CS 188: Artificial Intelligence
Search with other Agents II

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[These slides adapted from Dan Klein and Pieter Abbeel]
Minimax Example
Minimax Example

```
  a
 / \
h  b
  / \  
 i  e  
  / \  
 j  f  
  / \  
 k  g  
  / \  
 l  c  
  /  
d  
```

Values:
- a: 10
- h: 2
- b: 10
- i: 2
- j: 1
- k: 2
- l: 20
- c: 10
- d: 6
- f: 100
- g: 8
- m: 20
- n: 4
Minimax Example
Resource Limits
Resource Limits

- Problem: In realistic games, cannot search to leaves!

- Solution: Depth-limited search
  - Instead, search only to a limited depth in the tree
  - Replace terminal utilities with an evaluation function for non-terminal positions

- Example:
  - Suppose we have 100 seconds, can explore 10K nodes / sec
  - So can check 1M nodes per move
  - $\alpha$-$\beta$ reaches about depth 8 – decent chess program

- Guarantee of optimal play is gone

- More plies makes a BIG difference

- Use iterative deepening for an anytime algorithm
Evaluation Functions
Evaluation Functions

- Evaluation functions score non-terminals in depth-limited search

- Ideal function: returns the actual minimax value of the position
- In practice: typically weighted linear sum of features:
  \[ \text{Eval}(s) = w_1 f_1(s) + w_2 f_2(s) + \ldots + w_n f_n(s) \]
- e.g. \( f_1(s) = (\text{num white queens} - \text{num black queens}) \), etc.
Other Game Types
Multi-Agent Utilities

- What if the game is not zero-sum, or has multiple players?

- Generalization of minimax:
  - Terminals have utility tuples
  - Node values are also utility tuples
  - Each player maximizes its own component
  - Can give rise to cooperation and competition dynamically…
Uncertain Outcomes
Worst-Case vs. Average Case

Idea: Uncertain outcomes controlled by chance, not an adversary!
Expectimax Search

- Why wouldn’t we know what the result of an action will be?
  - Explicit randomness: rolling dice
  - Unpredictable opponents: the ghosts respond randomly
  - Unpredictable humans: humans are not perfect
  - Actions can fail: when moving a robot, wheels might slip

- Values should now reflect average-case (expectimax) outcomes, not worst-case (minimax) outcomes

- Expectimax search: compute the average score under optimal play
  - Max nodes as in minimax search
  - Chance nodes are like min nodes but the outcome is uncertain
  - Calculate their expected utilities
  - I.e. take weighted average (expectation) of children

- Later, we’ll learn how to formalize the underlying uncertain-result problems as Markov Decision Processes

[Demo: min vs exp (L7D1,2)]
Video of Demo Minimax vs Expectimax (Min)
Video of Demo Minimax vs Expectimax (Exp)
**Expectimax Pseudocode**

```python
def value(state):
    if the state is a terminal state: return the state’s utility
    if the next agent is MAX: return max-value(state)
    if the next agent is EXP: return exp-value(state)

def max-value(state):
    initialize v = -\infty
    for each successor of state:
        v = max(v, value(successor))
    return v

def exp-value(state):
    initialize v = 0
    for each successor of state:
        p = probability(successor)
        v += p * value(successor)
    return v
```
Expectimax Pseudocode

def exp-value(state):
    initialize v = 0
    for each successor of state:
        p = probability(successor)
        v += p * value(successor)
    return v

v = (1/2) (8) + (1/3) (24) + (1/6) (-12) = 10
Expectimax Example
Expectimax Pruning?
Depth-Limited Expectimax

Estimate of true expectimax value (which would require a lot of work to compute)
Probabilities
A random variable represents an event whose outcome is unknown.

A probability distribution is an assignment of weights to outcomes.

