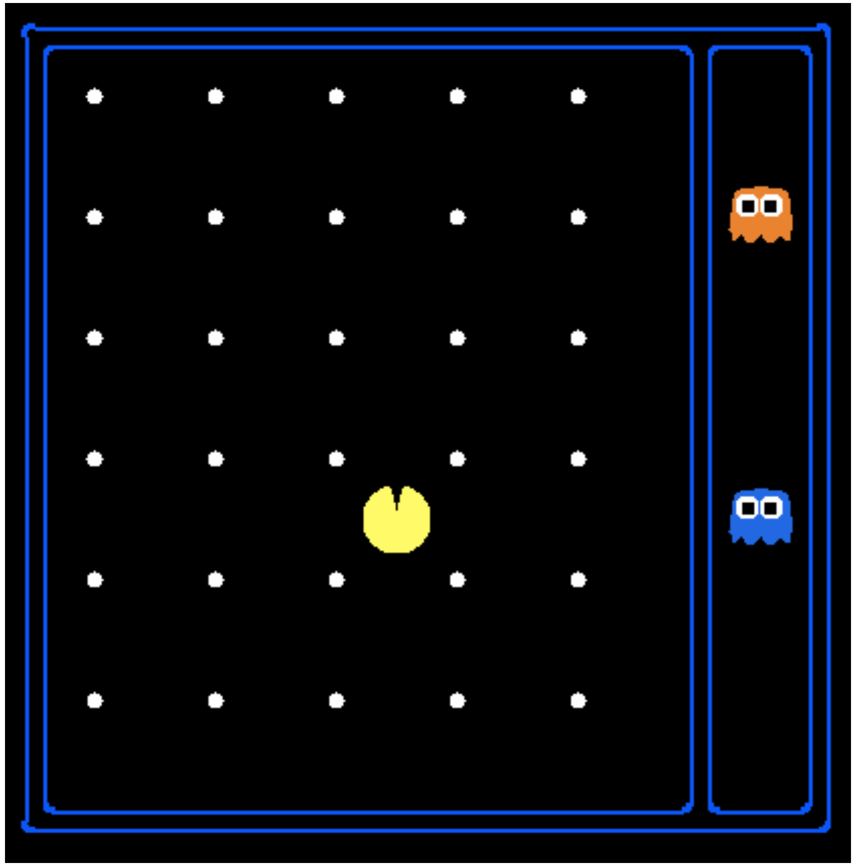

A search state keeps only the details needed for planning (abstraction)

- Problem: Pathing
  - States: (x,y) location
  - Actions: NSEW
  - Successor: update location only
  - Goal test: is (x,y)=END

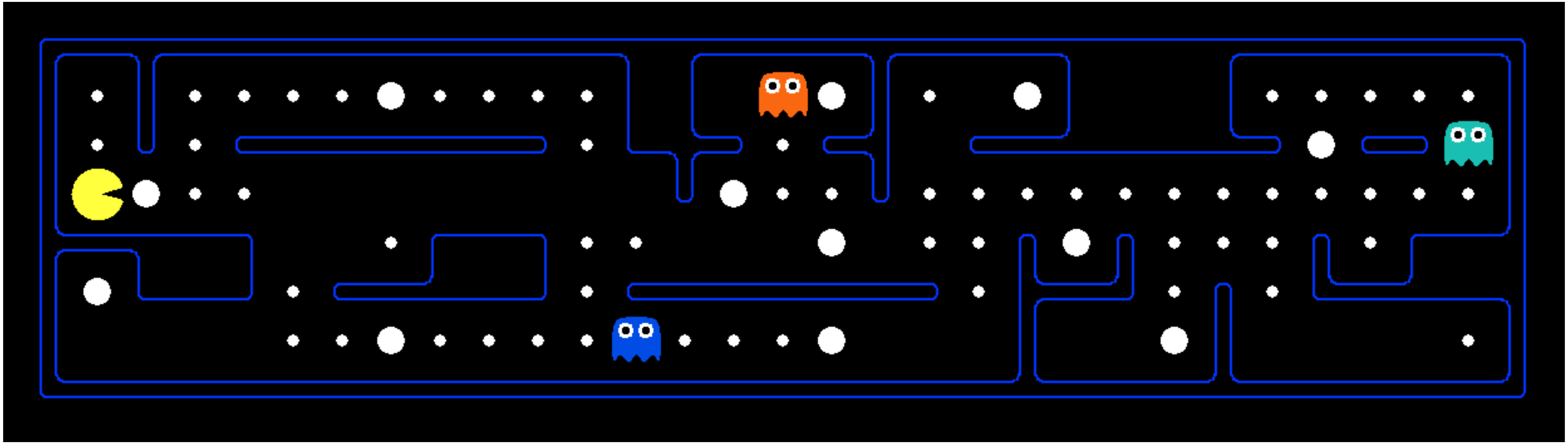
- Problem: Eat-All-Dots
  - States: {(x,y), dot booleans}
  - Actions: NSEW
  - Successor: update location and possibly a dot boolean
  - Goal test: dots all false

# 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?
    $120 \times (2^{30})$

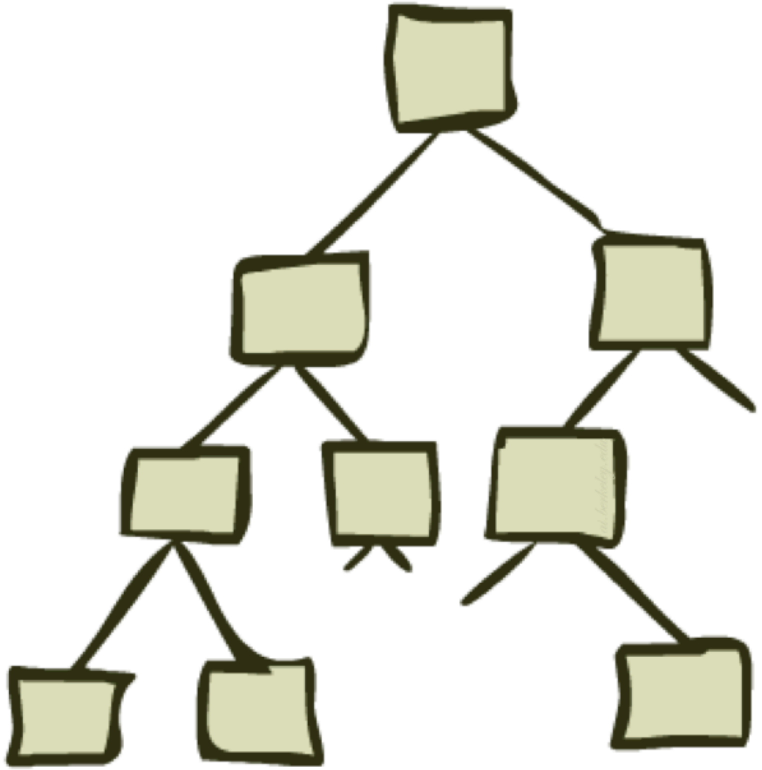


# Quiz: Safe Passage



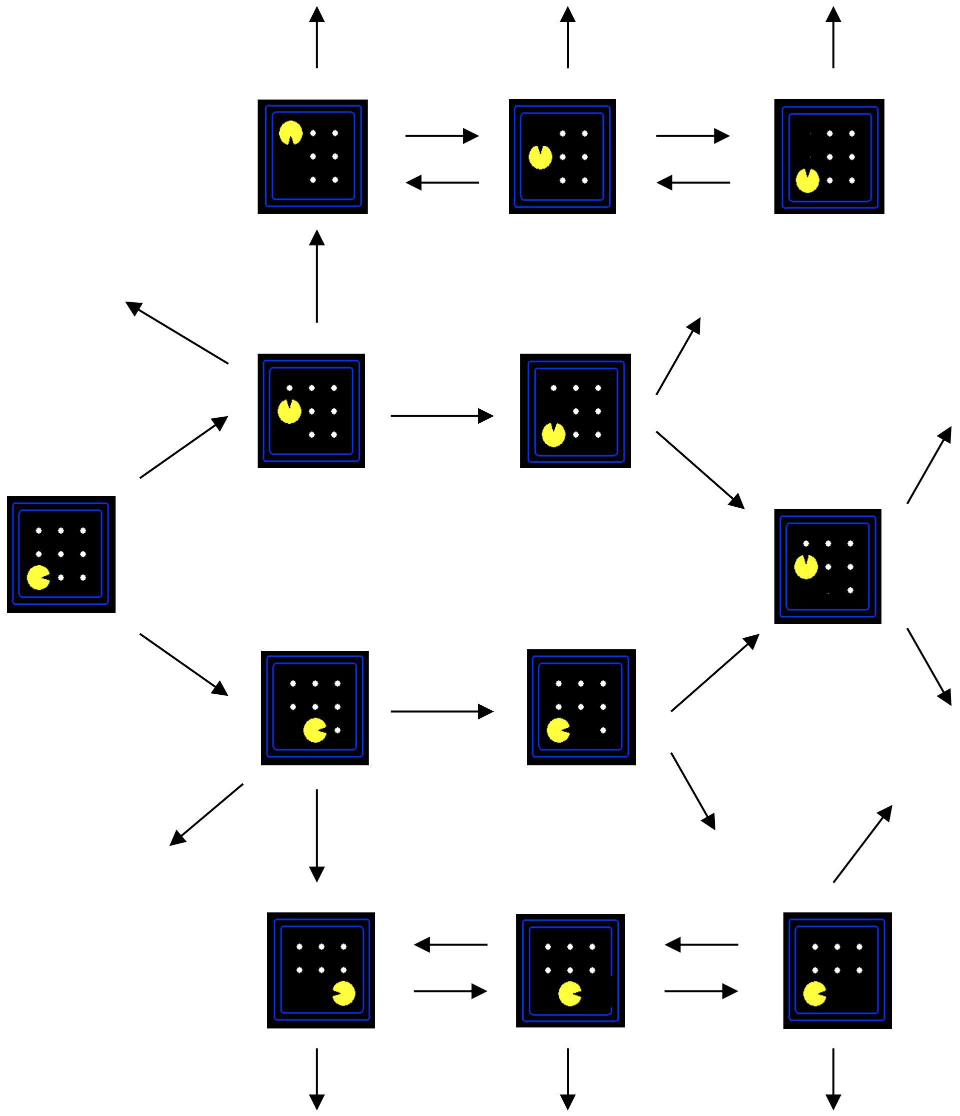
- Problem: eat all dots while keeping the ghosts perma-scared
- What does the state space have to specify?
  - (agent position, dot booleans, power pellet booleans, remaining scared time)

