Warm-up as you come in

Write the pseudo code for breadth first search and depth first search

- Iterative version, not recursive

```
class TreeNode
    TreeNode[] children()
    boolean isGoal()

BFS(TreeNode start)…
DFS(TreeNode start)…
```

Announcements

If you are not on Piazza, Gradescope, and Canvas

- E-mail me: srosenth@andrew.cmu.edu

Recitation starting this Friday

- Start P0 before recitation to make sure Python 3.10 is working for you
- Choose any section for first two weeks
- We'll have you commit to a recitation section after the third week
- Priority given to students in the section
- Stay tuned to Piazza for form to informally switch sections if space

Announcements

Assignments:

- P0: Python & Autograder Tutorial
  - Due Friday 1/20, 10 pm
  - No pairs, submit individually
  - No OH on Fridays!
- HW1 (online)
  - Out
  - Due Tuesday 1/24, 10 pm
- P1 out Tuesday!

Remaining programming assignments may be done in pairs

Note about course grading…

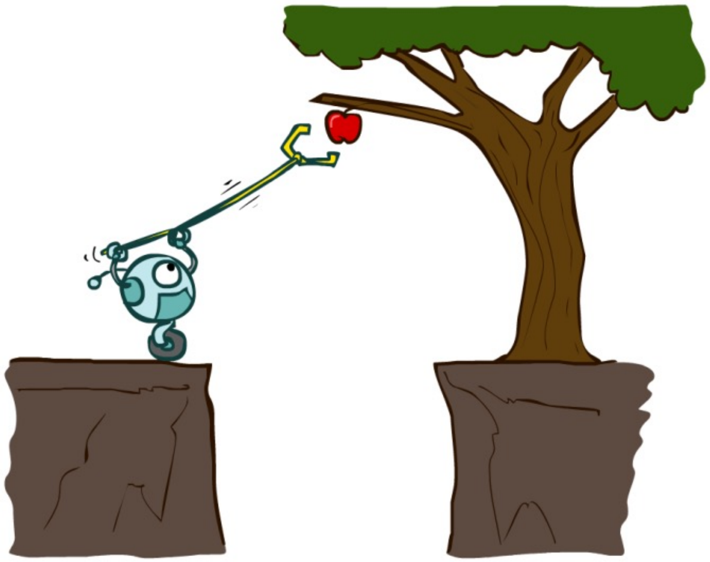
Designing Agents

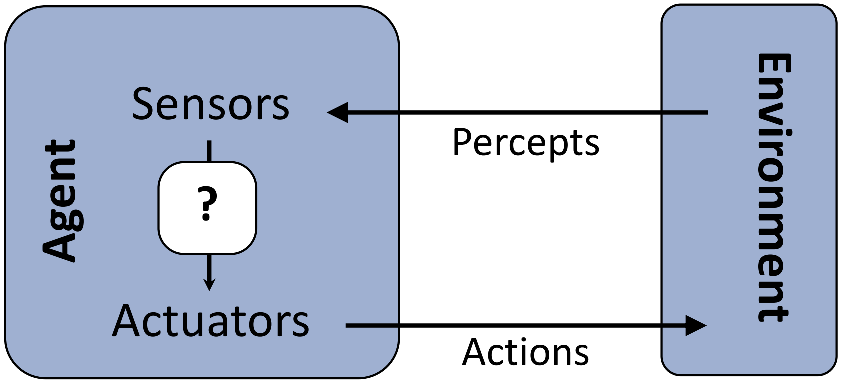
An **agent** is an entity that *perceives* and *acts*.

Characteristics of the **percepts and state, environment,** and **action space** dictate techniques for selecting actions

This course is about:

- General AI techniques for a variety of problem types
- Learning to recognize when and how a new problem can be solved with an existing technique





Missed Lecture 1 Activity

1) An agent controls the elevator in a 10-story building. On each floor, the doors can be open or closed. The elevator can also be ``moving'' between floors. How many states could the agent be in?

10 × 2

1(× 2)

21 or 22

[✓ Single] or Multi-agent?

[✓ Discrete] or Continuous states?

[✓ Static] or Dynamic environment?

[✓ Deterministic] or Stochastic actions?

[✓ Fully observable] or partially states?

Missed Lecture 1 Activity

$10 \times 10 \times 2$

Hopscotch is a game where **10 squares** are drawn and labeled 1-10. There is also a **“start state”** to stand on a throw a stone. A player **throws the stone** and then **hops the squares** in order, **avoiding the one with the stone** in it. Other players watch.

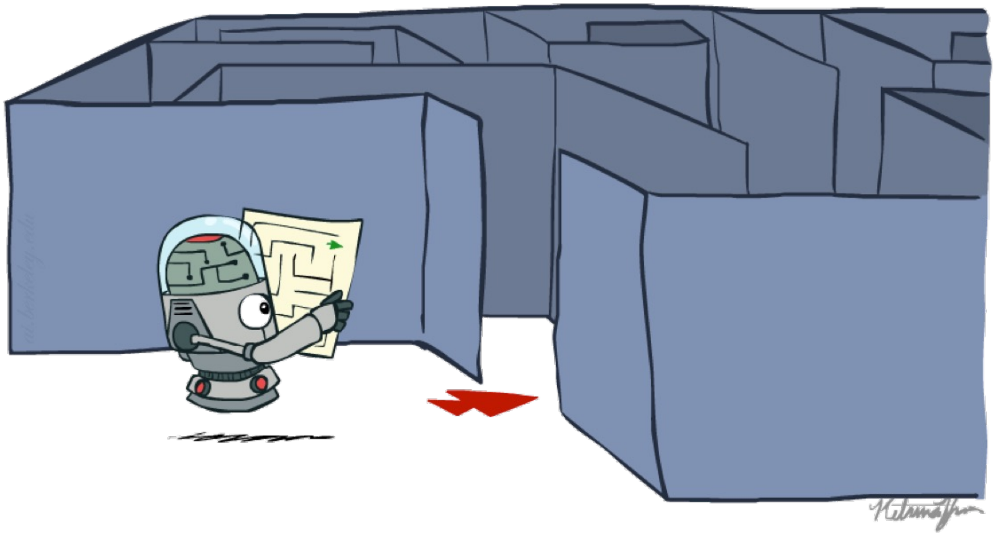
Consider the **states where two players** – scotcher and observer - **and the stone are situated** in the middle of the game. Ignore the state where the player is holding the stone, but do consider when they have not started jumping yet. Assume the game is played on a flat surface.

How many states are there in hopscotch?

Continuous or discrete states?

AI: Representation and Problem Solving

Agents and Search



Instructors: Stephanie Rosenthal

Slide credits: CMU AI, http://ai.berkeley.edu

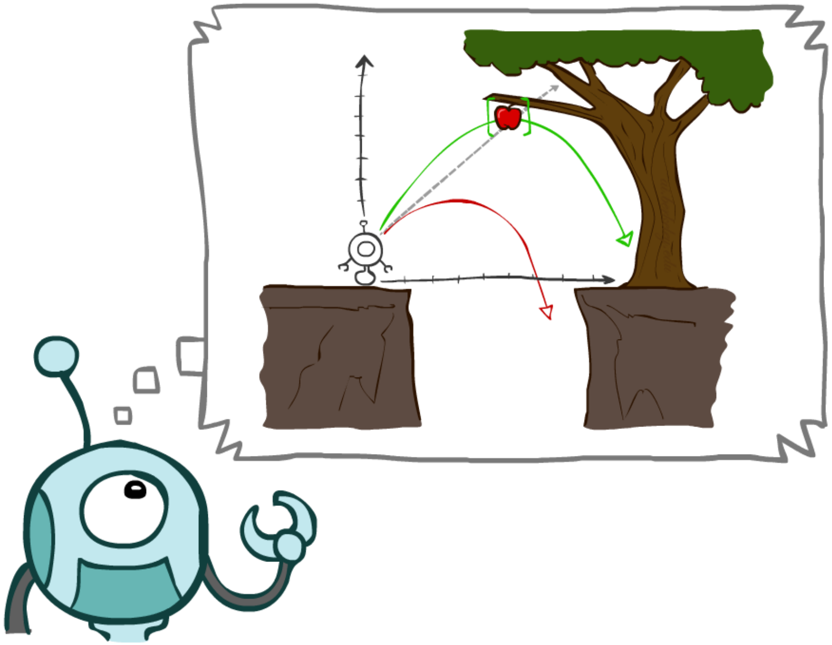
Today

Reflex vs Planning Agents

Search Problems

Uninformed Search Methods

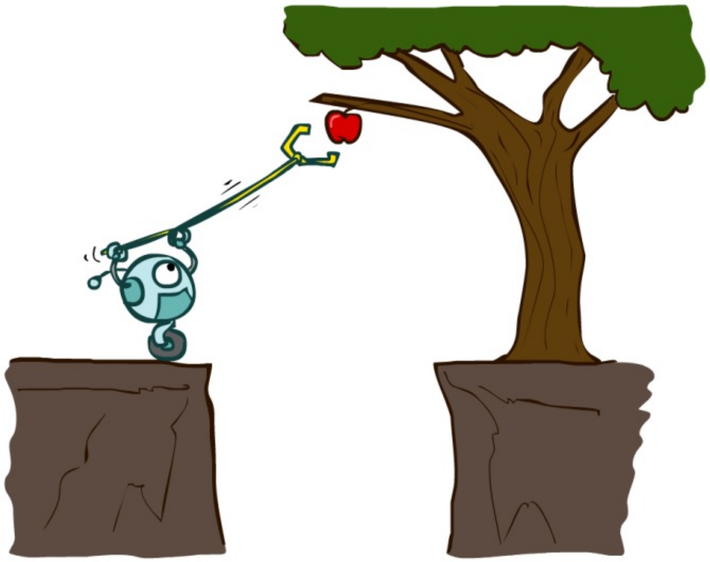
- Depth-First Search
- Breadth-First Search
- Uniform-Cost Search

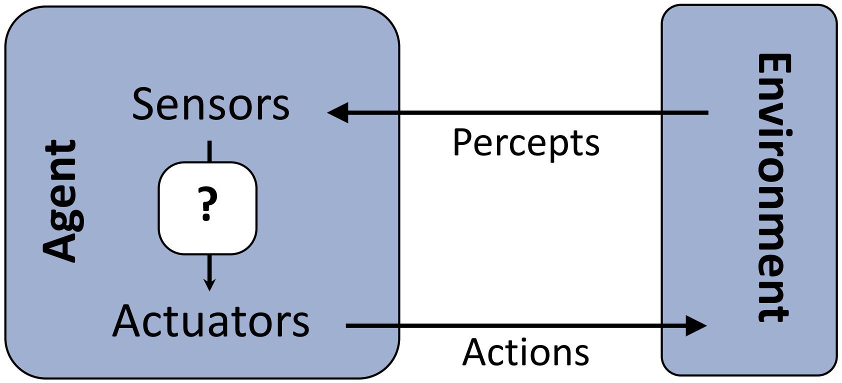


Designing Agents

An **agent** is an entity that *perceives* and *acts*.