Example: Traffic on freeway
- Random variable: \( T = \) whether there’s traffic
- Outcomes: \( T \in \{ \text{none, light, heavy} \} \)
- Distribution: \( P(T=\text{none}) = 0.25, P(T=\text{light}) = 0.50, P(T=\text{heavy}) = 0.25 \)

Some laws of probability (more later):
- Probabilities are always non-negative
- Probabilities over all possible outcomes sum to one

As we get more evidence, probabilities may change:
- \( P(T=\text{heavy}) = 0.25, P(T=\text{heavy} \mid \text{Hour=8am}) = 0.60 \)
- We’ll talk about methods for reasoning and updating probabilities later
Reminder: Expectations

- The expected value of a function of a random variable is the average, weighted by the probability distribution over outcomes.

- Example: How long to get to the airport?

<table>
<thead>
<tr>
<th>Time</th>
<th>Probability</th>
<th>Calculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 min</td>
<td>0.25</td>
<td>0.25 x 20 min = 5 min</td>
</tr>
<tr>
<td>30 min</td>
<td>0.50</td>
<td>0.50 x 30 min = 15 min</td>
</tr>
<tr>
<td>60 min</td>
<td>0.25</td>
<td>0.25 x 60 min = 15 min</td>
</tr>
</tbody>
</table>

  Total: 35 min
What Probabilities to Use?

- In expectimax search, we have a probabilistic model of how the opponent (or environment) will behave in any state
  - Model could be a simple uniform distribution (roll a die)
  - Model could be sophisticated and require a great deal of computation
  - We have a chance node for any outcome out of our control: opponent or environment
  - The model might say that adversarial actions are likely!

- For now, assume each chance node magically comes along with probabilities that specify the distribution over its outcomes

Having a probabilistic belief about another agent’s action does not mean that the agent is flipping any coins!
Quiz: Informed Probabilities

- Let’s say you know that your opponent is actually running a depth 2 minimax, using the result 80% of the time, and moving randomly otherwise.
- Question: What tree search should you use?

**Answer: Expectimax!**

- To figure out EACH chance node’s probabilities, you have to run a simulation of your opponent.
- This kind of thing gets very slow very quickly.
- Even worse if you have to simulate your opponent simulating you…
- … except for minimax and maximax, which have the nice property that it all collapses into one game tree.

This is basically how you would model a human, except for their utility: their utility might be the same as yours (i.e. you try to help them, but they are depth 2 and noisy), or they might have a slightly different utility (like another person navigating in the office).
Modeling Assumptions
The Dangers of Optimism and Pessimism

Dangerous Optimism
Assuming chance when the world is adversarial

Dangerous Pessimism
Assuming the worst case when it’s not likely
Assumptions vs. Reality

Pacman used depth 4 search with an eval function that avoids trouble
Ghost used depth 2 search with an eval function that seeks Pacman

[Demos: world assumptions (L7D3,4,5,6)]
Assumptions vs. Reality

Pacman used depth 4 search with an eval function that avoids trouble.
Ghost used depth 2 search with an eval function that seeks Pacman.

<table>
<thead>
<tr>
<th></th>
<th>Adversarial Ghost</th>
<th>Random Ghost</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Minimax Pacman</strong></td>
<td>Won 5/5</td>
<td>Won 5/5</td>
</tr>
<tr>
<td>Avg. Score: 483</td>
<td></td>
<td>Avg. Score: 493</td>
</tr>
<tr>
<td><strong>Expectimax Pacman</strong></td>
<td>Won 1/5</td>
<td>Won 5/5</td>
</tr>
<tr>
<td>Avg. Score: -303</td>
<td></td>
<td>Avg. Score: 503</td>
</tr>
</tbody>
</table>

Results from playing 5 games

[Demos: world assumptions (L7D3,4,5,6)]
Video of Demo World Assumptions
Random Ghost – Expectimax Pacman
Video of Demo World Assumptions
Adversarial Ghost – Minimax Pacman
Video of Demo World Assumptions
Adversarial Ghost – Expectimax Pacman
Video of Demo World Assumptions
Random Ghost – Minimax Pacman
Why not minimax?