# 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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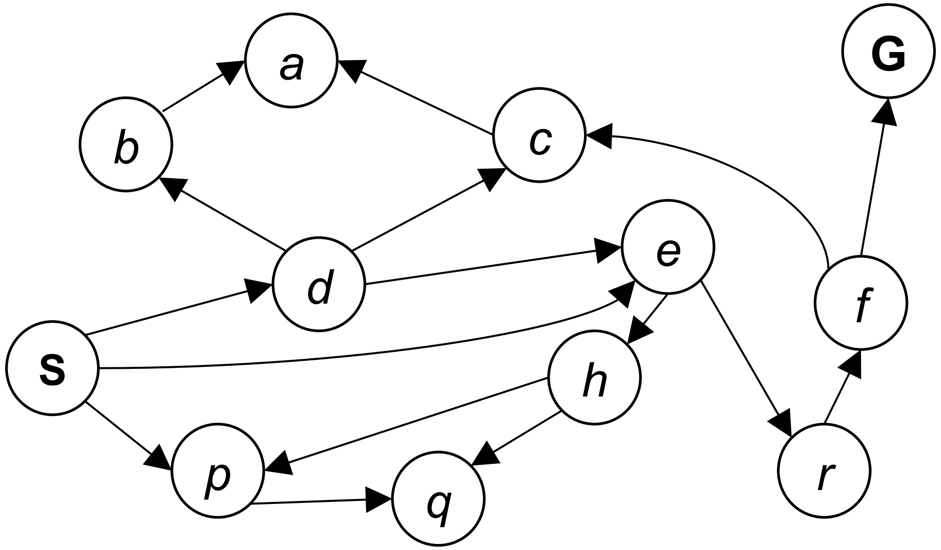
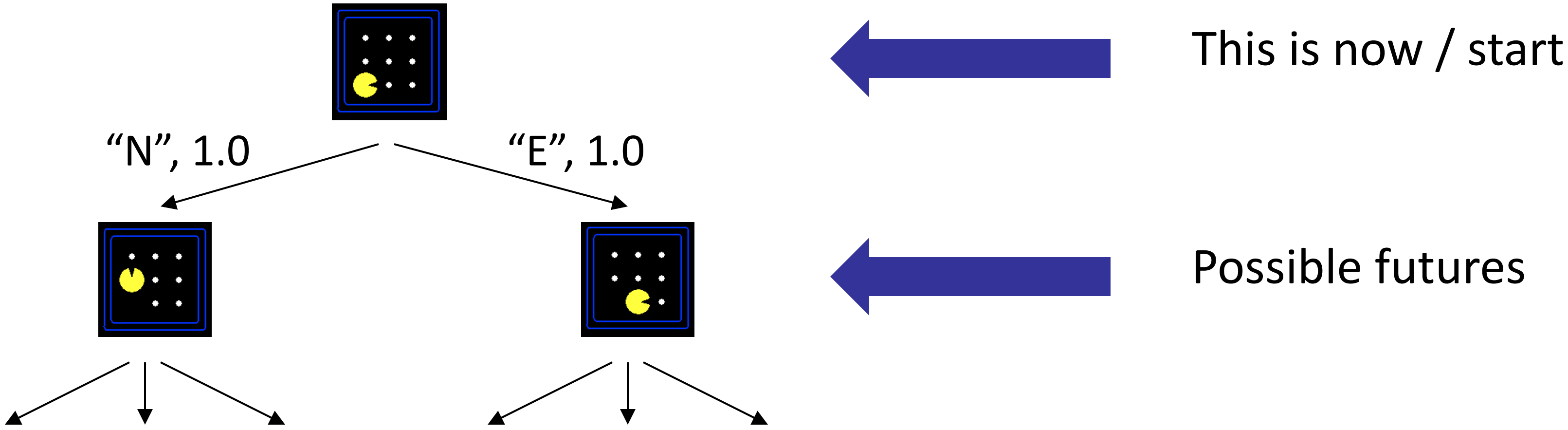


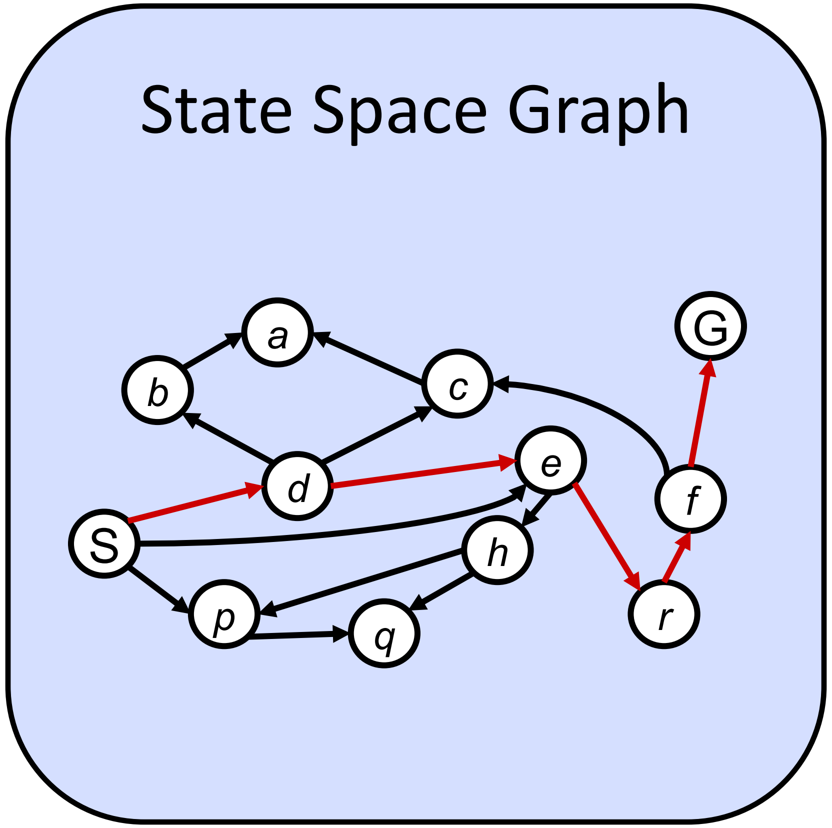

*Tiny state space graph for a tiny search problem*

# Search Trees



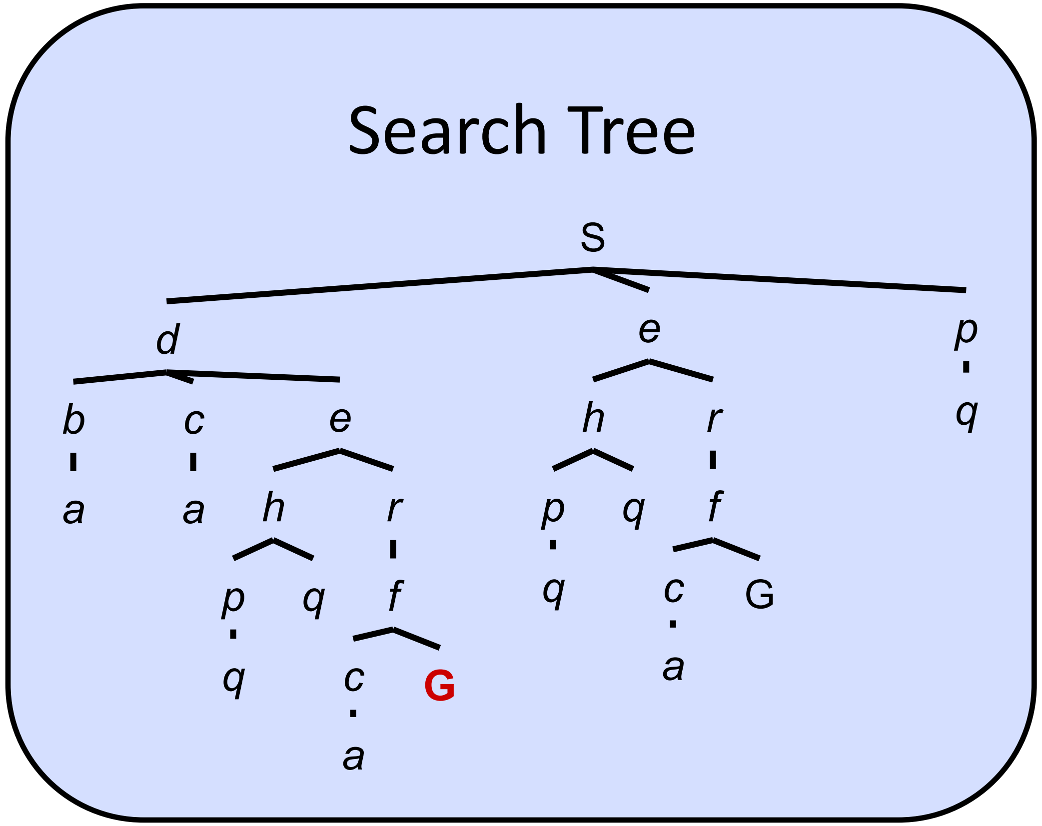

- A search tree:
  - A "what if" tree of plans and their outcomes
  - The start state is the root node
  - Children correspond to successors
  - Nodes show states, but correspond to PLANS that achieve those states
  - For most problems, we can never actually build the whole tree

# State Space Graphs vs. Search Trees



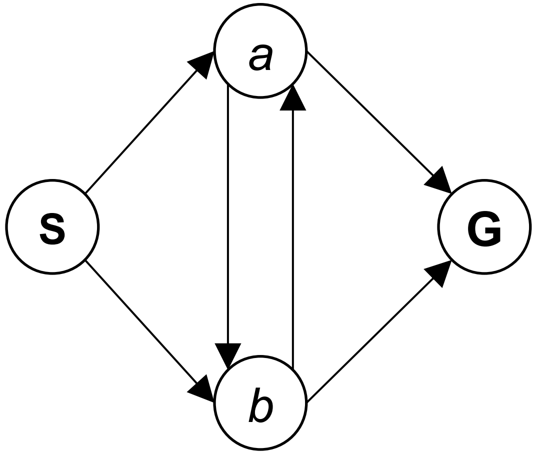

*Each NODE in in the search tree is an entire PATH in the state space graph.*

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



# Quiz: State Space Graphs vs. Search Trees

Consider this 4-state graph:

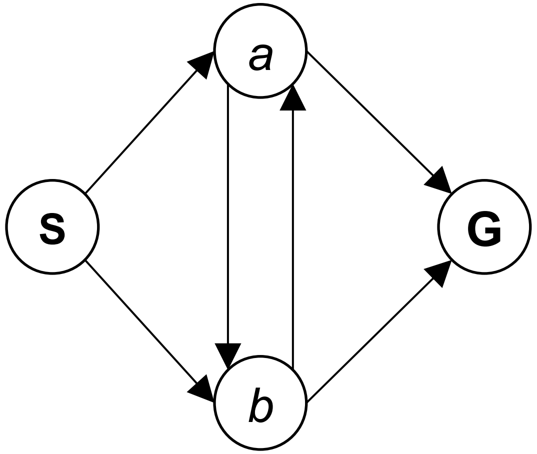



How big is its search tree (from S)?