Characteristics of the **percepts and state, environment,** and **action space** dictate techniques for selecting actions





Agent

Sensors

?

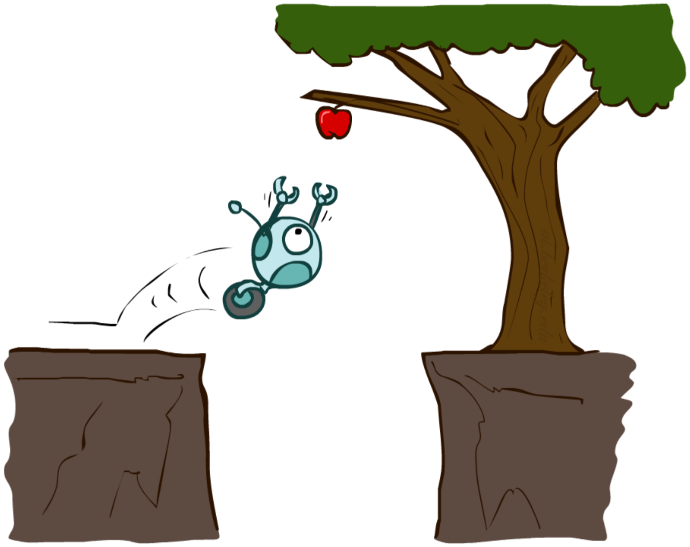
Actuators

Percepts

Actions

Environment

Reflex Agents



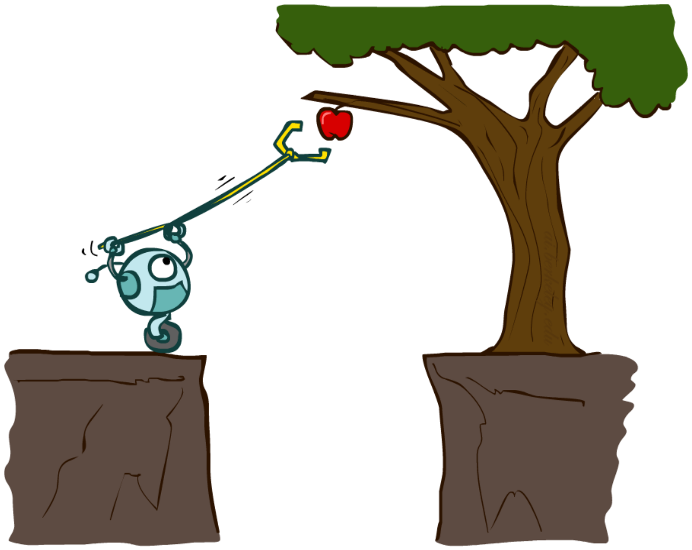
Reflex agents:

- Choose actions based on current/historic state
- Do not consider the future consequences of their actions
- May have memory or a model of the world's current state
- Consider how the world IS

Can a reflex agent be rational?

Yes

Agents that Plan Ahead



Planning agents:

- Decisions based on ***predicted consequences*** of actions
- Must have a ***transition model***: how the world evolves in response to actions
- Must formulate a goal
- Consider how the world WOULD BE

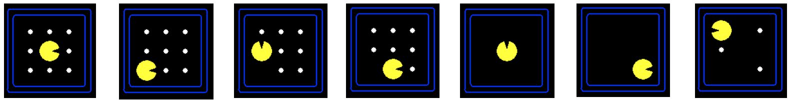
Spectrum of deliberativeness:

- Generate complete, optimal plan offline, then execute
- Generate a simple, greedy plan, start executing, replan when something goes wrong

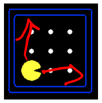
Search Problems

A search problem consists of:

- A state space



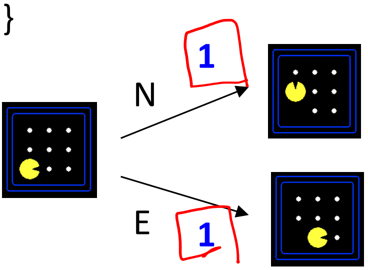
- For each state, a set Actions(s) of allowable actions



{N, E}

- A transition model Result(s,a) = s'

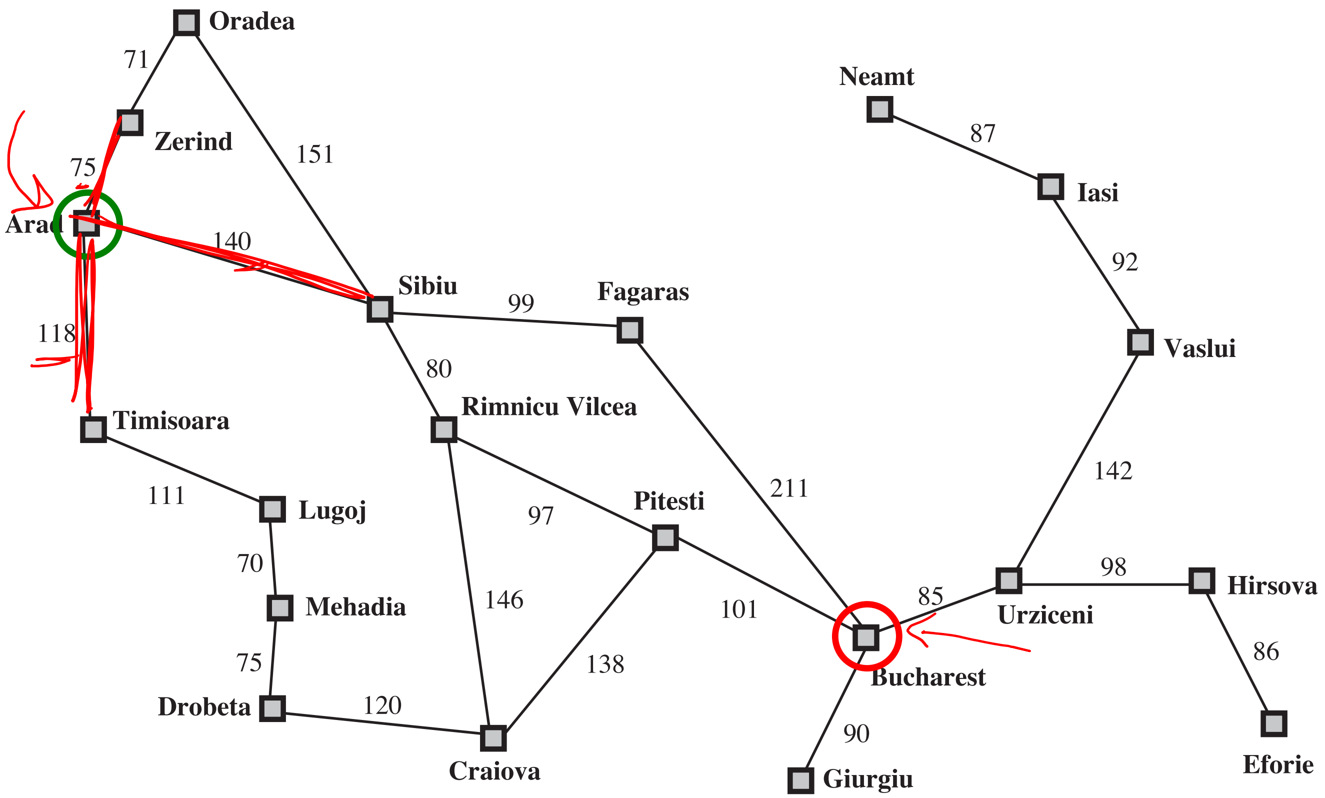
T(s,a,s') = {0,1}



- A step cost function c(s,a,s')
- 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

Example: Travelling in Romania



State space:
- Cities

Actions:
- Go to adjacent city

Transition model
- Result(A, Go(B)) = B

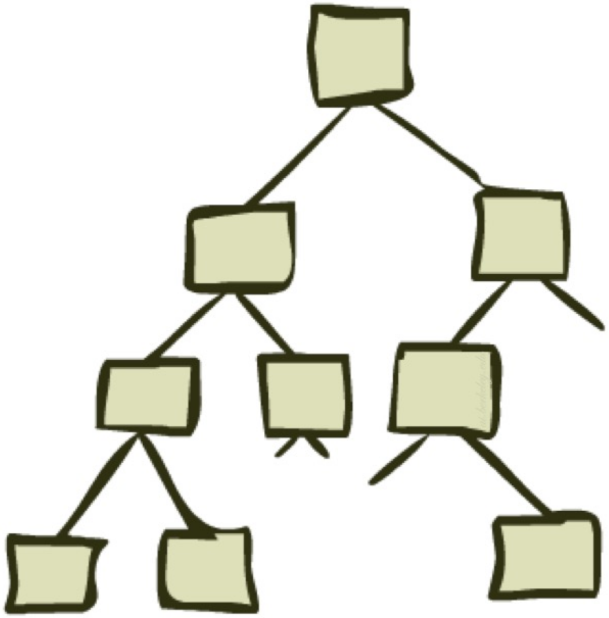
Step cost
- Distance along road link

Start state:
- Arad

Goal test:
- Is state == Bucharest?

Solution?