- Worst case reasoning is too conservative
- Need average case reasoning
Mixed Layer Types

- E.g. Backgammon
- Expectiminimax
  - Environment is an extra “random agent” player that moves after each min/max agent
  - Each node computes the appropriate combination of its children
Example: Backgammon

- Dice rolls increase $b$: 21 possible rolls with 2 dice
  - Backgammon ≈ 20 legal moves
  - Depth 2 = $20 \times (21 \times 20)^3 = 1.2 \times 10^9$

- As depth increases, probability of reaching a given search node shrinks
  - So usefulness of search is diminished
  - So limiting depth is less damaging
  - But pruning is trickier...

- Historic AI: TDGammon uses depth-2 search + very good evaluation function + reinforcement learning:
  - world-champion level play

- 1st AI world champion in any game!
Utilities
Utilities

- Utilities are functions from outcomes (states of the world) to real numbers that describe an agent's preferences.

- Where do utilities come from?
  - In a game, may be simple (+1/-1)
  - Utilities summarize the agent's goals
  - Theorem: any “rational” preferences can be summarized as a utility function.

- We hard-wire utilities and let behaviors emerge
  - Why don’t we let agents pick utilities?
  - Why don’t we prescribe behaviors?
Utilities: Uncertain Outcomes

Getting ice cream

Get Single

Get Double

Oops

Whew!
Why should we average utilities? Why not minimax?

Principle of maximum expected utility:
- A rational agent should choose the action that maximizes its expected utility, given its knowledge.

Questions:
- Where do utilities come from?
- How do we know such utilities even exist?
- How do we know that averaging even makes sense?
- What if our behavior (preferences) can’t be described by utilities?
What Utilities to Use?

- For worst-case minimax reasoning, terminal function scale doesn’t matter
  - We just want better states to have higher evaluations (get the ordering right)
  - We call this **insensitivity to monotonic transformations**

- For average-case expectimax reasoning, we need *magnitudes* to be meaningful
Preferences

- An agent must have preferences among:
  - Prizes: $A$, $B$, etc.
  - Lotteries: situations with uncertain prizes
    \[ L = [p, A; (1 - p), B] \]

- Notation:
  - $A \succ B$
    - Preference: $A \sim B$
    - Indifference:
Rationality
Rational Preferences

- We want some constraints on preferences before we call them rational, such as:
  - For example: an agent with intransitive preferences can be induced to give away all of its money
    - If $B > C$, then an agent with $C$ would pay (say) 1 cent to get $B$
    - If $A > B$, then an agent with $B$ would pay (say) 1 cent to get $A$
    - If $C > A$, then an agent with $A$ would pay (say) 1 cent to get $C$

Axiom of Transitivity: $(A \succ B) \land (B \succ C) \Rightarrow (A \succ C)$
Rational Preferences

The Axioms of Rationality

Orderability
\((A \succ B) \lor (B \succ A) \lor (A \sim B)\)

Transitivity
\((A \succ B) \land (B \succ C) \Rightarrow (A \succ C)\)

Continuity
\(A \succ B \succ C \Rightarrow \exists p \ [p, A; 1 - p, C] \sim B\)

Substitutability
\(A \sim B \Rightarrow [p, A; 1 - p, C] \sim [p, B; 1 - p, C]\)

Monotonicity
\(A \succ B \Rightarrow (p \geq q \iff [p, A; 1 - p, B] \succeq [q, A; 1 - q, B])\)

Theorem: Rational preferences imply behavior describable as maximization of expected utility
MEU Principle

- **Theorem** [Ramsey, 1931; von Neumann & Morgenstern, 1944]
  - Given any preferences satisfying these constraints, there exists a real-valued function $U$ such that:
    
    $$ U(A) \geq U(B) \iff A \succeq B $$
    
    $$ U([p_1, S_1; \ldots; p_n, S_n]) = \sum_i p_i U(S_i) $$
  - I.e. values assigned by $U$ preserve preferences of both prizes and lotteries!