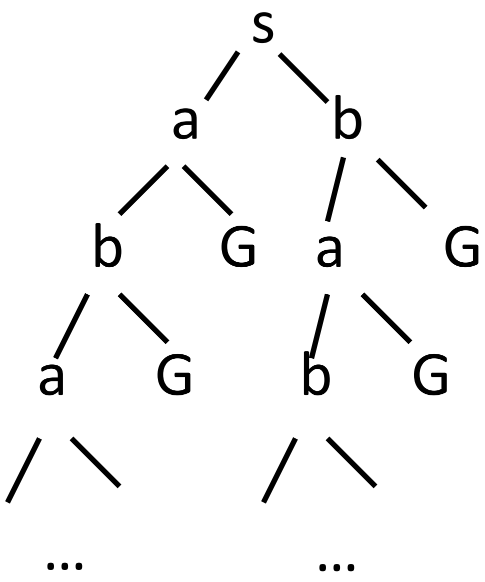
$$\infty$$

# Quiz: State Space Graphs vs. Search Trees

Consider this 4-state graph:

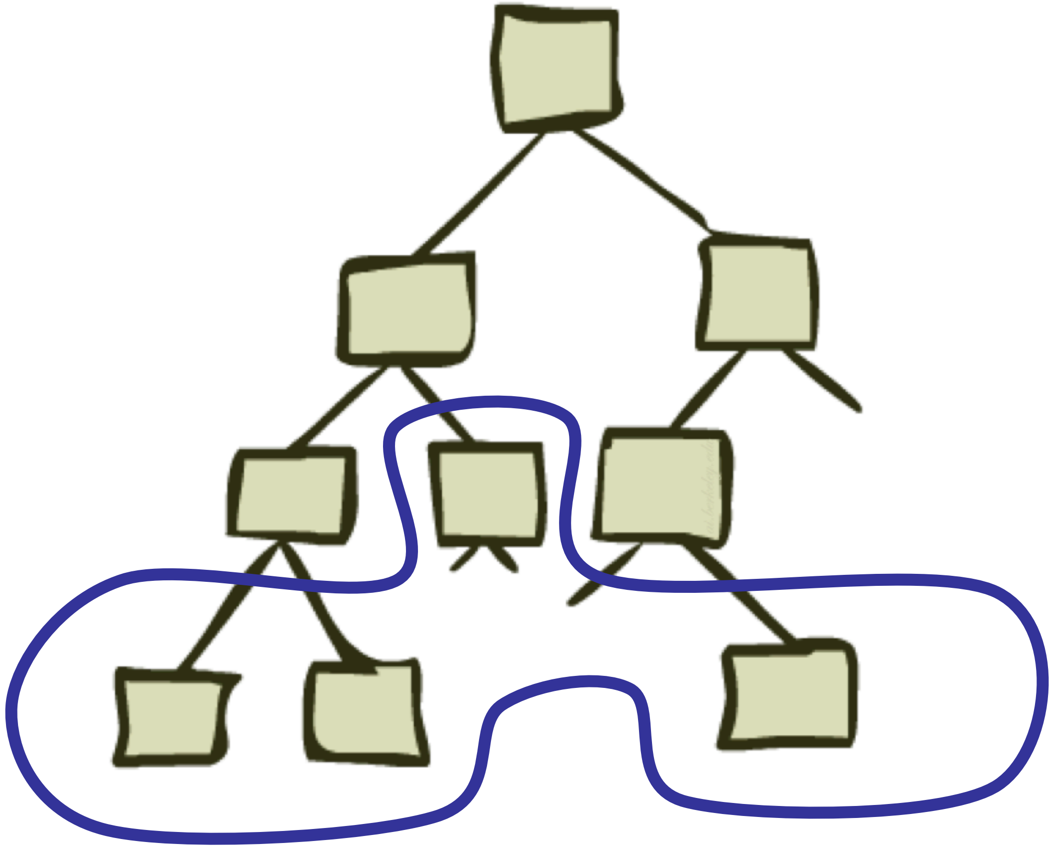



How big is its search tree (from S)?

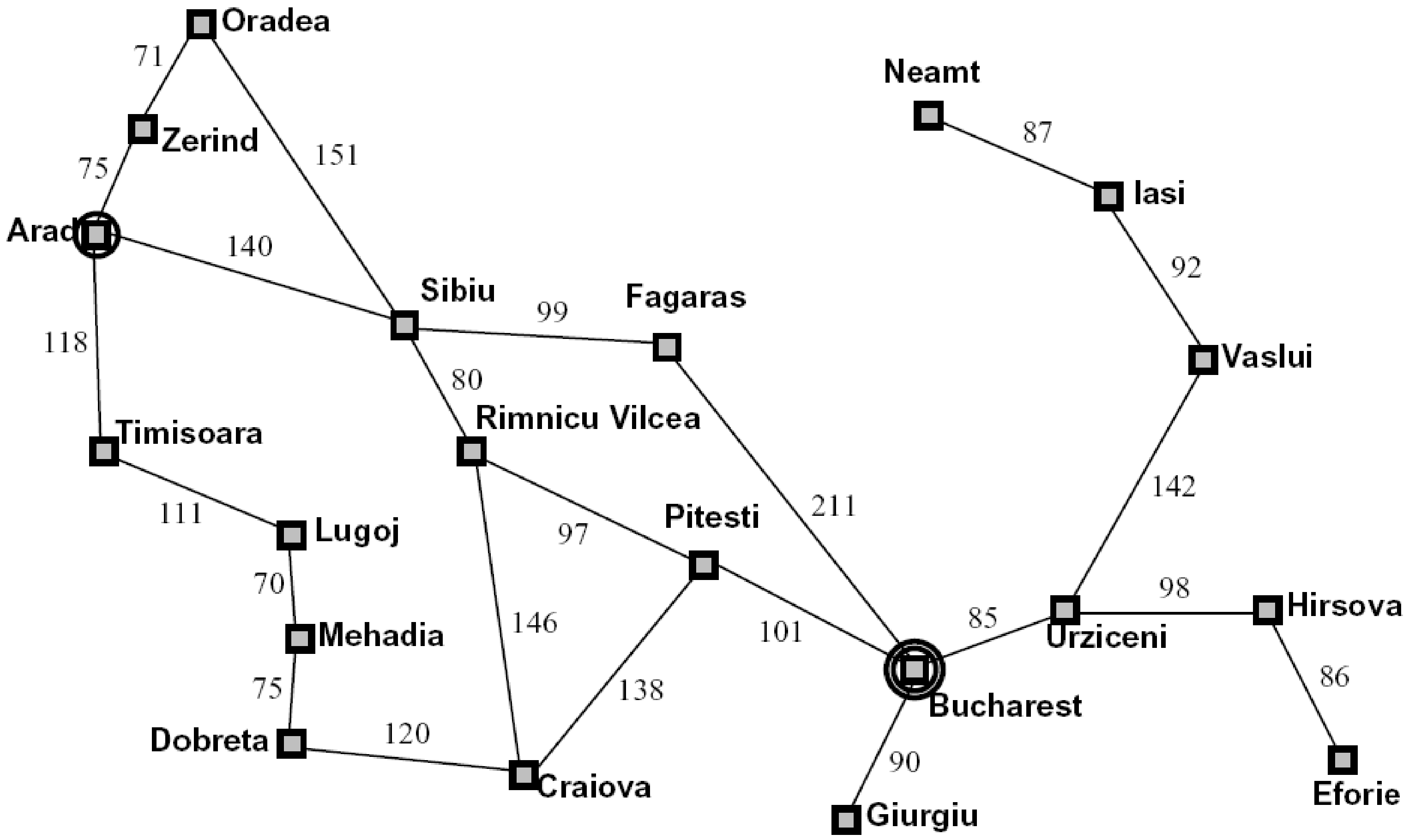



Important: Lots of repeated structure in the search tree!

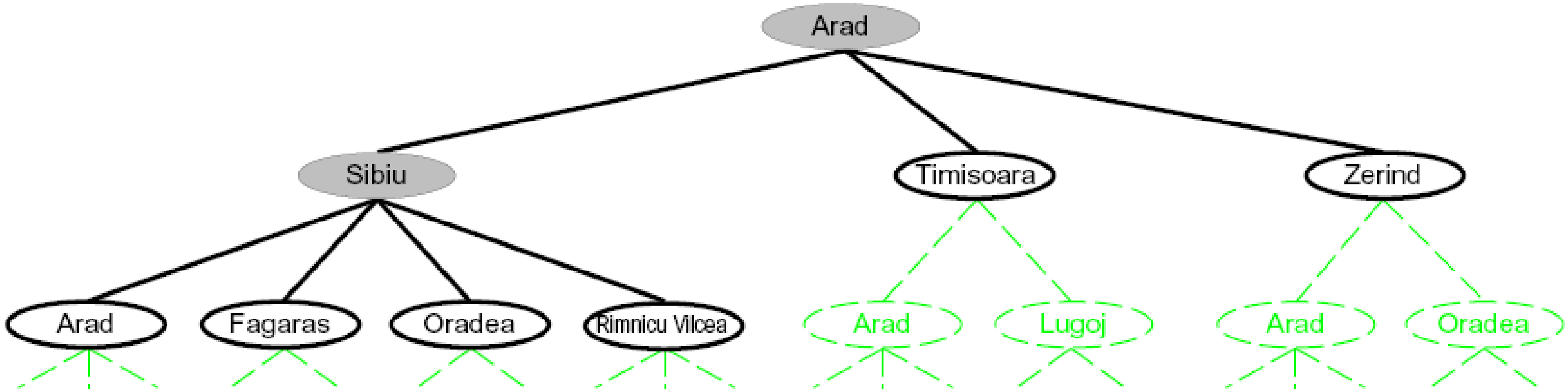
# Tree Search



# Search Example: Romania



# Searching with a Search Tree



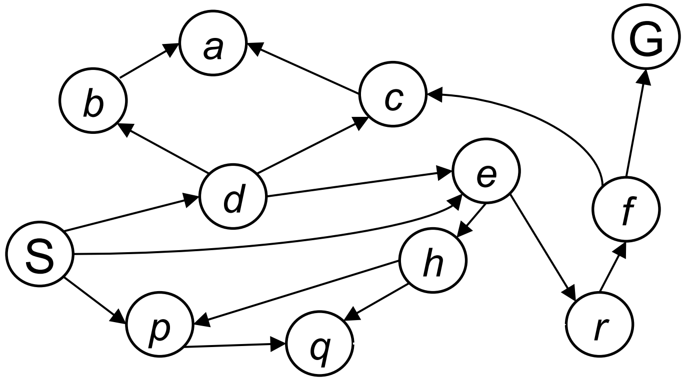

- Search:
  - Expand out potential plans (tree nodes)
  - Maintain a fringe of partial plans under consideration
  - Try to expand as few tree nodes as possible