State Space Graphs and Search Trees



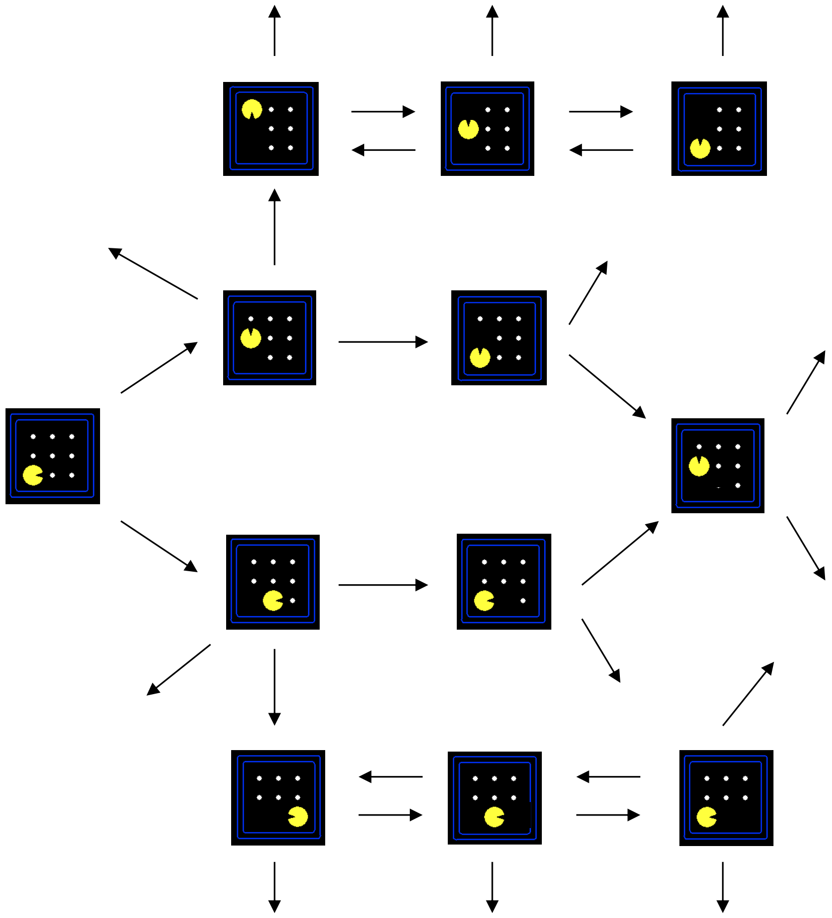
State Space Graphs

State space graph: A mathematical representation of a search problem

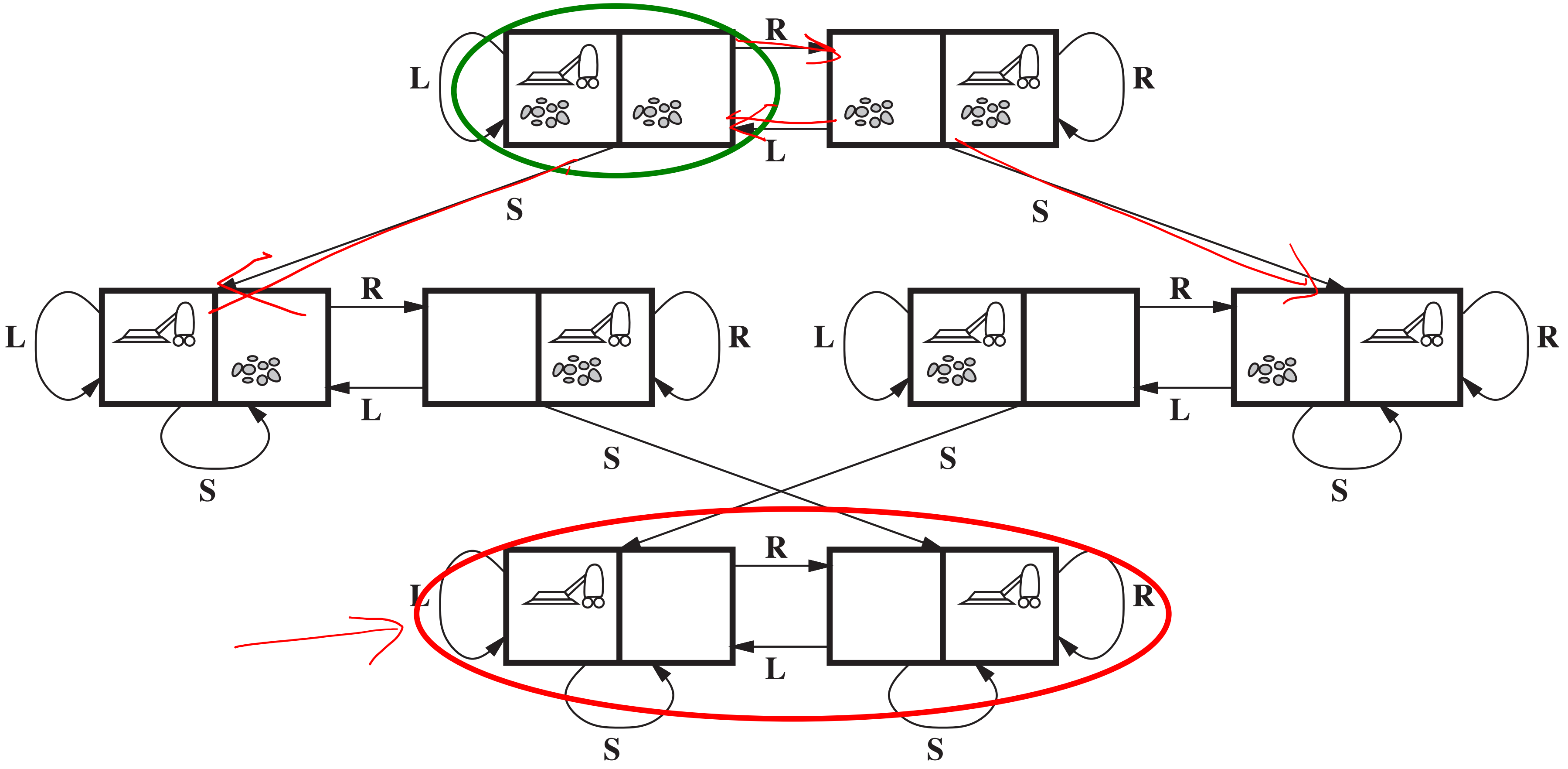
- Nodes are (abstracted) world configurations
- Arcs represent transitions resulting from actions
- The goal test is a set of goal nodes (maybe only one)

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

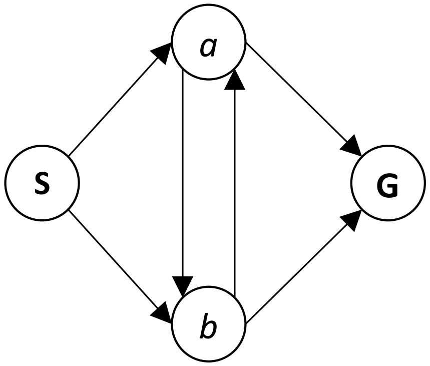


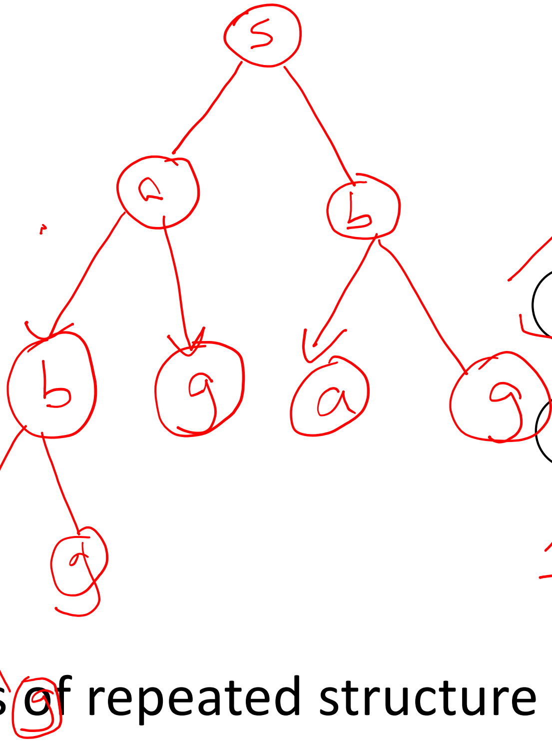
More Examples



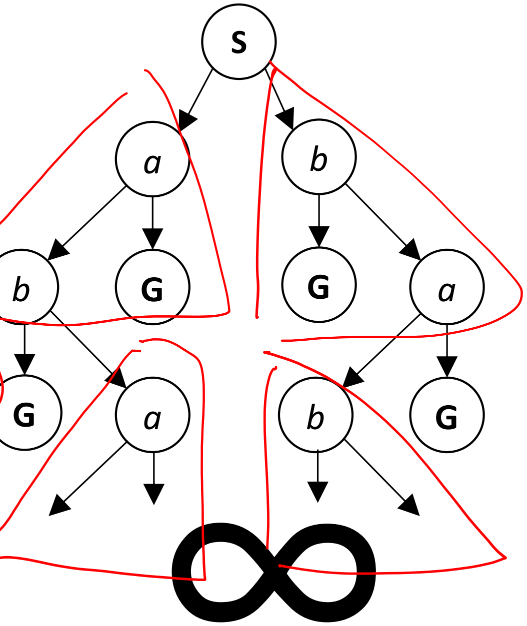
State Space Graphs vs. Search Trees

Consider this 4-state graph:



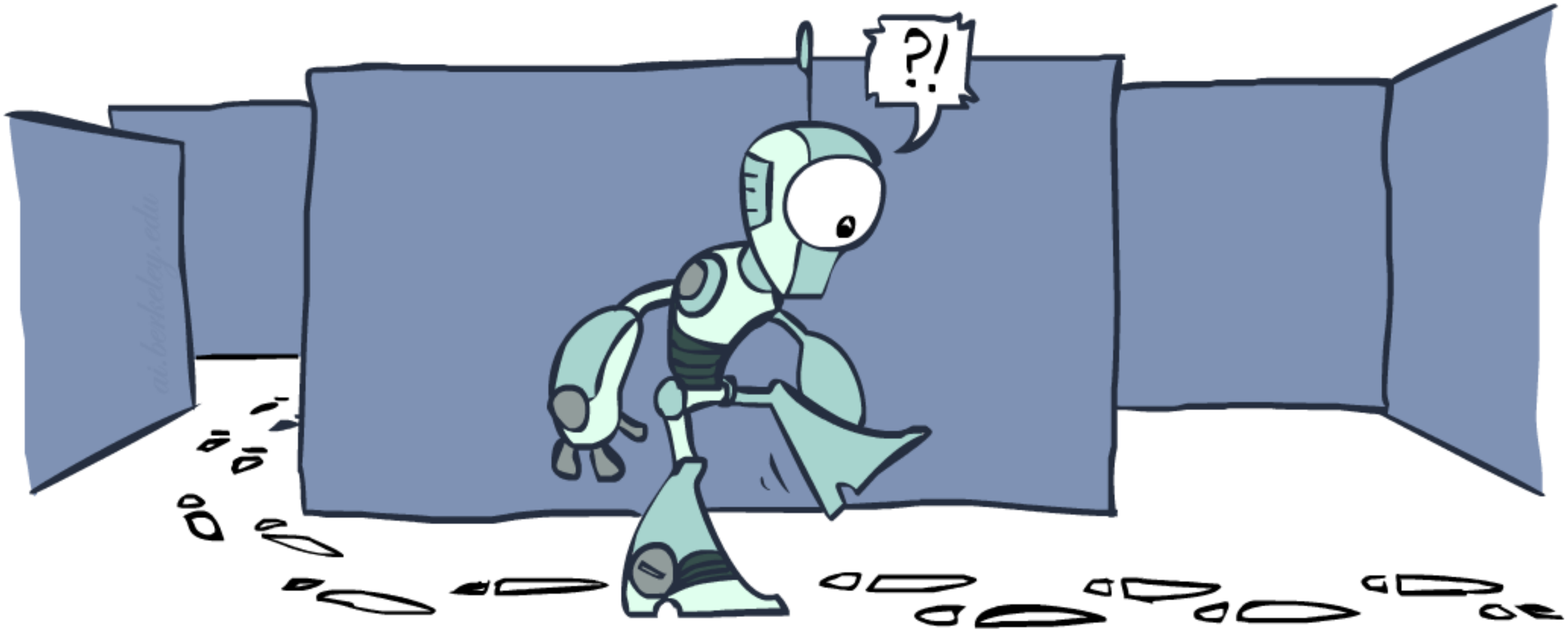


How big is its search tree (from S)?



