CSE 473: Artificial Intelligence  
Spring 2018  
Adversarial Search  
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Most of these slides originate from: Dan Klein and Pieter Abbeel.

Game Playing State-of-the-Art


- **Chess:** 1997: Deep Blue defeats human champion Gary Kasparov in a six-game match. Deep Blue examined 200M positions per second, used very sophisticated evaluation and undisclosed methods for extending some lines of search up to 40 ply. Current programs are even better, if less historic.

- **Go:** 2016: Google’s DeepMind beats world-class player Lee Se-dol in 4 out of 5 games. Deep convolutional neural nets played an important role in DeepMind’s success.

- **Pacman**

Behavior from Computation

Types of Games

- Many different kinds of games!

- **Axes:**
  - Deterministic or stochastic?
  - One, two, or more players?
  - Zero sum?
  - Perfect information (can you see the state)?

- Want algorithms for calculating a strategy (policy) which recommends a move from each state.
Deterministic Games

- Many possible formalizations, one is:
  - States: $S$ (start at $s_0$)
  - Players: $P=\{1, \ldots, N\}$ (usually take turns)
  - Actions: $A$ (may depend on player / state)
  - Transition Function: $S \times A \rightarrow S$
  - Terminal Test: $S \rightarrow \{T,F\}$
  - Terminal Utilities: $S \times P \rightarrow R$

- Solution for a player is a policy: $S \rightarrow A$

Zero-Sum Games

- Zero-Sum Games
  - Agents have opposite utilities (values on outcomes)
  - Let us think of a single value that one maximizes and the other minimizes
  - Adversarial, pure competition

- General Games
  - Agents have independent utilities (values on outcomes)
  - Cooperation, indifference, competition, and more are all possible
  - More later on non-zero-sum games

Adversarial Search

Adversarial Game Trees

Single-Agent Trees

Value of a State

- Value of a State:
  - The best achievable outcome (utility) from that state

- Non-Terminal States:
  $$V(s) = \max_{a \in A(s)} \min_{s' \in S(s,a)} V(s')$$

- Terminal States:
  $$V(s) = \text{known}$$
Minimax Values

States Under Agent’s Control:
\( V(s) = \max_{a'(\text{Successful}(s))} V(s') \)

States Under Opponent’s Control:
\( V(s') = \min_{a'(\text{Successful}(s'))} V(s') \)

Terminal States:
\( V(s) = \text{known} \)

Adversarial Search (Minimax)
- Deterministic, zero-sum games:
  - Tic-tac-toe, chess, checkers
  - One player maximizes result
  - The other minimizes result

Minimax search:
- A state-space search tree
- Players alternate turns
- Compute each node’s minimax value:
  - the best achievable utility against a rational (optimal) adversary

Minimax Implementation

\[
def \text{max-value}(state):
    \text{initialize } v = -\infty
    \text{for each successor of state:}
    v = \max(v, \text{value(successor)})
    \text{return } v
\]

\[
def \text{min-value}(state):
    \text{initialize } v = +\infty
    \text{for each successor of state:}
    v = \min(v, \text{value(successor)})
    \text{return } v
\]

Minimax Implementation (Dispatch)

\[
def \text{value}(state):
    \text{if the state is a terminal state: return the state’s utility}
    \text{if the next agent is } \text{MAX: return } \text{max-value(state)}
    \text{if the next agent is } \text{MIN: return } \text{min-value(state)}
\]

Minimax Example
Minimax Efficiency

- How efficient is minimax?
  - Just like (exhaustive) DFS
  - Time: $O(b^m)$
  - Space: $O(bm)$
- Example: For chess, $b \approx 35$, $m \approx 100$
  - Exact solution is completely infeasible
  - But, do we need to explore the whole tree?

Minimax Properties

Optimal against a perfect player. Otherwise?

Video of Demo Min vs. Exp (Min)

Video of Demo Min vs. Exp (Exp)

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
  - $\alpha$-$\beta$ 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
Depth Matters

- Evaluation functions are always imperfect
- The deeper in the tree the evaluation function is buried, the less the quality of the evaluation function matters
- An important example of the tradeoff between complexity of features and complexity of computation

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. \( f(s) = (\text{num white queens} - \text{num black queens}) \), etc.
Video of Demo Thrashing (d=2)

Why Pacman Starves

- A danger of replanning agents!
  - He knows his score will go up by eating the dot now (west, east)
  - He knows his score will go up just as much by eating the dot later (east, west)
  - There are no point-scoring opportunities after eating the dot (within the horizon, two here)
  - Therefore, waiting seems just as good as eating: he may go east, then back west in the next round of replanning!

Video of Demo Thrashing -- Fixed (d=2)

Video of Demo Smart Ghosts (Coordination)

Video of Demo Smart Ghosts (Coordination) – Zoomed In

Game Tree Pruning
### Minimax Example

![Minimax Tree](image)

### Minimax Pruning

![Pruned Minimax Tree](image)

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### Alpha-Beta Pruning

- **General configuration (MIN version)**
  - We’re computing the MIN-VALUE at some node \( n \)
  - We’re looping over \( n \)’s children
  - \( n \)’s estimate of the children’s min is dropping
  - Who cares about \( n \)’s value? MAX
  - Let \( a \) be the best value that MAX can get at any choice point along the current path from the root
  - If \( n \) becomes worse than \( a \), MAX will avoid it, so we can stop considering \( n \)’s other children (it’s already bad enough that it won’t be played)
  - MAX version is symmetric

- **Alpha-Beta Pruning Properties**
  - This pruning has no effect on minimax value computed for the root!
  - Values of intermediate nodes might be wrong
    - Important: children of the root may have the wrong value
    - So the most naive version won’t let you do action selection
  - Good child ordering improves effectiveness of pruning
  - With “perfect ordering”:
    - Time complexity drops to \( O(b^{m/2}) \)
    - Doubles solvable depth!
    - Full search of, e.g., chess, is still hopeless...
  - This is a simple example of metareasoning (computing about what to compute)

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### Alpha-Beta Implementation

**Defining min-value[state, α, β]:**

```python
def min-value(state, α, β):
    initialize v = +∞
    for each successor of state:
        v = min(v, value(successor, α, β))
    if v ≤ α return v
    β = min(β, v)
    return v
```

**Defining max-value[state, α, β]:**

```python
def max-value(state, α, β):
    initialize v = -∞
    for each successor of state:
        v = max(v, value(successor, α, β))
    if v ≥ β return v
    α = max(α, v)
    return v
```

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### Alpha-Beta Quiz

![Quiz Tree](image)
Iterative Deepening uses DFS as a subroutine:
1. Do a DFS which only searches for paths of length 1 or less. (DFS gives up on any path of length 2)
2. If “1” failed, do a DFS which only searches paths of length 2 or less.
3. If “2” failed, do a DFS which only searches paths of length 3 or less.
   …and so on

Why do we want to do this for multiplayer games?

Note: wrongness of eval functions matters less and less the deeper the search goes!