# General Tree Search

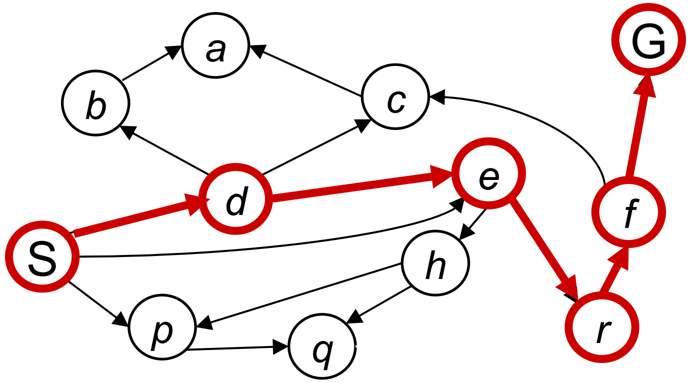
```
function TREE-SEARCH( problem, strategy) returns a solution, or failure
    initialize the search tree using the initial state of problem
    loop do
        if there are no candidates for expansion then return failure
        choose a leaf node for expansion according to strategy
        if the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

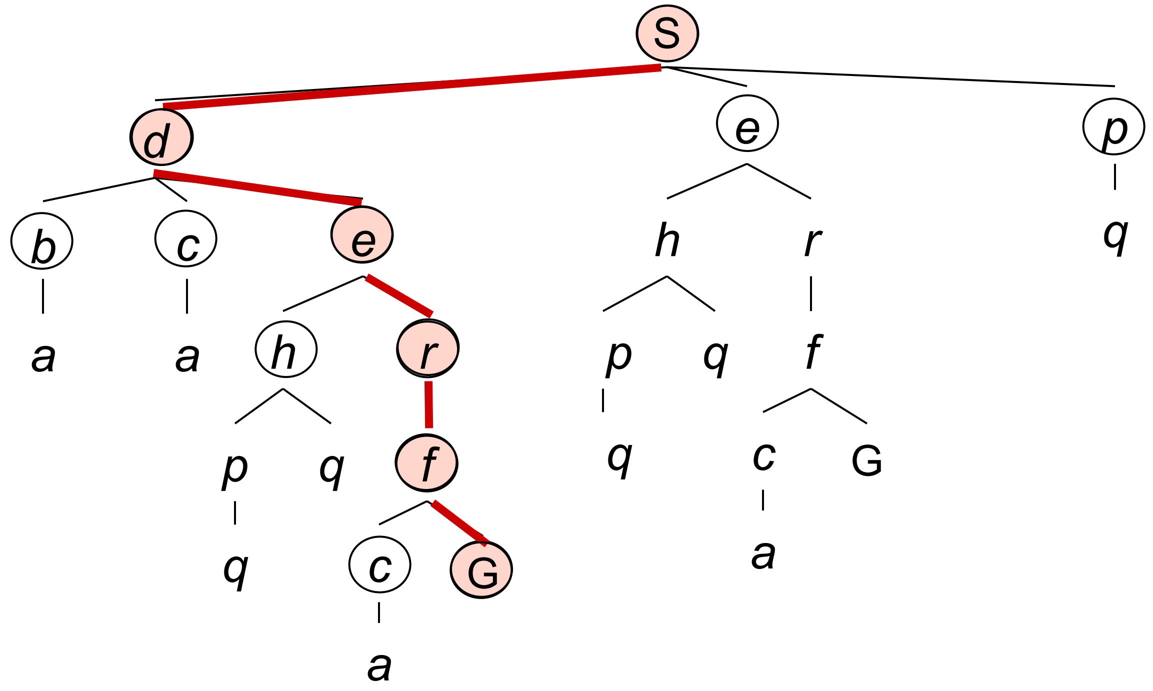
- Important ideas:
    - Fringe
    - Expansion
    - Exploration strategy
- Main question: which fringe nodes to explore?

# 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

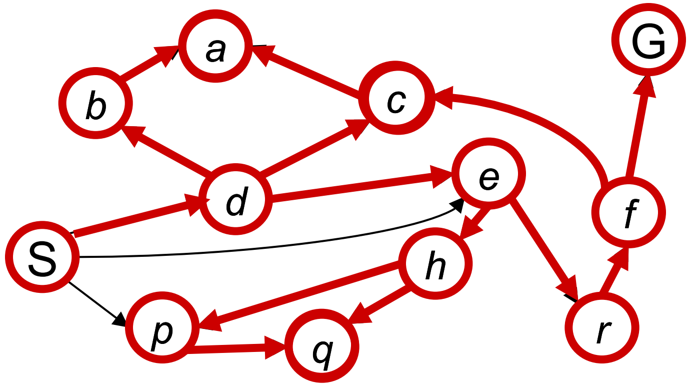