Important: Lots of repeated structure in the search tree!

Tree Search vs Graph Search

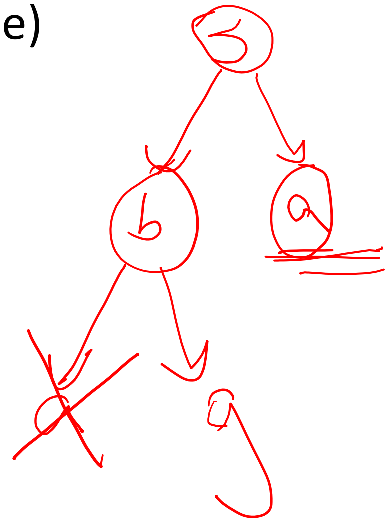


```
function TREE_SEARCH(problem) returns a solution, or failure

    initialize the frontier as a specific work list (stack, queue, priority queue)
    add initial state of problem to frontier
    loop do
        if the frontier is empty then
            return failure
        choose a node and remove it from the frontier
        if the node contains a goal state then
            return the corresponding solution

        for each resulting child from node
            add child to the frontier
```

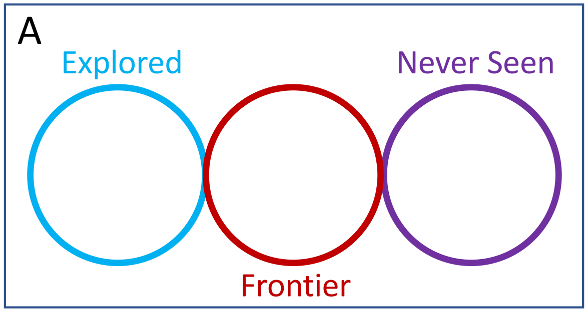
```
function GRAPH_SEARCH(problem) returns a solution, or failure
    initialize the explored set to be empty
    initialize the frontier as a specific work list (stack, queue, priority queue)
    add initial state of problem to frontier
    loop do
        if the frontier is empty then
            return failure
        choose a node and remove it from the frontier
        if the node contains a goal state then
            return the corresponding solution
        add the node state to the explored set
        for each resulting child from node
            if the child state is not already in the frontier or explored set then
                add child to the frontier
```



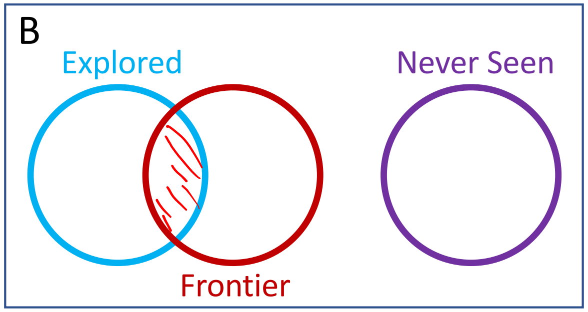
Poll 1

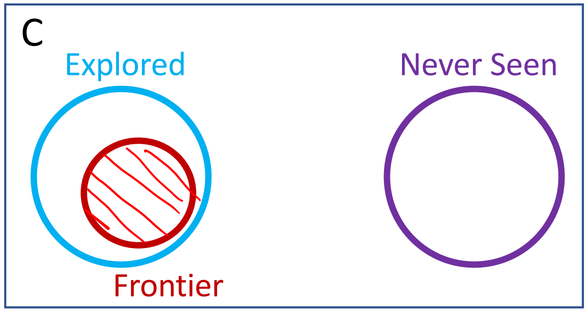
What is the relationship between these sets of states after each loop iteration in GRAPH_SEARCH?

(Loop invariants!!!)



disjoint



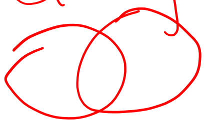


Poll 1

```
function GRAPH-SEARCH(problem) returns a solution, or failure
    initialize the explored set to be empty
    initialize the frontier as a specific work list (stack, queue, priority queue)
    add initial state of problem to frontier
    loop do
        if the frontier is empty then
            return failure
        choose a node and remove it from the frontier
        if the node contains a goal state then
            return the corresponding solution
        add the node state to the explored set
        for each resulting child from node
            if the child state is not already in the frontier or explored set then
                add child to the frontier
```

A disjoint

B



C frontier subset of explored

A Note on Implementation

Nodes have

state, parent, action, path-cost

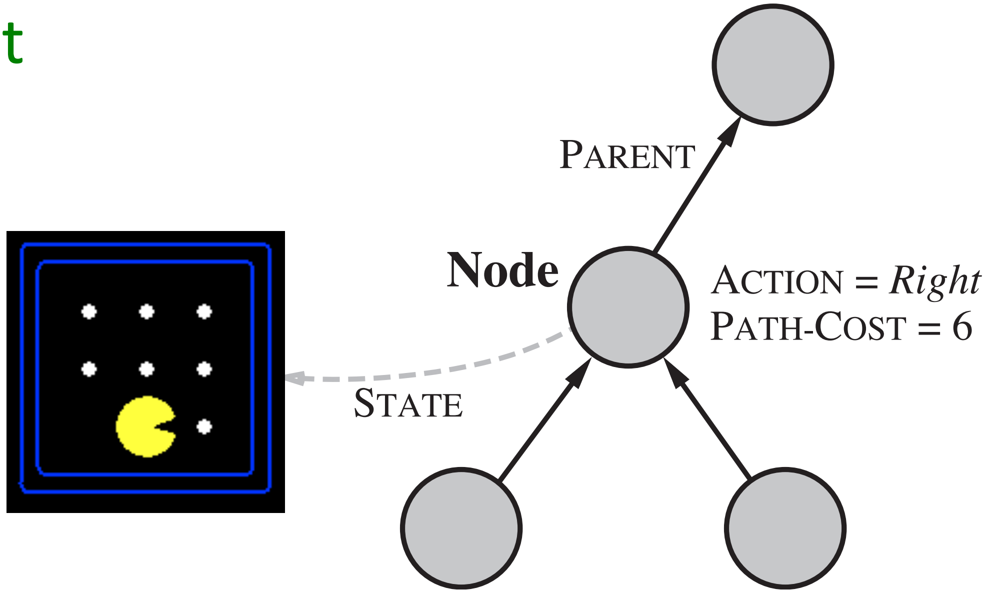
A child of node by action *a* has

state = result(node.state,*a*)

parent = node

action = *a*

path-cost = node.path_cost + step_cost(node.state, *a*, self.state)

