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?
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

A solution is a sequence of actions (a plan) which transforms the start state to a goal state.
Search: it is not just for agents

Route Planning

Hardware verification

Planning optimal repair sequences

- Search: Modeling the world
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
This lecture is about search algorithms.

- **Input:**
  - Set of states
  - Operations
  - Start state
  - Goal state (test)

- **Output:**
State Space Sizes?

- **World state:**
  - Agent positions: 120
  - Food count: 30
  - Ghost positions: 12
  - Agent facing: NS EW

- **How many**
  - *World states?*
    - $120 \times (2^{30}) \times (12^2) \times 4$
  - *States for pathing?*
    - 120
  - *States for eat-all-dots?*
    - $120 \times (2^{30})$
State Representation

- Real-world applications:
  - Requires approximations and heuristics
  - Need to design state representation so that search is feasible
    - Only focus on important aspects of the state
    - E.g., Use features to represent world states
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
  - Arrows 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
A search tree:
- 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.
State Space Graphs vs. Search Trees

Consider this 4-state graph: How big is its search tree (from S)?
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?
Recap: Search

- **Search problem:**
  - States (configurations of the world)
  - Actions and costs
  - Successor function (world dynamics)
  - Start state and goal test

- **Search tree:**
  - Nodes: represent plans for reaching states

- **Search algorithm:**
  - Systematically builds a search tree
  - Chooses an ordering of the fringe (unexplored nodes)
Search Algorithms

- Uninformed Search Methods
  - Depth-First Search
  - Breadth-First Search
  - Uniform-Cost Search

- Heuristic Search Methods
  - Best First / Greedy Search
  - A*
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 $O(b^m)$

- 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

Search Tiers

Diagram illustrating the Breadth-First Search process.
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)
**BFS**

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Complete</th>
<th>Optimal</th>
<th>Time</th>
<th>Space</th>
</tr>
</thead>
<tbody>
<tr>
<td>DFS w/ Path Checking</td>
<td>Y</td>
<td>N</td>
<td>$O(b^m)$</td>
<td>$O(bm)$</td>
</tr>
<tr>
<td>BFS</td>
<td>Y</td>
<td>$Y^*$</td>
<td>$O(b^s)$</td>
<td>$O(b^s)$</td>
</tr>
</tbody>
</table>
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!
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 the 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!
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 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...
To Do:

- Try python practice (PS 0)
  - Won’t be graded

- PS 1 on the website
  - Start ASAP
  - Submission: Canvas

- Website:
  - Do readings for search algorithms
  - Try this search visualization tool
    - [http://qiao.github.io/PathFinding.js/visual/](http://qiao.github.io/PathFinding.js/visual/)