~~s → d → e → r → f → G~~

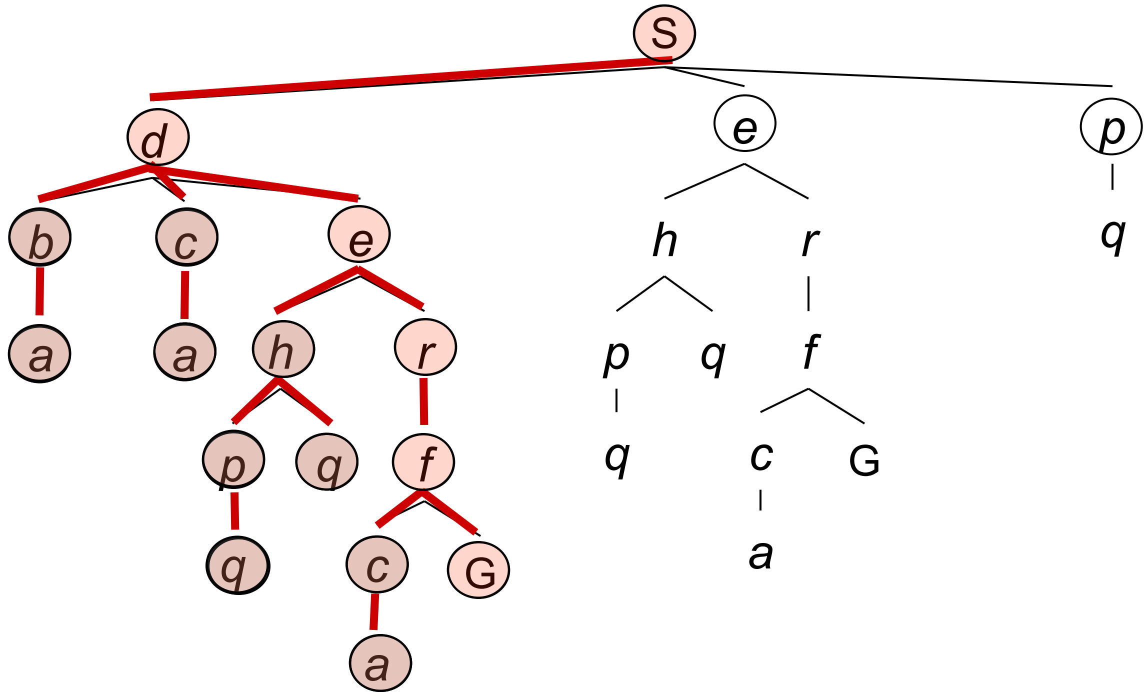
# Depth-First Search

# Depth-First Search

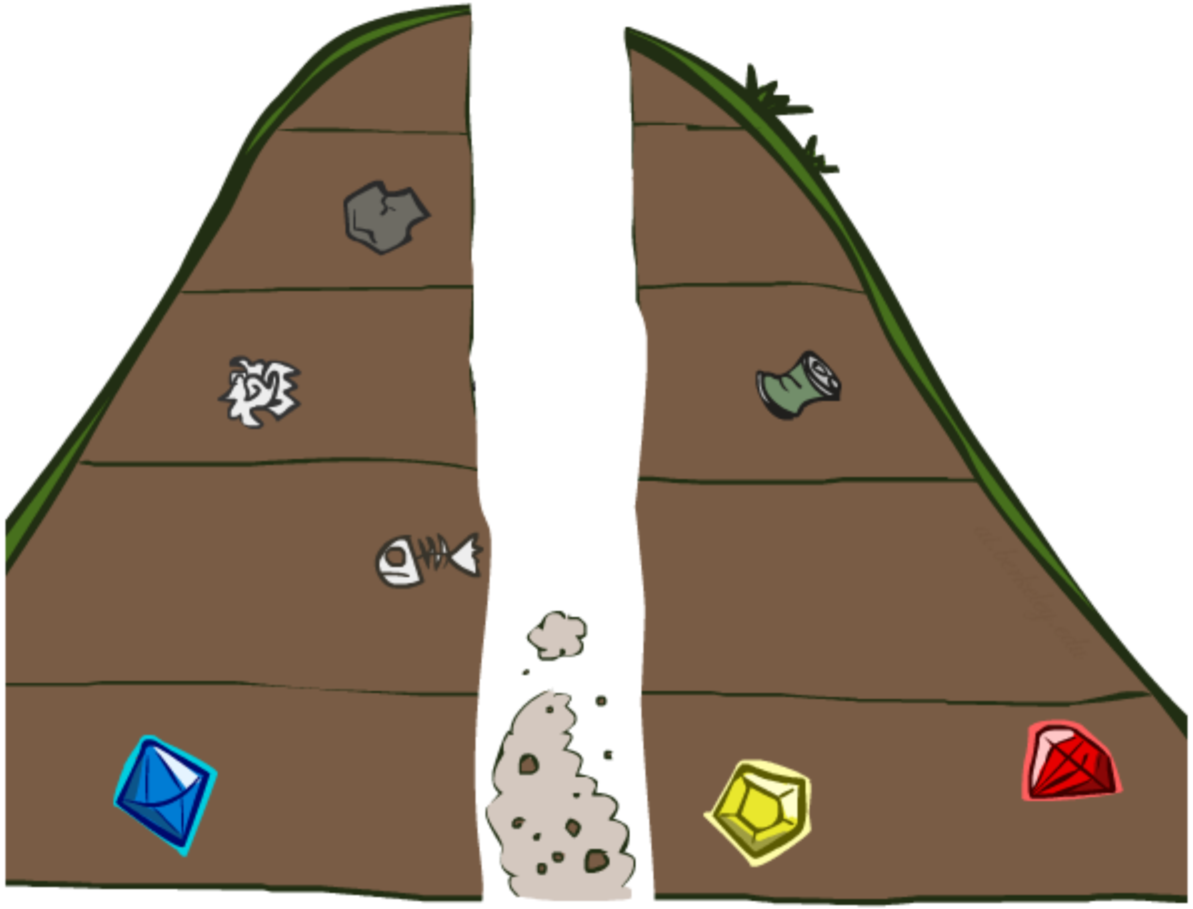
*Strategy: expand a deepest node first*

*Implementation: Fringe is a LIFO stack*



# Search Algorithm Properties

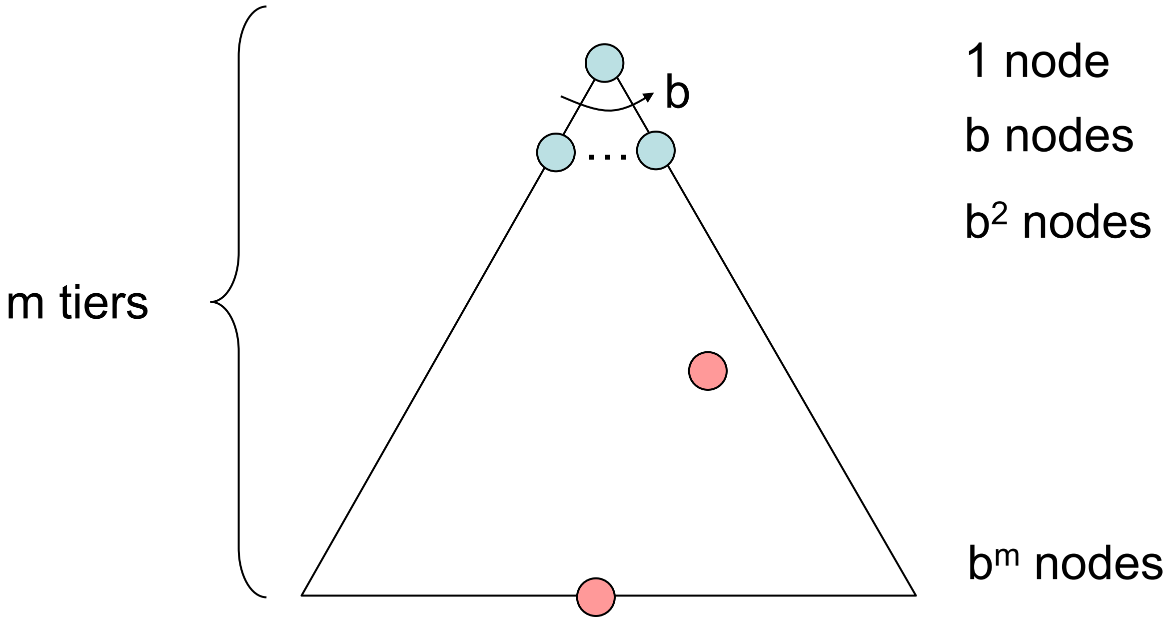


# Search Algorithm Properties

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

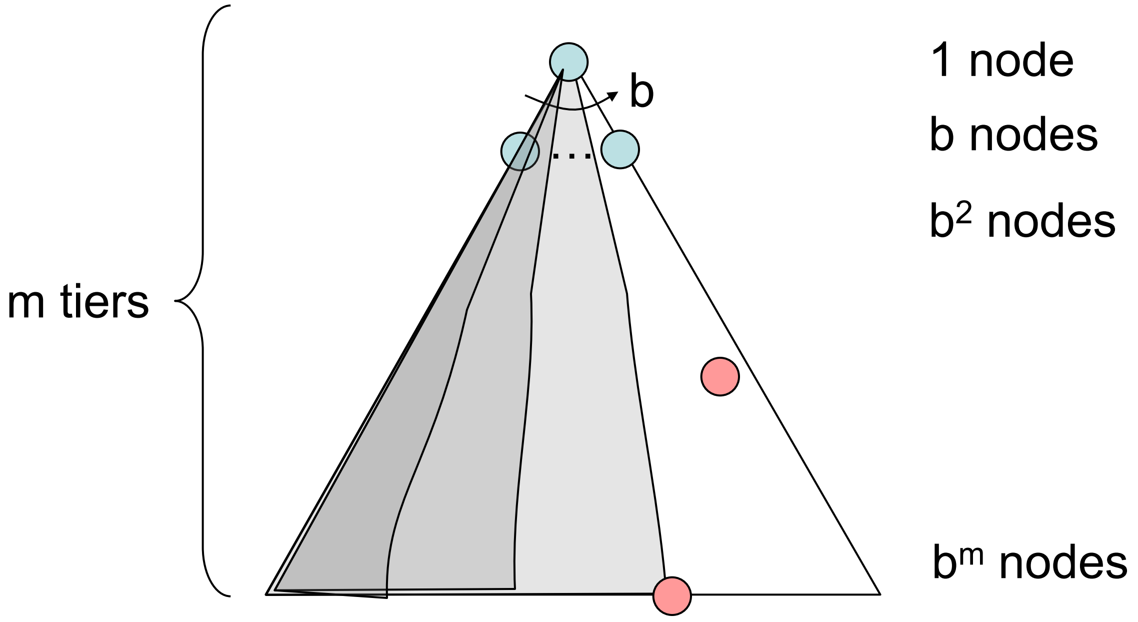
- Cartoon of search tree:
  - b is the branching factor
  - m is the maximum depth
  - solutions at various depths

- Number of nodes in entire tree?
  - $1 + b + b^2 + \ldots.\ b^m = O(b^m)$