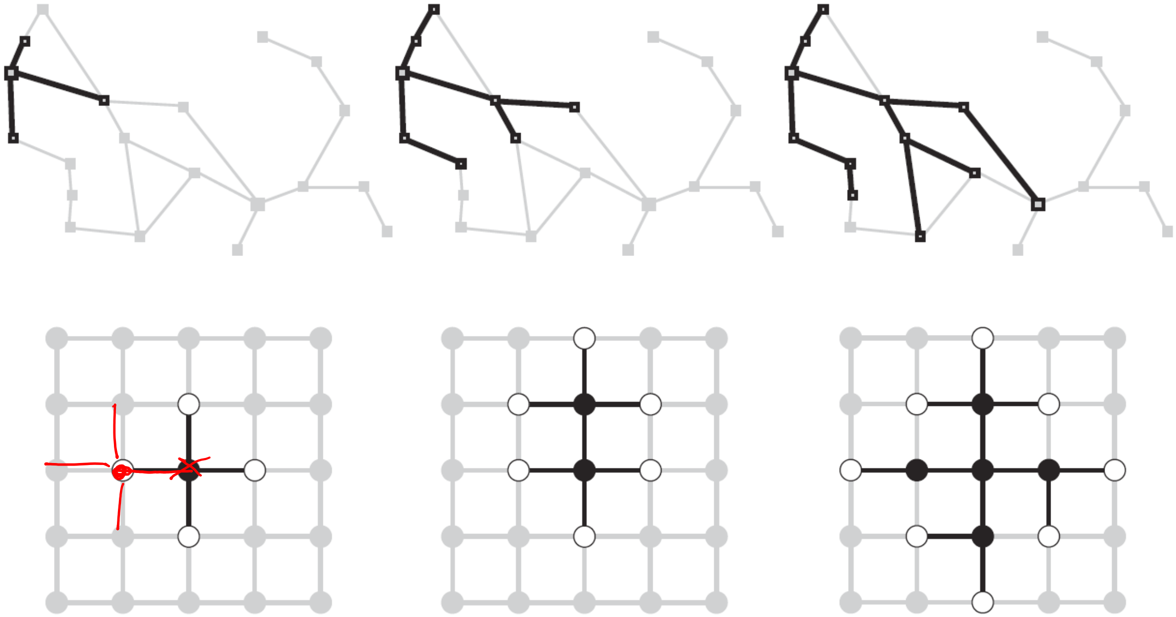


Extract solution by tracing back parent pointers, collecting actions

Graph Search

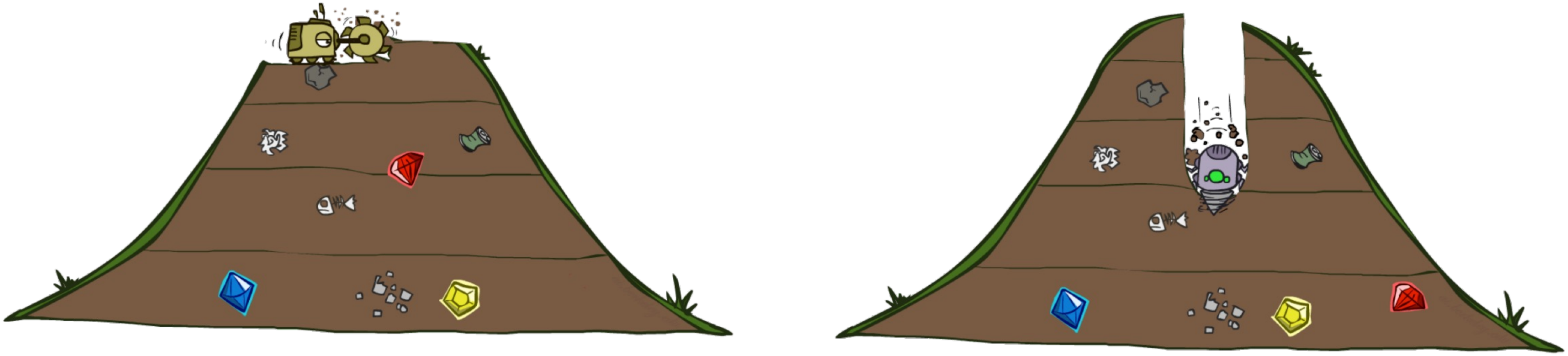
This graph search algorithm overlays a tree on a graph

The frontier states separate the explored states from never seen states

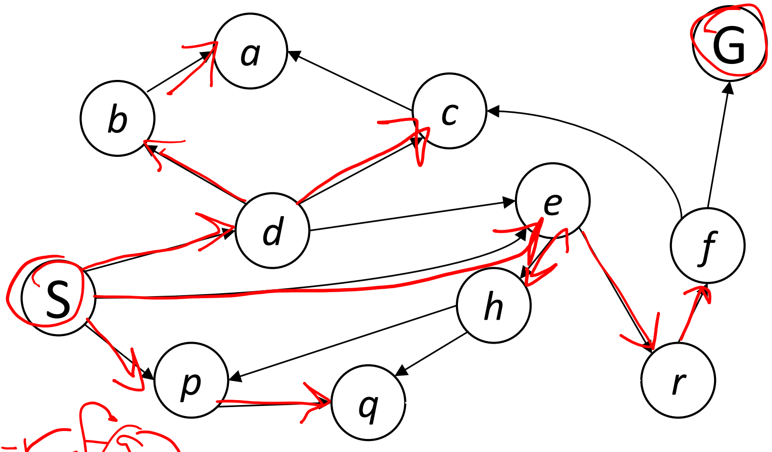


Images: AIMA, Figure 3.8, 3.9

BFS vs DFS



Walk-through BFS Graph Search



frontier

~~S~~ ~~S-d~~ ~~S-e~~ ~~S-p~~ ~~S-d-b~~ ~~S-d-c~~

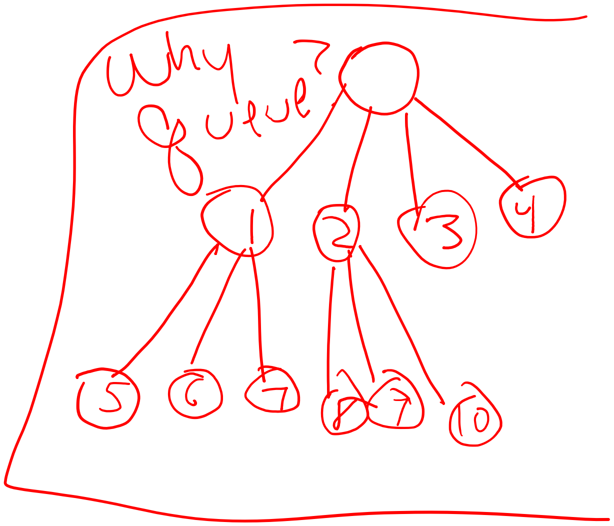
~~S-e-h~~ ~~S-e-r~~ ~~S-p-q~~

~~S-d-b-a~~ ~~S-e-r-f~~ S-e-r-f-G

explored set

S d e p b c

h r q a f



Walk-through DFS Graph Search

frontier

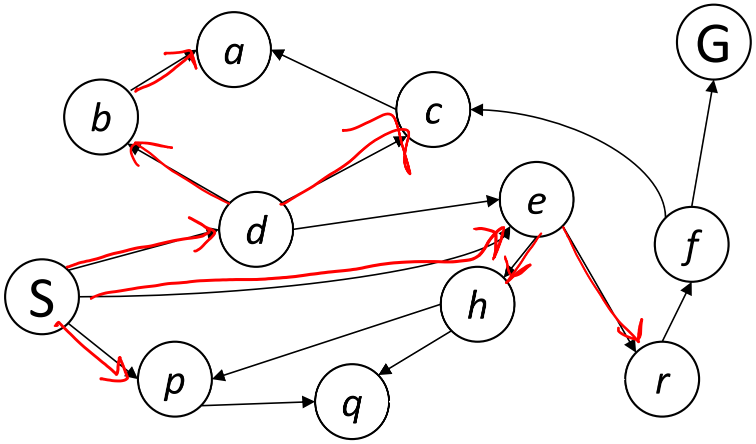
~~S~~ ~~s-d~~ s-e s-p

→ ~~s-d-b~~ ~~s-d-c~~ ~~s-d-b-a~~

~~s-e-h~~ s-e-r

explored

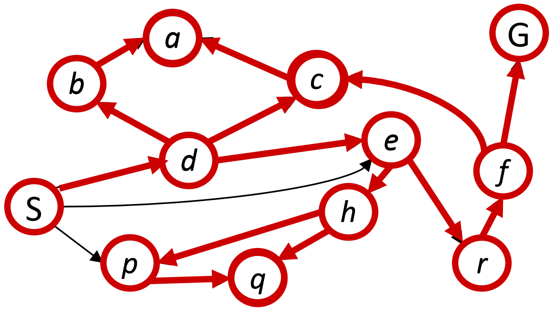
s d b a c e

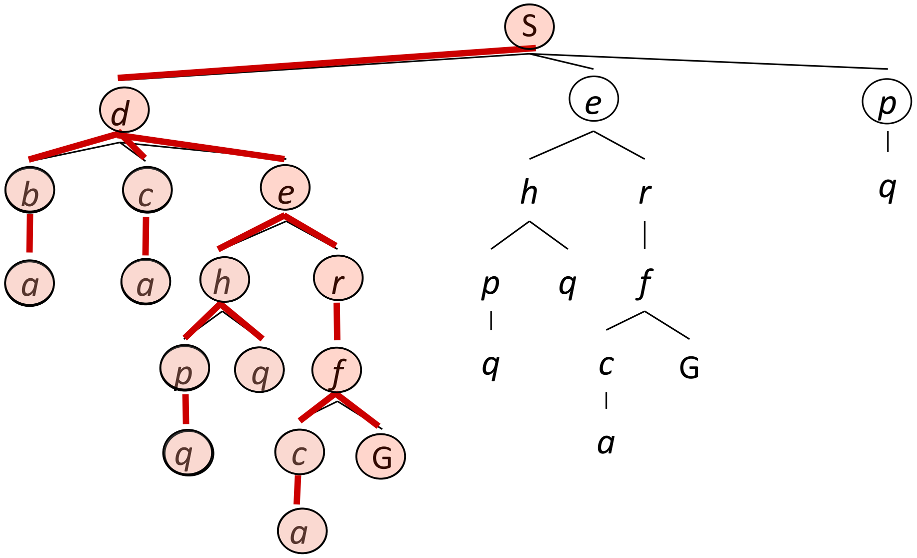


Depth-First (Tree) Search

Strategy: expand a deepest node first

Implementation:
Frontier is a LIFO stack



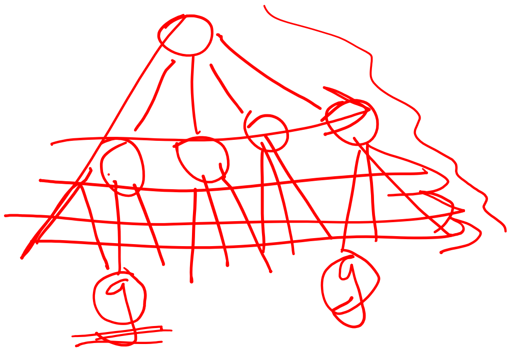


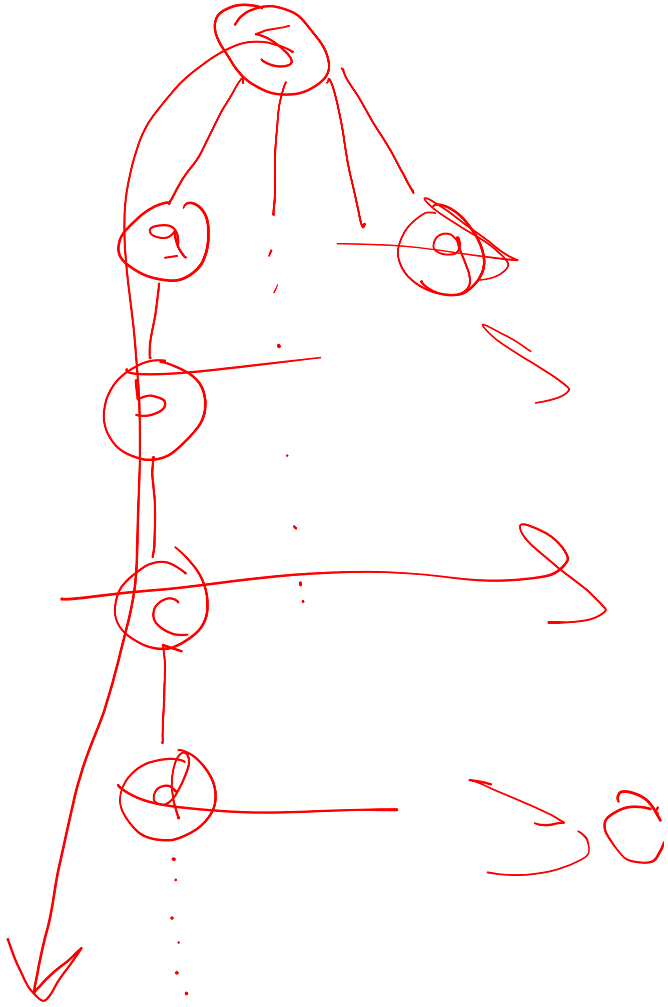
BFS vs DFS

When will BFS outperform DFS?