- **Maximum expected utility (MEU) principle:**
  - Choose the action that maximizes expected utility
  - Note: an agent can be entirely rational (consistent with MEU) without ever representing or manipulating utilities and probabilities
  - E.g., a lookup table for perfect tic-tac-toe, a reflex vacuum cleaner
Human Utilities

Spin the wheel or pay $ to pass

OK
Utility Scales

- **Normalized utilities**: $u_+ = 1.0$, $u_- = 0.0$

- **Micromorts**: one-millionth chance of death, useful for paying to reduce product risks, etc.

- **QALYs**: quality-adjusted life years, useful for medical decisions involving substantial risk

- Note: behavior is invariant under positive linear transformation

\[ U'(x) = k_1 U(x) + k_2 \quad \text{where} \quad k_1 > 0 \]

- With deterministic prizes only (no lottery choices), only **ordinal utility** can be determined, i.e., total order on prizes
Human Utilities

- Utilities map states to real numbers. Which numbers?
- Standard approach to assessment (elicitation) of human utilities:
  - Compare a prize A to a standard lottery \( L_p \) between
    - “best possible prize” \( u_+ \) with probability \( p \)
    - “worst possible catastrophe” \( u_- \) with probability \( 1-p \)
  - Adjust lottery probability \( p \) until indifference: \( A \sim L_p \)
  - Resulting \( p \) is a utility in \([0,1]\)
Money

- Money does not behave as a utility function, but we can talk about the utility of having money (or being in debt).
- Given a lottery $L = [p, X; (1-p), Y]$
  - The expected monetary value $EMV(L)$ is $pX + (1-p)Y$
  - $U(L) = pU(X) + (1-p)U(Y)$
  - Typically, $U(L) < U(EMV(L))$
  - In this sense, people are risk-averse.
  - When deep in debt, people are risk-prone.
Example: Insurance

- Consider the lottery $[0.5, $1000; 0.5, $0]$
  - What is its expected monetary value? ($500)
  - What is its certainty equivalent?
    - Monetary value acceptable in lieu of lottery
    - $400 for most people
  - Difference of $100 is the insurance premium
    - There’s an insurance industry because people will pay to reduce their risk
    - If everyone were risk-neutral, no insurance needed!
  - It’s win-win: you’d rather have the $400 and the insurance company would rather have the lottery (their utility curve is flat and they have many lotteries)
Example: Human Rationality?

- Famous example of Allais (1953)
  - A: [0.8, $4k; 0.2, $0]
  - B: [1.0, $3k; 0.0, $0]
  - C: [0.2, $4k; 0.8, $0]
  - D: [0.25, $3k; 0.75, $0]

- Most people prefer B > A, C > D

- But if U($0) = 0, then
  - B > A \Rightarrow U($3k) > 0.8 U($4k)
  - C > D \Rightarrow 0.8 U($4k) > U($3k)
Next Time: MDPs!
What are Probabilities?

- **Objectivist / frequentist answer:**
  - Averages over repeated *experiments*
  - E.g. empirically estimating $P(\text{rain})$ from historical observation
  - Assertion about how future experiments will go (in the limit)
  - New evidence changes the *reference class*
  - Makes one think of inherently random events, like rolling dice

- **Subjectivist / Bayesian answer:**
  - Degrees of belief about unobserved variables
  - E.g. an agent’s belief that it’s raining, given the temperature
  - E.g. pacman’s belief that the ghost will turn left, given the state
  - Often *learn* probabilities from past experiences (more later)
  - New evidence *updates beliefs* (more later)
Uncertainty Everywhere

- Not just for games of chance!
  - I’m sick: will I sneeze this minute?
  - Email contains “FREE!”: is it spam?
  - Tooth hurts: have cavity?
  - 60 min enough to get to the airport?
  - Robot rotated wheel three times, how far did it advance?
  - Safe to cross street? (Look both ways!)

- Sources of uncertainty in random variables:
  - Inherently random process (dice, etc)
  - Insufficient or weak evidence
  - Ignorance of underlying processes
  - Unmodeled variables
  - The world’s just noisy – it doesn’t behave according to plan!

- Compare to fuzzy logic, which has degrees of truth, rather than just degrees of belief