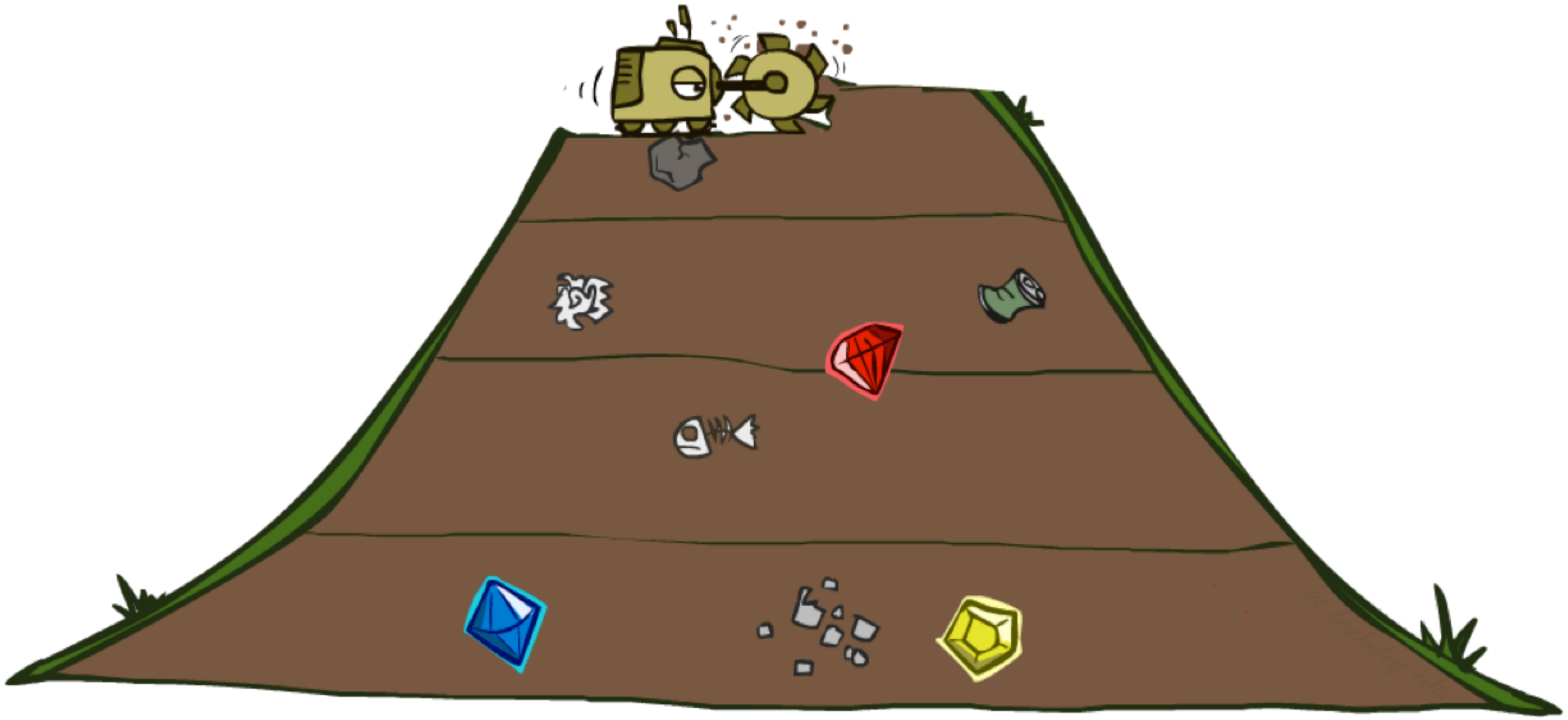


# Depth-First Search (DFS) Properties

- 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



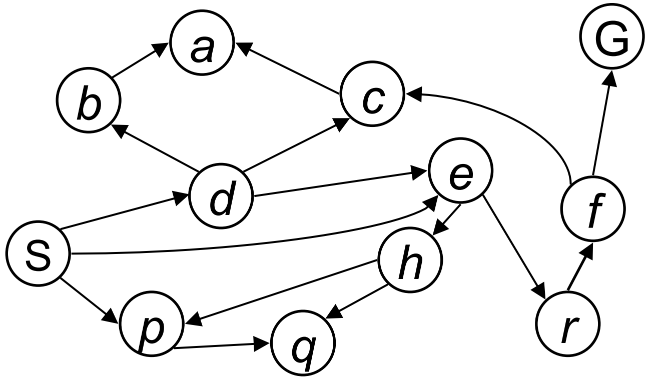
# Breadth-First Search

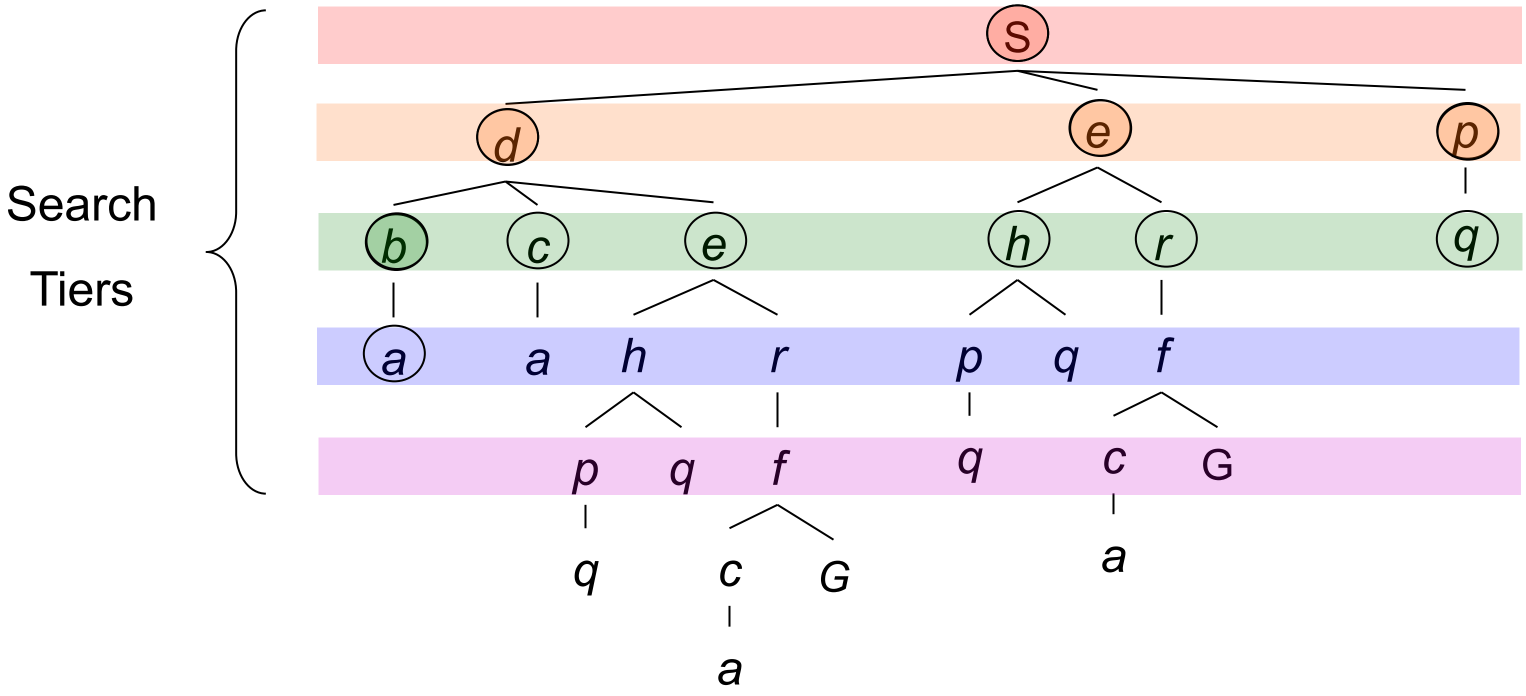


# Breadth-First Search

*Strategy: expand a shallowest node first*

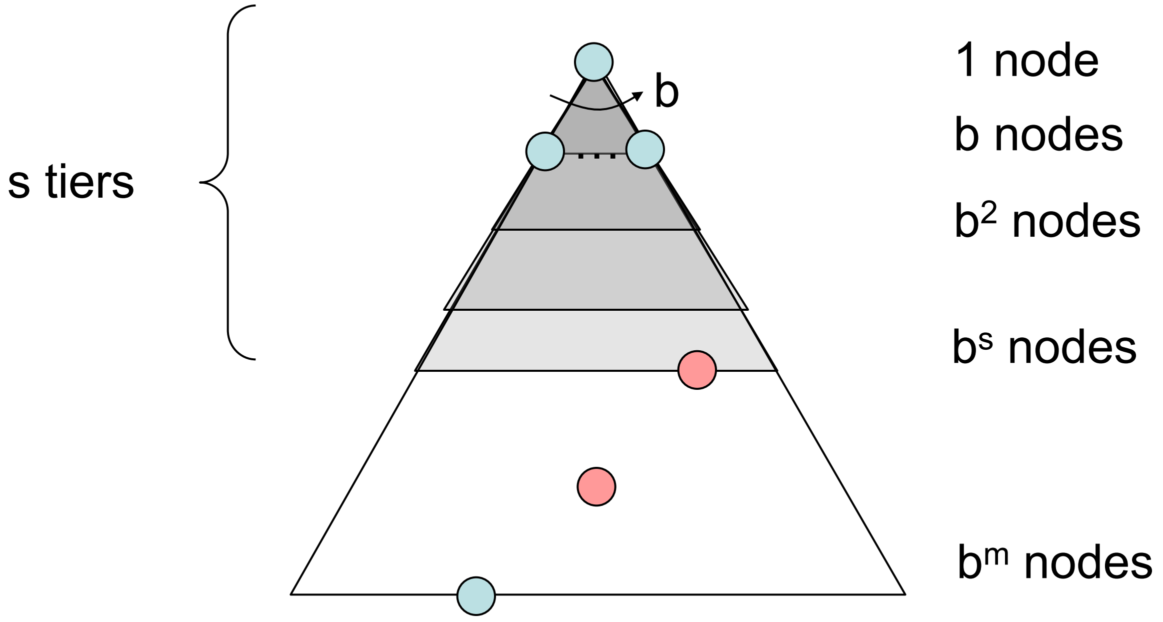
*Implementation: Fringe is a FIFO queue*



# 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

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

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

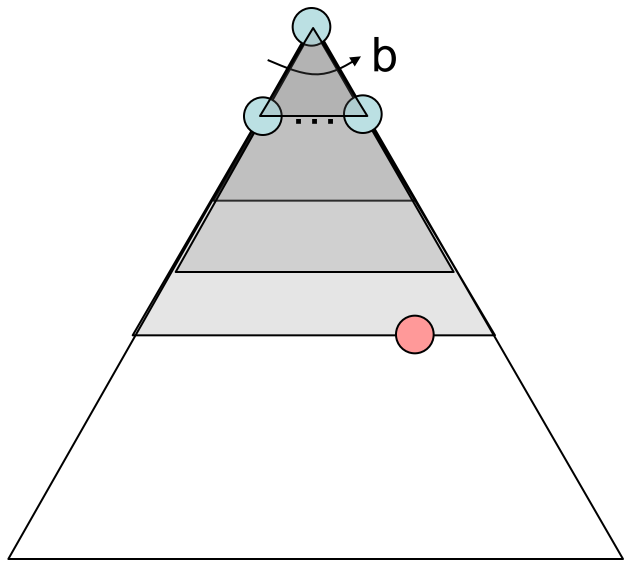
# Quiz: DFS vs BFS

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