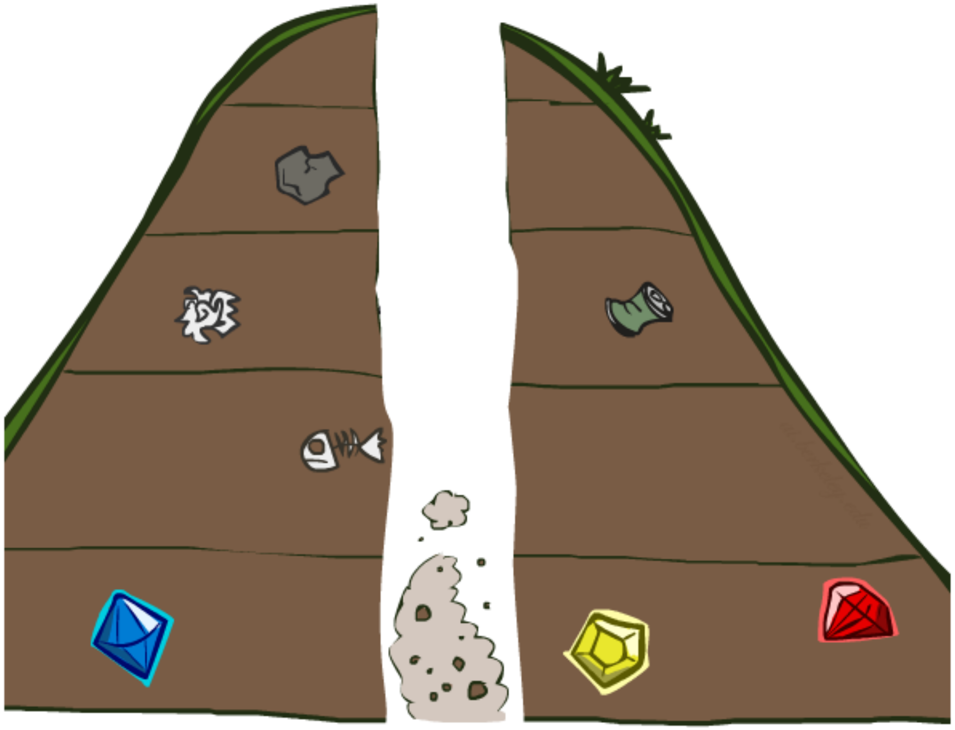
shallow

When will DFS outperform BFS?

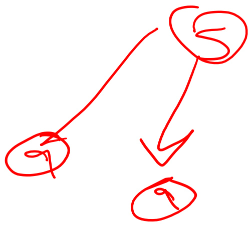




Search Algorithm Properties



Search Algorithm Properties



Complete: Guaranteed to find a solution if one exists?

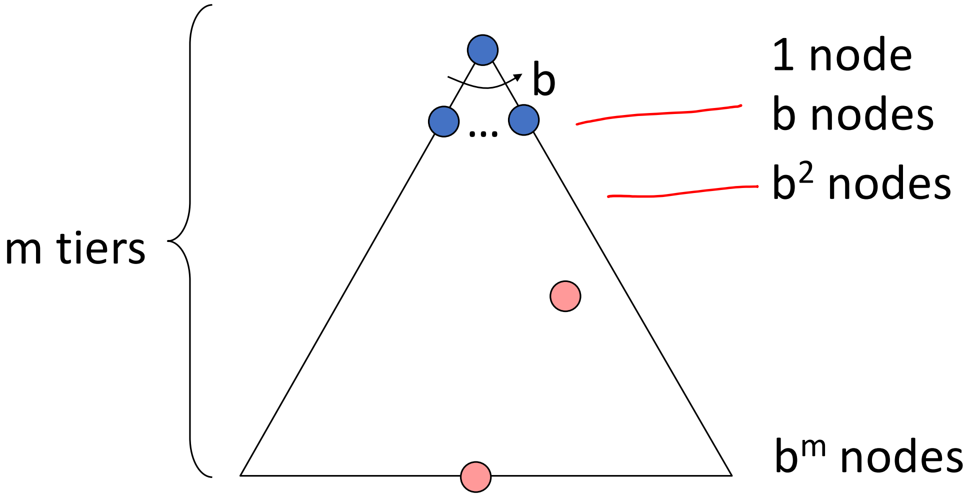
Optimal: Guaranteed to find the least cost path?

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?

- $1 + b + b^2 + \ldots . b^m = O(b^m)$

Search Algorithm Properties

Complete: Guaranteed to find a solution if one exists?

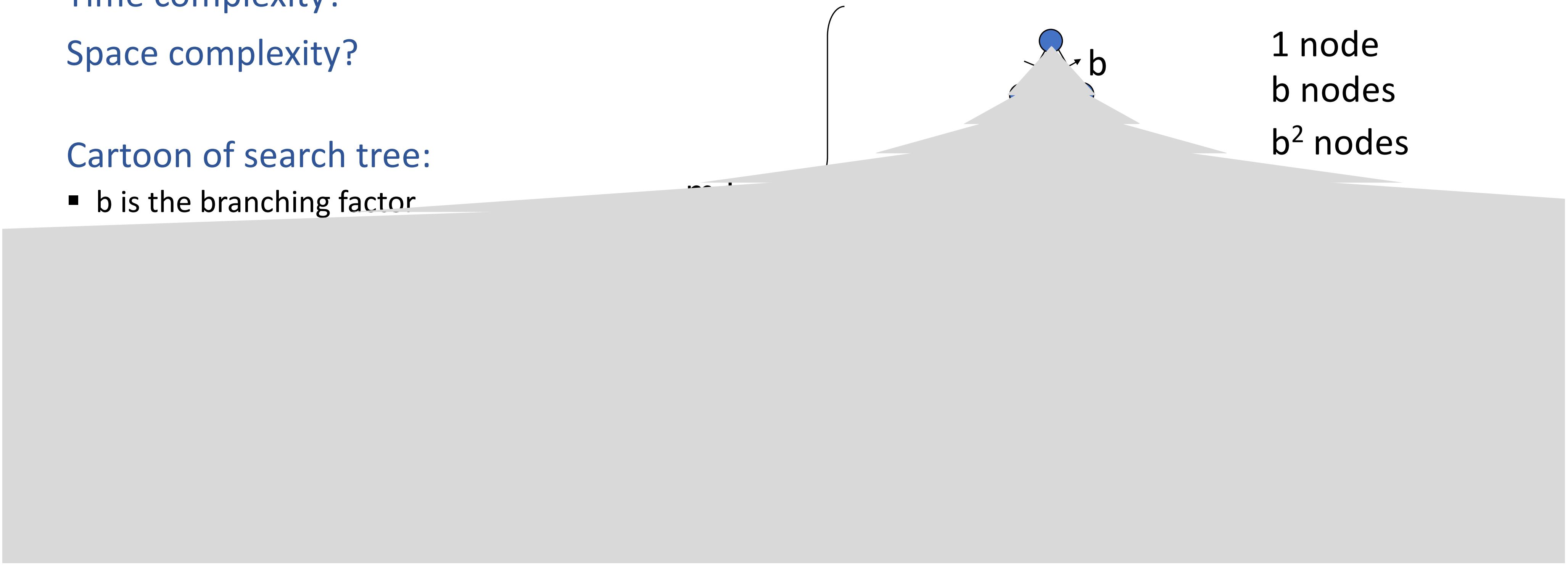
Optimal: Guaranteed to find the least cost path?

Time complexity?

Space complexity?

Cartoon of search tree:

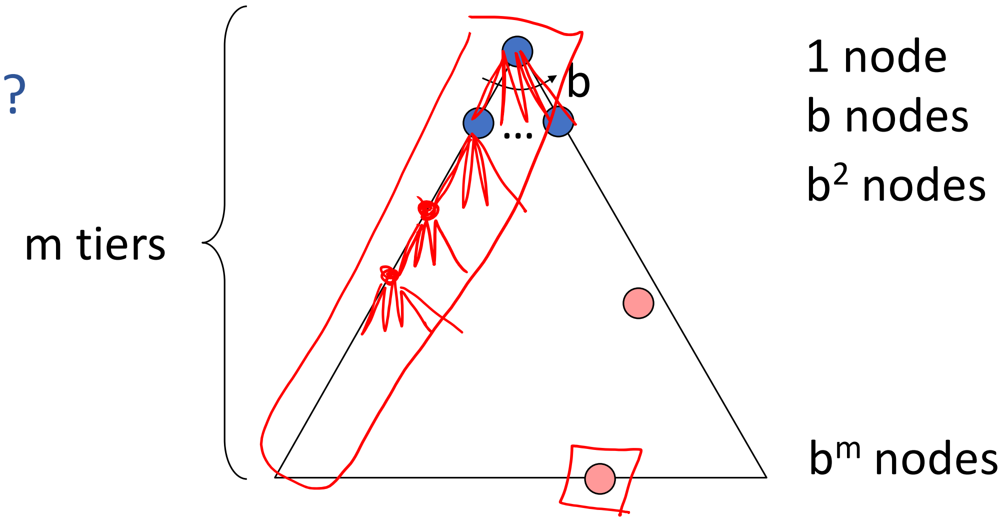
- b is the branching factor



Think about it…

Are these the properties for BFS or DFS?

- Takes O(b^m) time
- Uses O(bm) space on frontier
- Complete with graph search
- Not optimal unless all goals are in the same level (and the same step cost everywhere)



Depth-First Search (DFS) Properties

What nodes does 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 frontier take?

