Announcements

- Project 0 (optional) is due **Friday, January 19, 11:59 PM PT**
- HW0 (optional) is due **Tuesday, January 23, 11:59 PM PT**
- Project 1 is due **Friday, February 2, 11:59 PM PT**
- HW1 is due **Tuesday, February 6, 11:59 PM PT**
CS 188: Artificial Intelligence

Search

Spring 2024

University of California, Berkeley

[These slides were created by Dan Klein and Pieter Abbeel for CS188 Intro to AI at UC Berkeley (ai.berkeley.edu).]
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

![Pacman World State](image)

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

Each NODE 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)?

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

Diagram showing a tree structure with nodes labeled from A to G and connections between them.
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 that

- **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!
  - Branching factor 10, solution 5 deep:
    - BFS: $10 + 100 + 1,000 + 10,000 + 100,000 = 111,110$
    - IDS: $50 + 400 + 3,000 + 20,000 + 100,000 = 123,450$
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!

[Demo: empty grid UCS (L2D5)]
[Demo: maze with deep/shallow water DFS/BFS/UCS (L2D7)]
Video of Demo Contours UCS Pacman Small Maze
Video of Demo Empty UCS
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)
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
### 3.4.6 Comparing uninformed search algorithms

Figure 3.15 compares uninformed search algorithms in terms of the four evaluation criteria set forth in Section 3.3.4. This comparison is for tree-like search versions which don’t check for repeated states. For graph searches which do check, the main differences are that depth-first search is complete for finite state spaces, and the space and time complexities are bounded by the size of the state space (the number of vertices and edges, $|V| + |E|$).

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Breadth-First</th>
<th>Uniform-Cost</th>
<th>Depth-First</th>
<th>Depth-Limited</th>
<th>Iterative Deepening</th>
<th>Bidirectional (if applicable)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Complete?</td>
<td>Yes(^1)</td>
<td>Yes(^{1,2})</td>
<td>No</td>
<td>No</td>
<td>Yes(^1)</td>
<td>Yes(^{1,4})</td>
</tr>
<tr>
<td>Optimal cost?</td>
<td>Yes(^3)</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes(^3)</td>
<td>Yes(^{3,4})</td>
</tr>
<tr>
<td>Time</td>
<td>$O(b^d)$</td>
<td>$O(b^1 +</td>
<td>C^c</td>
<td>/\epsilon)$</td>
<td>$O(b^m)$</td>
<td>$O(b^e)$</td>
</tr>
<tr>
<td>Space</td>
<td>$O(b^d)$</td>
<td>$O(b^1 +</td>
<td>C^c</td>
<td>/\epsilon)$</td>
<td>$O(bm)$</td>
<td>$O(b\ell)$</td>
</tr>
</tbody>
</table>

Figure 3.15 Evaluation of search algorithms. \(b\) is the branching factor; \(m\) is the maximum depth of the search tree; \(d\) is the depth of the shallowest solution, or is \(m\) when there is no solution; \(\ell\) is the depth limit. Superscript caveats are as follows: \(^1\) complete if \(b\) is finite, and the state space either has a solution or is finite. \(^2\) complete if all action costs are $\geq \epsilon > 0$; \(^3\) cost-optimal if action costs are all identical; \(^4\) if both directions are breadth-first or uniform-cost.