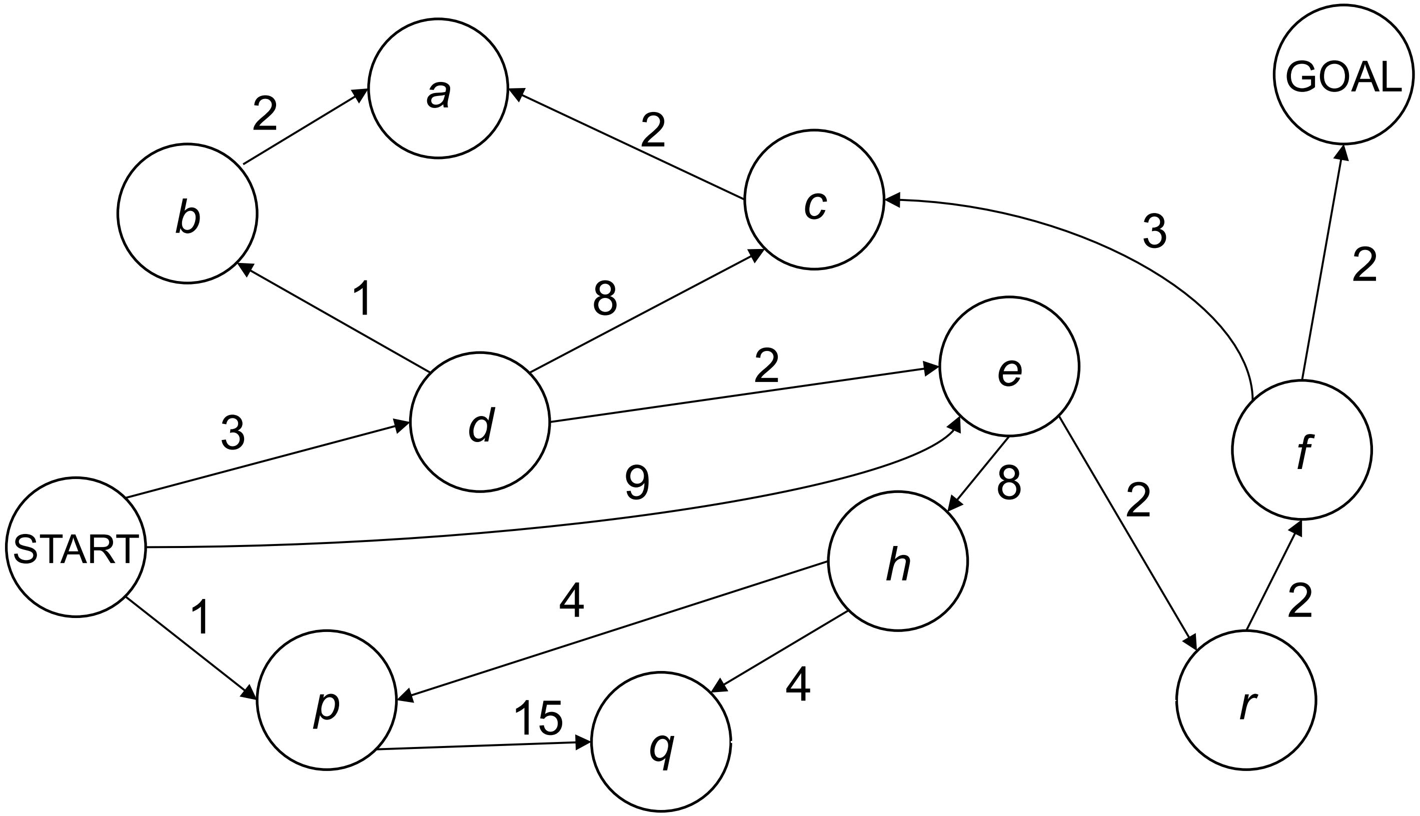
# Iterative Deepening

- 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!

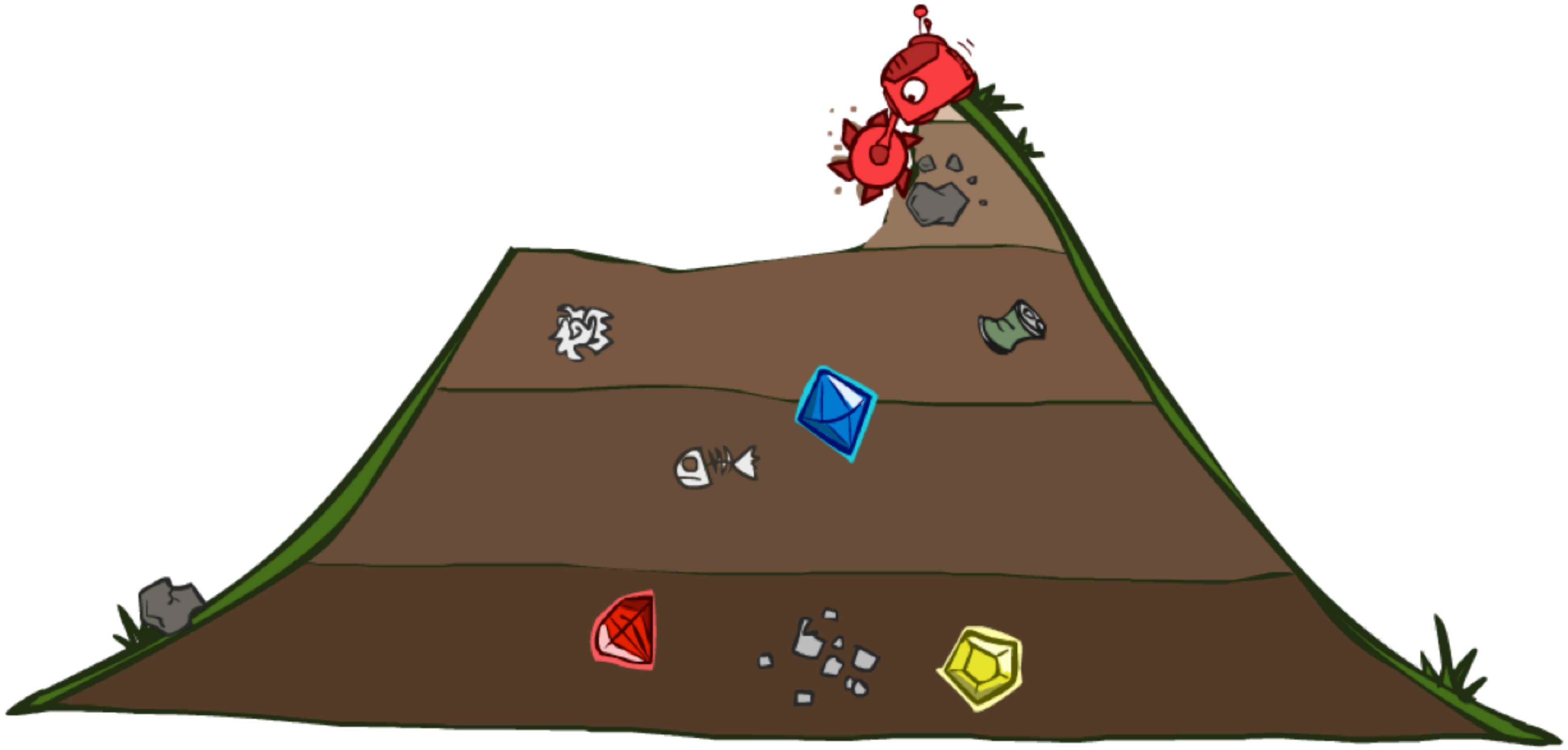


# Cost-Sensitive Search




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.

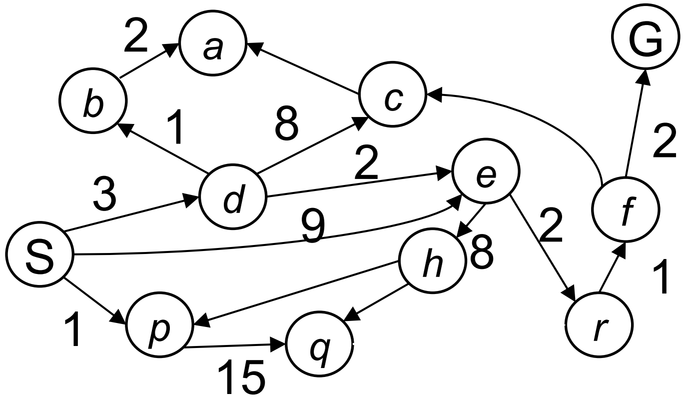
# Uniform Cost Search

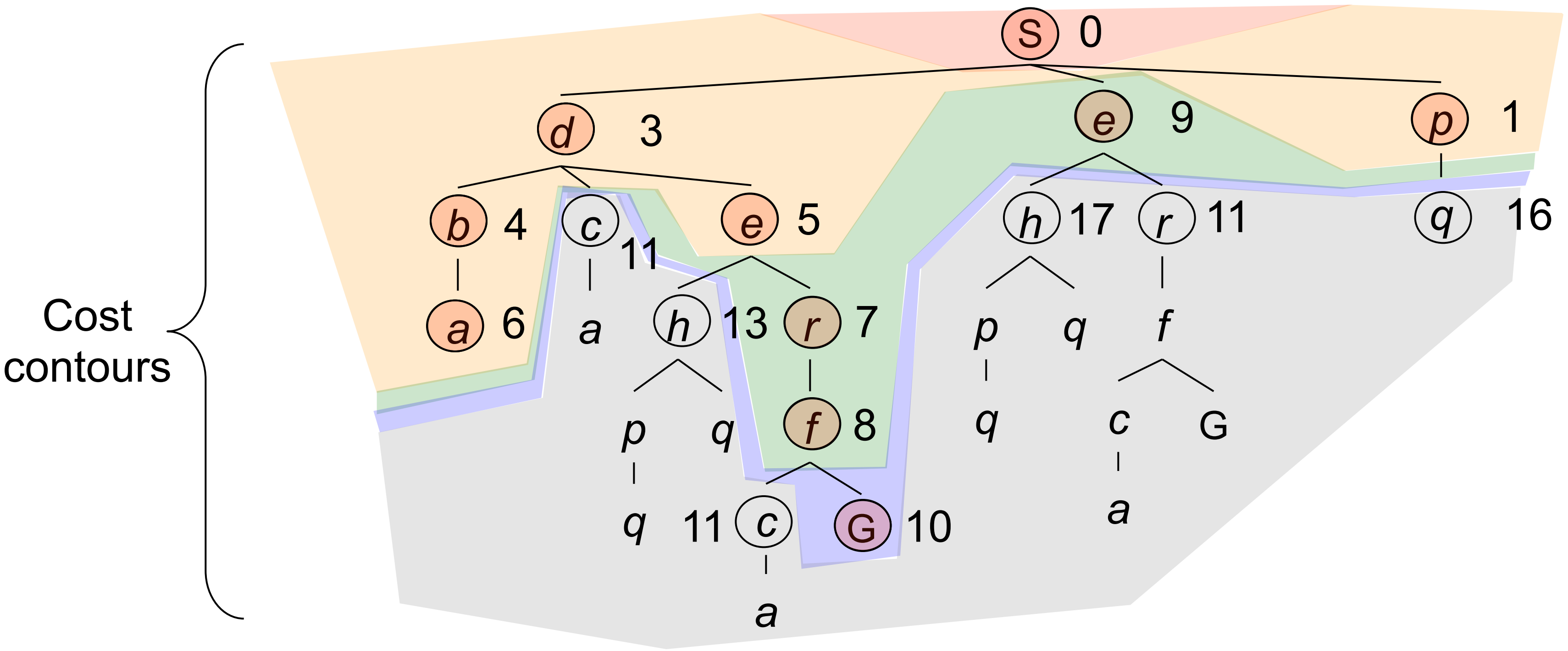


# Uniform Cost Search

*Strategy: expand a cheapest node first:*

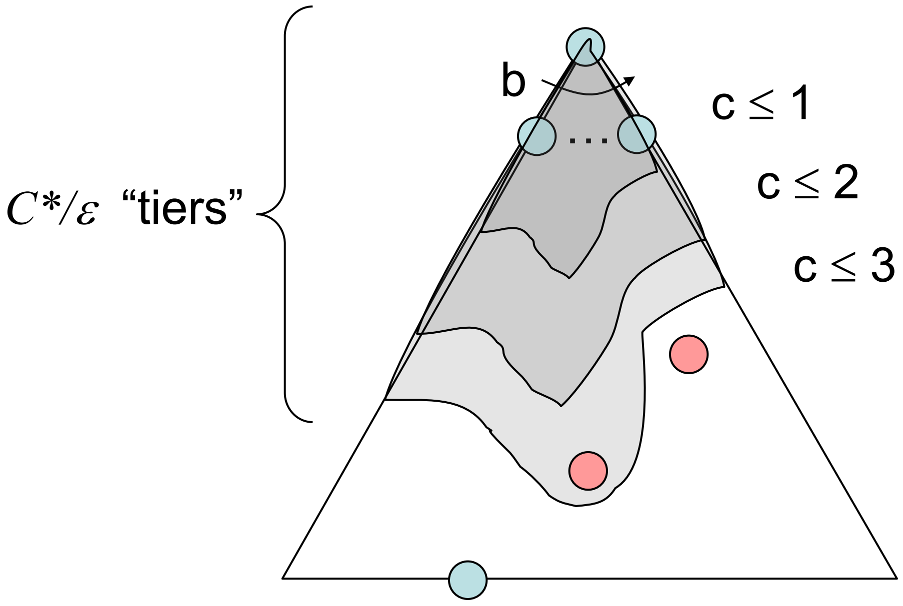
*Fringe is a priority queue (priority: cumulative cost)*



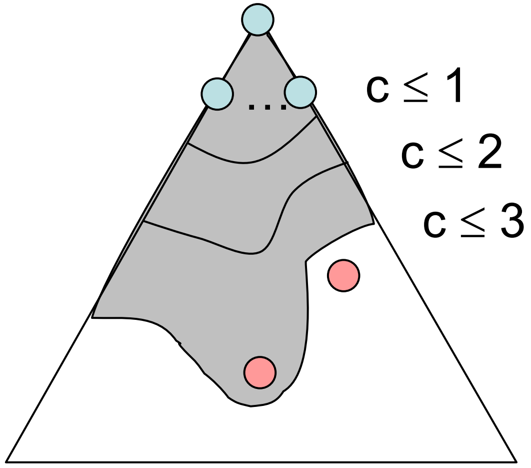
# Uniform Cost Search (UCS) Properties

- What nodes does UCS expand?