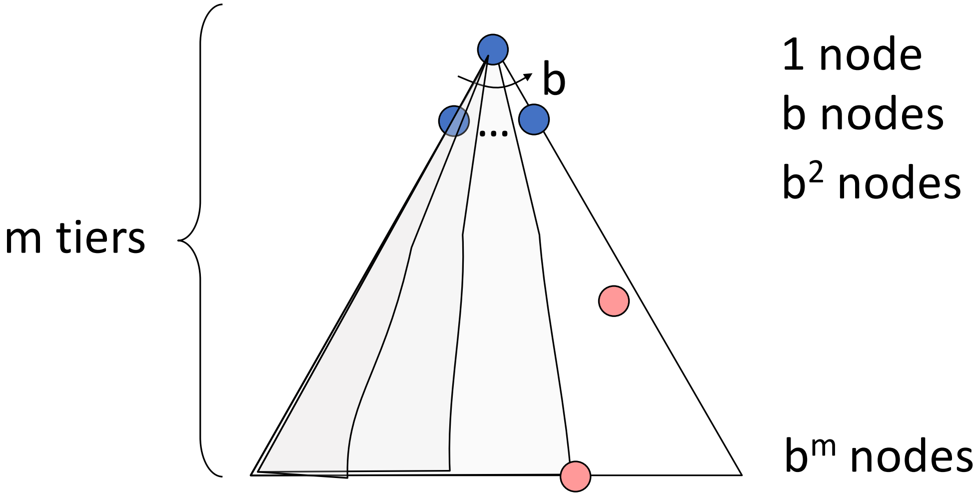
- Only has siblings on path to root, so $O(bm)$

Is it complete? (always find a solution)

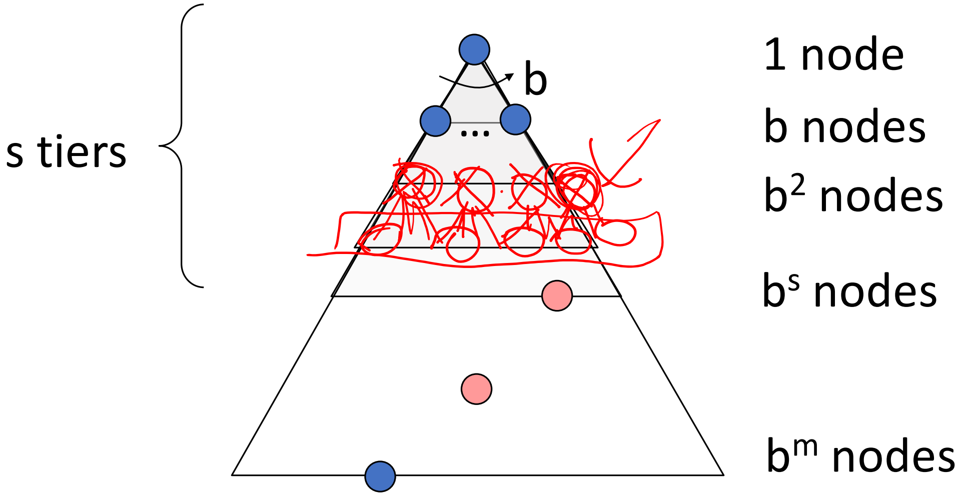
- m could be infinite, so only if we prevent cycles (graph search)

Is it optimal? (solution is “best”)

- No, it finds the “leftmost” solution, regardless of depth or cost



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 frontier 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 the same (more on costs later)

Iterative Deepening

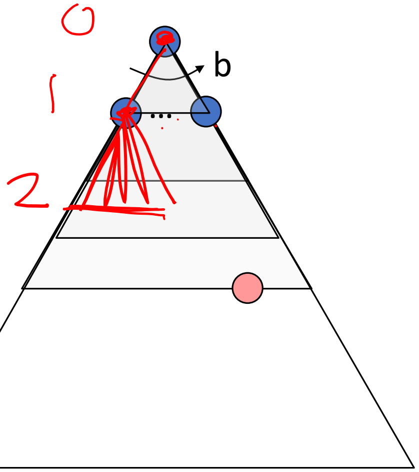
Idea: get DFS’s space advantage with BFS’s time / shallow-solution advantages

- 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. …..

max depth

2

bm



Isn’t that wastefully redundant?

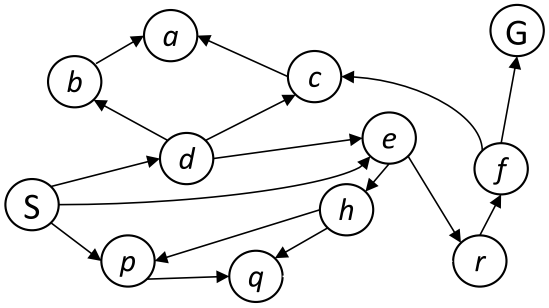
- Generally most work happens in the lowest level searched, so not so bad!

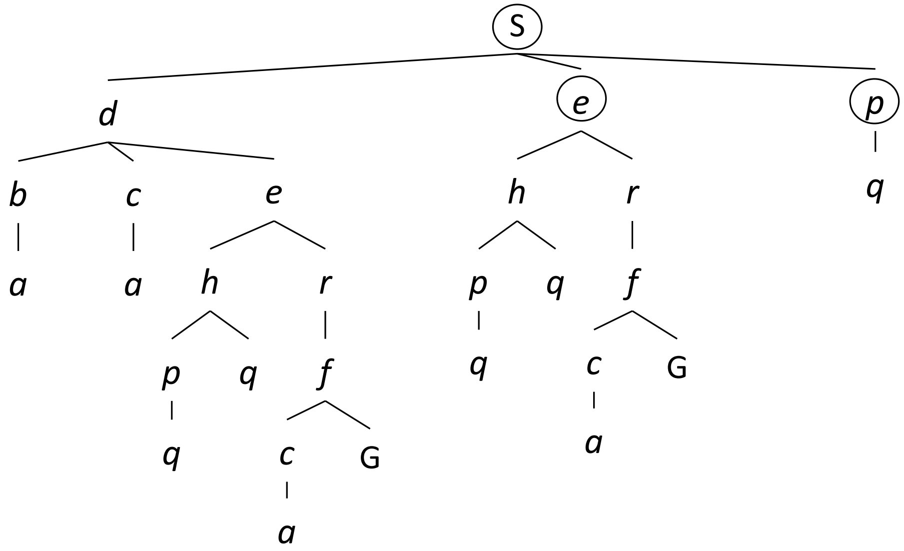
Iterative Deepening

Strategy: expand a deepest node first to a max depth, iteratively increase the depth

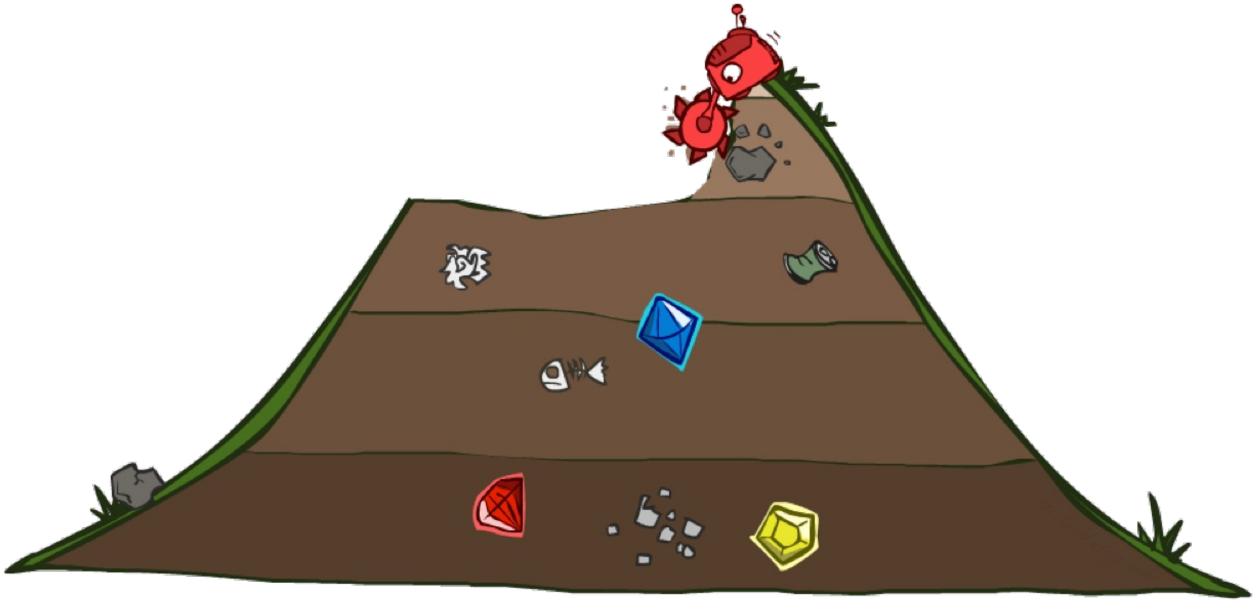
Implementation:

Frontier is a LIFO stack





Uniform Cost Search

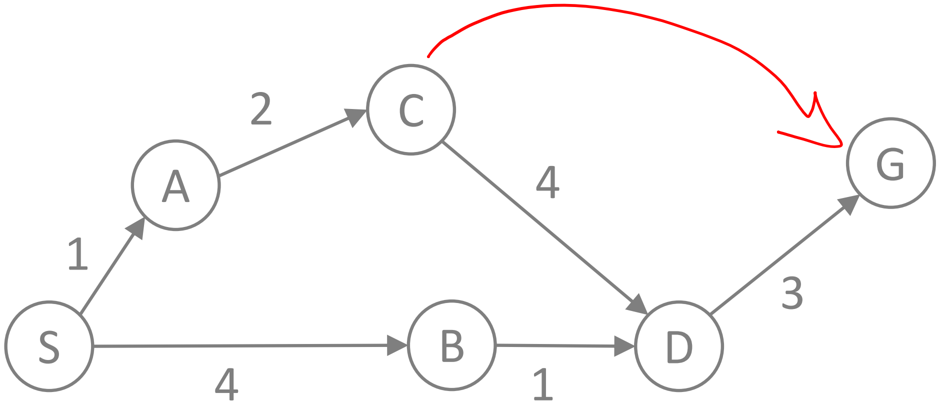


```
function GRAPH_SEARCH(problem) returns a solution, or failure
    initialize the explored set to be empty
    initialize the frontier as a specific work list (stack, queue, priority queue)
    add initial state of problem to frontier
    loop do
        if the frontier is empty then
            return failure
        choose a node and remove it from the frontier
        if the node contains a goal state then
            return the corresponding solution
        add the node state to the explored set
        for each resulting child from node
            if the child state is not already in the frontier or explored set then
                add child to the frontier
```

```
function UNIFORM-COST-SEARCH(problem) returns a solution, or failure
    initialize the explored set to be empty
    initialize the frontier as a priority queue using node path_cost as the priority
    add initial state of problem to frontier with path_cost = 0
    loop do
        if the frontier is empty then
            return failure
        choose a node and remove it from the frontier
        if the node contains a goal state then
            return the corresponding solution
        add the node state to the explored set
        for each resulting child from node
            if the child state is not already in the frontier or explored set then
                add child to the frontier
            else if the child is already in the frontier with higher path_cost then
                replace that frontier node with child
```

