Today

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

- 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
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?

- **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

The *world state* includes every last detail of the environment.

A *search state* keeps only the details needed for planning (abstraction).
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
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Tiny search 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
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 Graph

Search Tree
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
Depth-First Search
Depth-First Search

**Strategy:** expand a deepest node first

**Implementation:** Fringe is a LIFO stack
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?
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
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)
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 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?
Some Hints for P1

- Graph search is almost always better than tree search (when not?)
- Implement your closed list as a dict or set!
- Nodes are conceptually paths, but better to represent with a state, cost, last action, and reference to the parent node