Announcements

- **Project 0: Python Tutorial**
  - Due today at 11:59pm (0 points in class, but pulse check to see you are in + get to know submission system)

- **Homework 0: Math self-diagnostic**
  - Optional, but important to check your preparedness for second half

- **Project 1: Search**
  - Will go out this week
  - Longer than most, and best way to test your programming preparedness

- **Sections**
  - Start this week, check Piazza for instructions for load balancing the sections!

- **Instructional accounts:** [https://inst.eecs.berkeley.edu/webacct](https://inst.eecs.berkeley.edu/webacct)

- **Pinned posts on Piazza**

- **Make sure you are signed up for Piazza and Gradescope**
CS 188: Artificial Intelligence

Search

Instructors: Sergey Levine & Stuart Russell

University of California, Berkeley

[slides adapted from Dan Klein, Pieter Abbeel]
Today

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

- An agent *perceives* its environment through *sensors* and *acts* upon it through *actuators*.
A rational agent chooses actions maximize the expected utility

- Today: agents that have a goal, and a cost
  - E.g., reach goal with lowest cost
- Later: agents that have numerical utilities, rewards, etc.
  - E.g., take actions that maximize total reward over time (e.g., largest profit in $)
Agent design

- The environment type largely determines the agent design
  - **Fully/partially observable** => agent requires memory (internal state)
  - **Discrete/continuous** => agent may not be able to enumerate all states
  - **Stochastic/deterministic** => agent may have to prepare for contingencies
  - **Single-agent-multi-agent** => agent may need to behave randomly
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?
Video of Demo Reflex Optimal
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
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?
    \[120 \times (2^{30})\]
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)
Agent design

- The environment type largely determines the agent design
  - *Fully/partially observable* => agent requires *memory* (internal state)
  - *Discrete/continuous* => agent may not be able to enumerate *all states*
  - *Stochastic/deterministic* => agent may have to prepare for *contingencies*
  - *Single-agent/multi-agent* => agent may need to behave *randomly*
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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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

This is now / start
Possible futures
We construct both on demand – and we construct as little as possible.

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

![Search Tree Diagram]
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
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
Quiz: DFS vs BFS

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

[Demo: dfs/bfs maze water (L2D6)]
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!
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
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!

[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...
Example: Pancake Problem

Cost: Number of pancakes flipped
Example: Pancake Problem

"BOUNDS FOR SORTING BY PREFIX REVERSAL"

William H. GATES
Microsoft, Albuquerque, New Mexico

Christos H. PAPADIMITRIOU*†
Department of Electrical Engineering, University of California, Berkeley, CA 94720, U.S.A.

Received 18 January 1978
Revised 28 August 1978

For a permutation $\sigma$ of the integers from 1 to $n$, let $f(\sigma)$ be the smallest number of prefix reversals that will transform $\sigma$ to the identity permutation, and let $f(n)$ be the largest such $f(\sigma)$ for all $\sigma$ in (the symmetric group) $S_n$. We show that $f(n) \leq (5n + 5)/3$, and that $f(n) \geq 17n/16$ for $n$ a multiple of 16. If, furthermore, each integer is required to participate in an even number of reversed prefixes, the corresponding function $g(n)$ is shown to obey $3n/2 - 1 \leq g(n) \leq 2n + 3$.
Example: Pancake Problem

State space graph with costs as weights
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

Action: flip top two  
Cost: 2

Path to reach goal:  
Flip four, flip three  
Total cost: 7
Uniform Cost Search

- Strategy: expand lowest path cost

- The good: UCS is complete and optimal!

- The bad:
  - Explores options in every “direction”
  - No information about goal location
Informed Search
Search Heuristics

- A heuristic is:
  - A function that *estimates* how close a state is to a goal
  - Designed for a particular search problem
  - Examples: Manhattan distance, Euclidean distance for pathing
Example: Heuristic Function

$h(x)$
Example: Heuristic Function

Heuristic: the number of the largest pancake that is still out of place
Greedy Search
Example: Heuristic Function

$h(x)$
Greedy Search

- Expand the node that seems closest...

- What can go wrong?
Greedy Search

- **Strategy:** expand a node that you think is closest to a goal state
  - **Heuristic:** estimate of distance to nearest goal for each state

- **A common case:**
  - Best-first takes you straight to the (wrong) goal

- **Worst-case:** like a badly-guided DFS
Video of Demo Contours Greedy (Pacman Small Maze)