S → S

Walk-through UCS



frontier

~~s:0~~ ~~s-a:1~~ ~~s-b:4~~

~~s-a-c:3~~ [illegible]

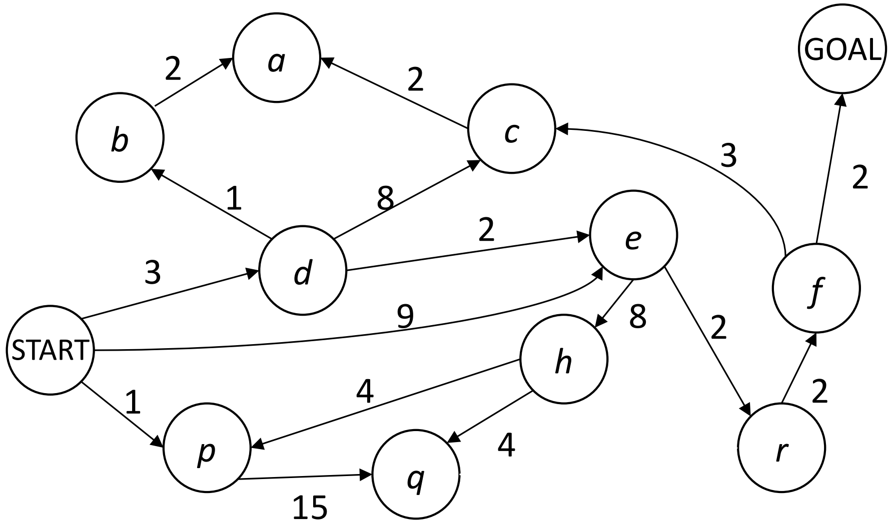
~~s-b-d:5~~ s-b-d-g:8

explored

s:0 s-a:1 s-a-c:3

s-b:4 s-b-d:5

Walk-through UCS



In Class Activity!

Q1 – practice running graph search. What gets added to the explored list in what order?

Q2 - Amazon warehouses use robots to transport items to packers along the outside edge of the warehouse to reduce the amount of walking those packers must do. These robots need to plan their paths to their goals without hitting each other.

Think about how we would apply graph search to this multi-robot problem…

Summary

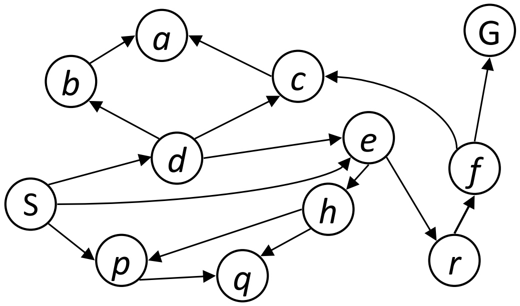
- Reflex vs Planning Agents
- Modeling state based on the problem you’re trying to solve
- Tree vs Graph Search
- BFS, DFS, UCS
- Branching factor, Search space (size of frontier)
- Completeness of search is whether it will always find A solution
- Optimality of search is whether it always finds the BEST solution

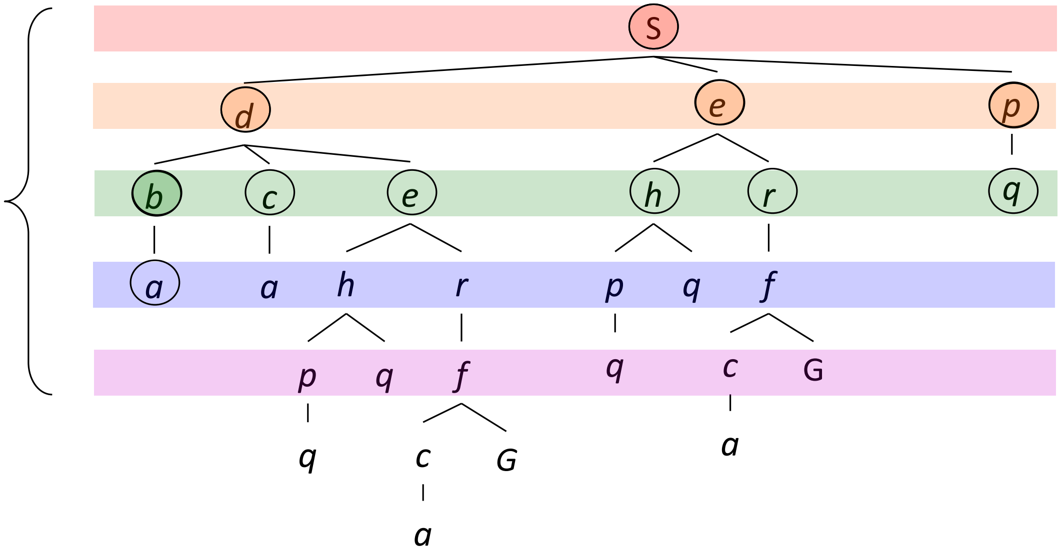
Extra slides below on search properties and iterative deepening

Breadth-First (Tree) Search

Strategy: expand a shallowest node first

Implementation:
Frontier is a FIFO queue



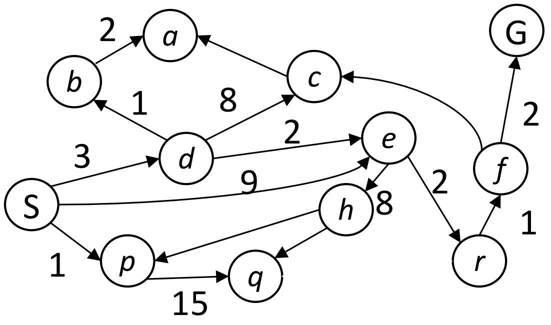

Search

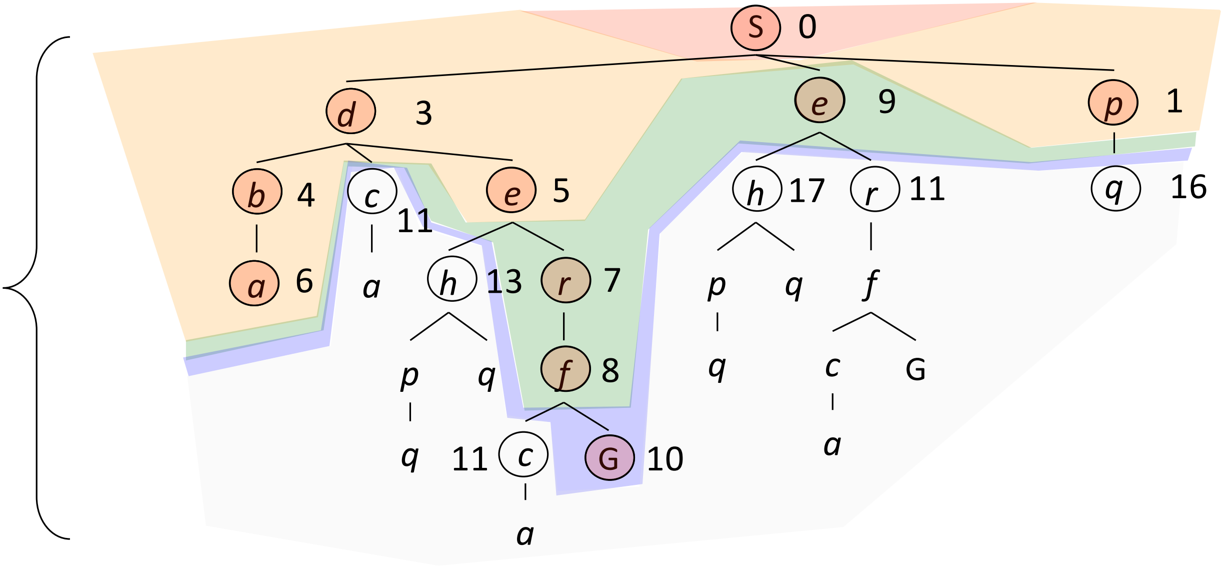
Tiers

Uniform Cost (Tree) Search

Strategy: expand a cheapest node first:

Frontier is a priority queue (priority: cumulative cost)



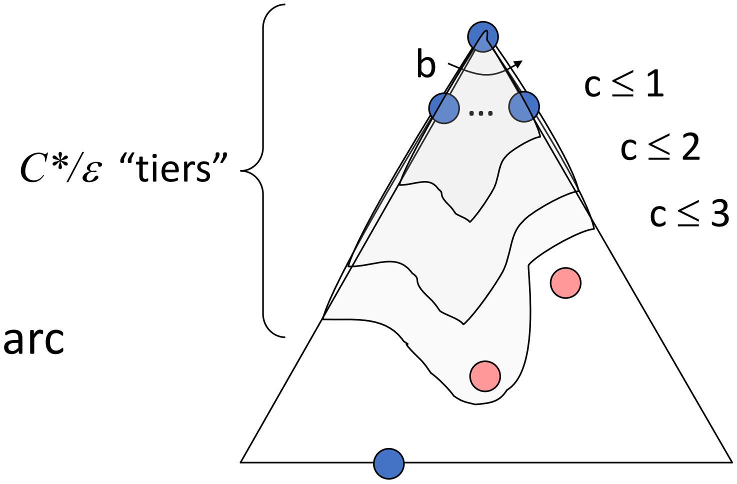


Cost contours

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 frontier take?

- Has roughly the last tier, so O($b^{C^*/\varepsilon}$)

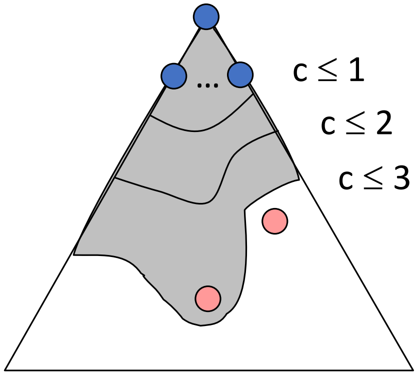
Is it complete?

- 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

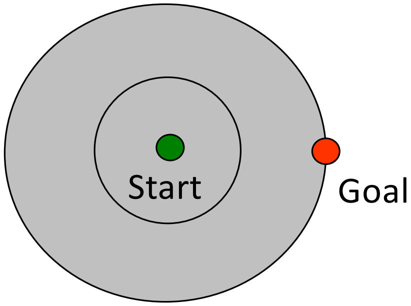


Remember:

- 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!