  - Processes all nodes with cost less than cheapest solution!
  - If that solution costs $C^*$ and arcs cost at least $\varepsilon$, then the "effective depth" is roughly $C^*/\varepsilon$
  - 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*)



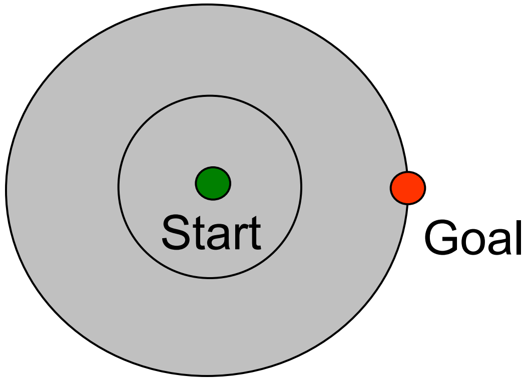
# Uniform Cost Issues

- 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!

# Video of Demo Empty UCS

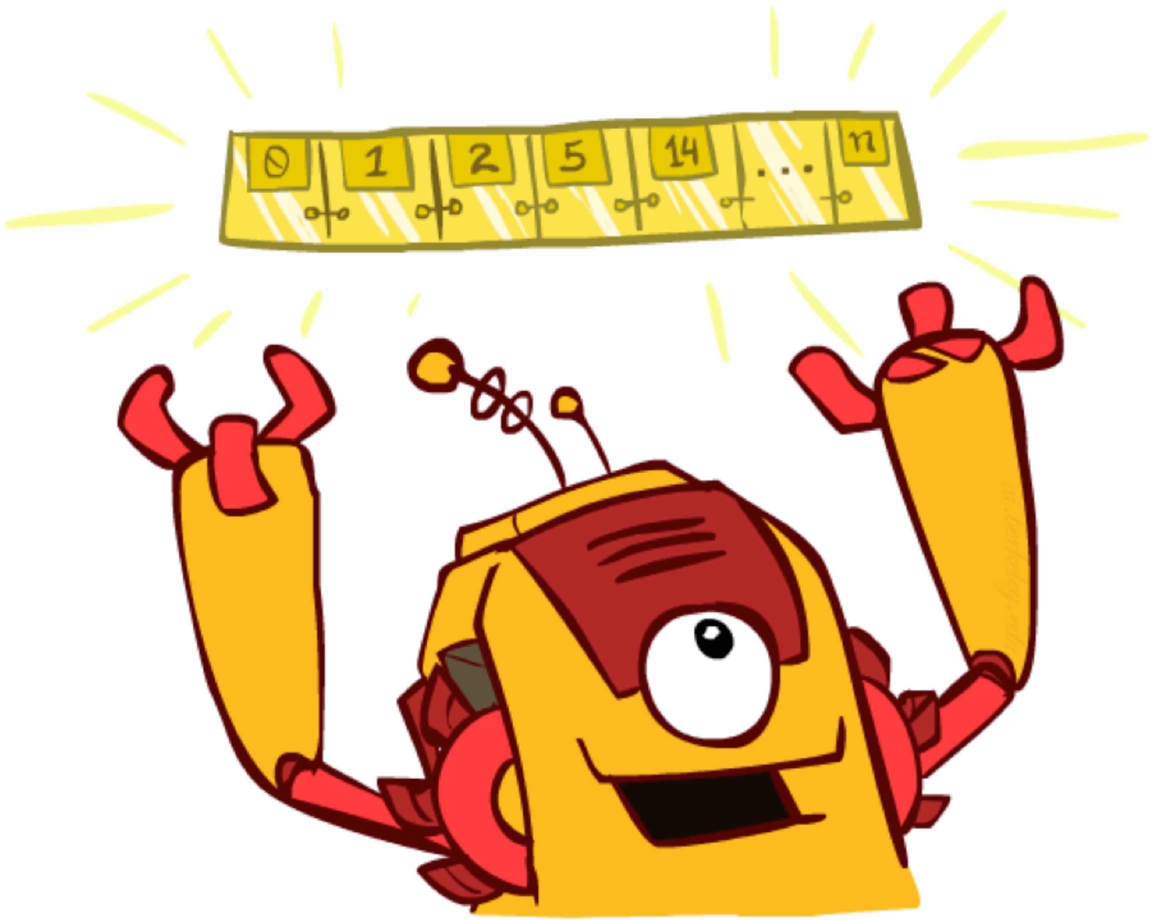
# Video of Demo Maze with Deep/Shallow Water --- DFS, BFS, or UCS? (part 1)

# 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)

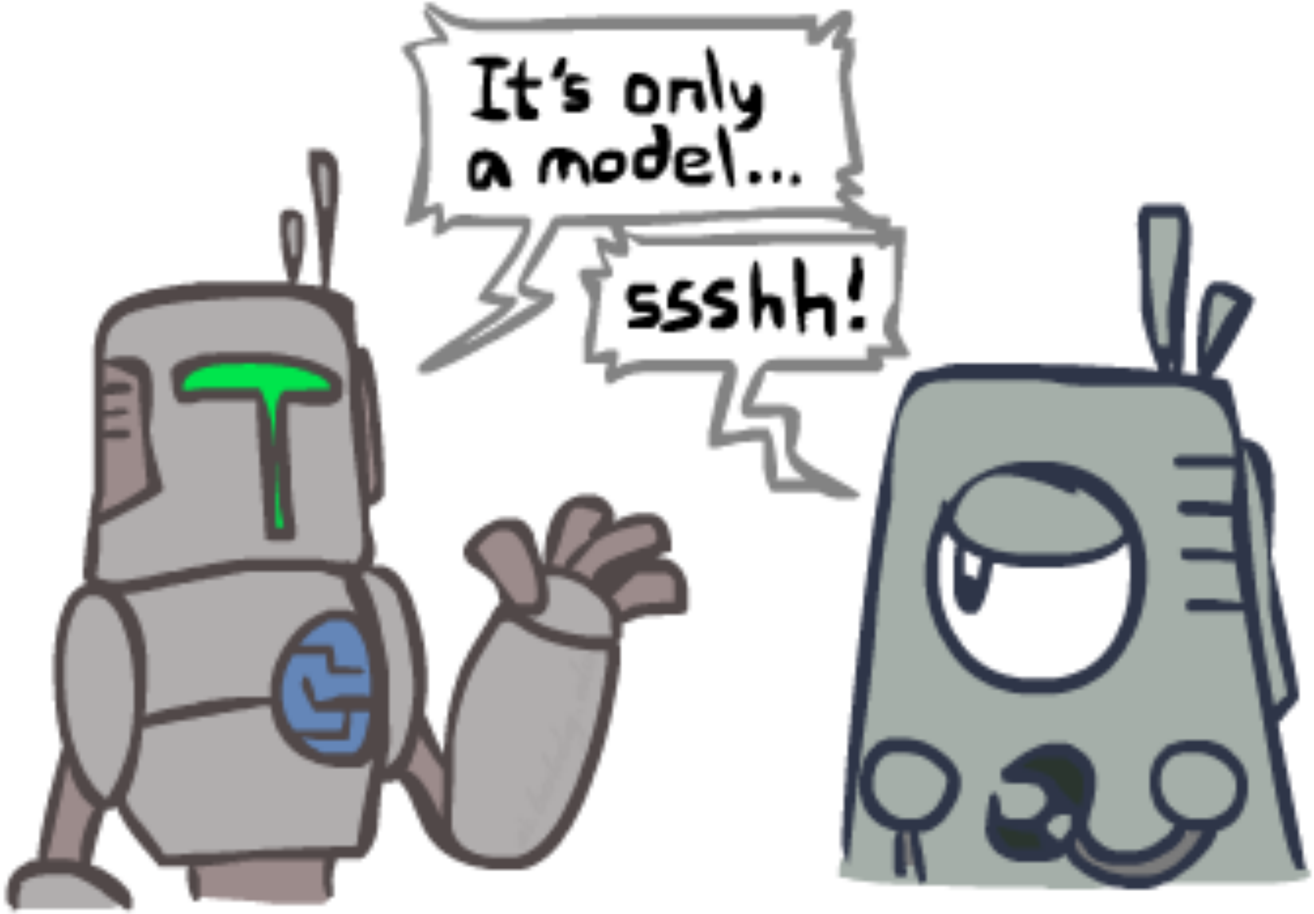
# The One Queue

- 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?