Intelligent Game Playing

Instructor: B. John Oommen

Chancellor’s Professor

Fellow: IEEE; Fellow: IAPR

School of Computer Science, Carleton University, Canada

The primary source of these notes are the slides of Professor Hwee Tou Ng from Singapore. The Multi-Player Game section was due to Mr. Spencer Polk. I sincerely thank them for this.
Games - Introduction

• Question: Can machines outplay humans?

• Captured imaginations for centuries
  – Appearance in myth and legend
  – Popular topic in fiction

• Thanks to AI and search techniques, the dream has come true!
The Turk (1770)

- “The Turk”: In 1770
- A chess playing machine
- Toured Europe
- Facing well-known opponents
  - e.g. Napoleon, Ben Franklin
- Of course: Revealed - fraud
History

• “The Turk” shows how fascinating this idea is

• 1914: King vs Rook strategies by automaton

• True AI game playing – Claude Shannon: 1950
  – Based on earlier work by Nash and Neumann

• Shannon's algorithm still used
  • Mini-Max Search (we will return to it shortly)
History

• Shannon's 1950 paper focused on Chess
  – Chess remains very important to game playing research

• At the time, seen as purely theoretical exercise

• 1970s: First commercial Chess programs

• 1980s: Chess programs playing at Expert level
  – Still some time until Grandmaster level...
History

- 1997: IBM's Deep Blue
  - Defeats Garry Kasparov
- First defeat of Grandmaster
- Field: Branched out since
  - Poker, Go: Now important games
  - IBM Watson on Jeopardy

Kasparov vs Deep Blue
Games vs. Search Problems

• “Unpredictable” opponent
  – Specifying a move for every possible opponent reply

• Time limits
  – Unlikely to find goal, must approximate
Mini-Max Search

• Search to find the correct move in a two player game

• The *optimal* solution:
  – Exponential algorithm
  – Generate all possible paths
  – Only play those that lead to a winning final position

• Realistic alternative to the Optimal

• Use finite depth look-ahead with a heuristic function
• Evaluate how good a given game state is
Mini-Max

- Extend Tree down to a given search depth

- Top of tree is the Computer’s move
  - Wants move to ultimately be one step closer to a winning position
  - Wants move that maximizes own chance of winning

- Next move is Opponent’s
  - Opponent assumed to perform a move that his best
  - Wants move that minimizes Computer’s chance of winning
Game tree
2-player, Deterministic, Turns
Mini-Max

- **Perfect** play for deterministic games
- **Idea**: Choose move to position with highest Mini-Max value
  = Best achievable payoff against best play
- Example: 2-ply game:
Mini-Max for Nim

• **Nim Game**
  – Two players start with a pile of tokens
  – Legal move: Split (any) existing pile into two non-empty differently sized piles
  – Game ends when no pile can be unevenly split
  – Player who cannot make his move loses the game

• **Search strategy**
  – Existing heuristic search methods do not work
Mini-Max for Nim

- Label nodes as MIN or MAX, alternating for each level
- Define utility function (payoff function).
- Do full search on tree
  - Expand all nodes until game is over for each branch
- Label leaves according to outcome
- Propagate result up the tree with:
  - $M(n) = \max(\text{child nodes})$ for a MAX node
  - $m(n) = \min(\text{child nodes})$ for a MIN node
- Best next move for MAX is the one leading to the child with the highest value (and vice versa for MIN)
Mini-Max for Nim
Mini-Max Algorithm

function MINIMAX-DECISION(game) returns an operator
for each op in OPERATORS[game] do
    VALUE[op] := MIN-VALUE(APPLY(op, game), game)
end
return the op with the highest VALUE[op]

function MAX-VALUE(state, game) returns a utility value
if CUTOFF-TEST(state,) then return EVAL(state)
value := - ∞
for each s in SUCCESSORS(state) do
    value := MAX(value, MIN-VALUE(s, game))
end
return value

function MIN-VALUE(state, game) returns a utility value
if CUTOFF-TEST(state,) then return EVAL(state)
value := ∞
for each s in SUCCESSORS(state) do
    value := MIN(value, MAX-VALUE(s, game))
end
return value
Problems with Mini-Max

• **Horizon effect:** Can’t see beyond depth
  – Due to exponential increase in tree size, only very limited depth feasible
  – Solution: Quiescence search. Start at the leaf nodes of the main search, and try to solve this problem.
  – In Chess, quiescence searches usually include all capture moves, so that tactical exchanges don't mess up the evaluation. In principle, quiescence searches should include any move which may destabilize the evaluation function--if there is such a move, the position is not quiescent.

• **May want to use look up tables**
  – For end games
  – Opening moves (called Book Moves)
Properties of Mini-Max

• **Complete?**
  - Yes (if tree is finite)

• **Optimal?**
  - Yes (against an optimal opponent)

• **Time complexity?**
  - \( O(b^m) \)

• **Space complexity?**
  - \( O(bm) \) (depth-first exploration)

• **Chess**: \( b \approx 35 \), \( m \approx 100 \) for “reasonable” games
  - Exact solution completely infeasible
Branch and Bound: The $\alpha$-$\beta$ Algorithm

- **Branch and Bound**: If current path (branch) is already worse than some other known path:
  - Stop expanding it (bound).

- **Alpha-Beta** is a branch and bound technique for Mini-Max search

- If you know that the level above won’t choose your branch because you have already found a value along one of your sub-branches that is too good, stop looking at other sub-branches that haven’t been looked at yet
The α-β Algorithm

• Instead of maintaining a single mini-max value, the α-β pruning algorithm, maintains two: α, β

• Together provide a bound on the possible values of the mini-max tree at any given point.

• At any given point, α: minimum the player can expect to receive

• At any given point, β: maximum value the player can expect
The α-β Algorithm

- If it is ever the case that this bound is reversed or has range of 0 (β ≤ α), then better options exist for the player at other pre-explored nodes.
- As α is the minimum value we know we can get.
- Thus this node cannot be the mini-max value of the tree.
- There is no point in exploring any more of this node's children.
- Potentially saving considerable computation time in a game with a large branching factor/depth.
Properties of $\alpha$-$\beta$

- Pruning does not affect final result
- Good move ordering improves pruning effectiveness
- With “perfect ordering” time complexity $= O(b^{m/2})$
  - Doubles depth of search
- $\alpha$-$\beta$ is a simple example of the value of reasoning about which computations are really relevant
Why it is called $\alpha$-\(\beta\)

- $\alpha$: Value of the best choice found so far at any choice point along the path for $\text{max}$
- If $v$ is worse than $\alpha$
  - $\text{max}$ will avoid it
  - prune that branch
- Define $\beta$ similarly for $\text{min}$
Effects of $\alpha-\beta$

A has $\beta = 3$ (A will be no larger than 3)
B is $\beta$ pruned, since 5 > 3
C has $\alpha = 3$ (C will be no smaller than 3)
D is $\alpha$ pruned, since 0 < 3
E is $\alpha$ pruned, since 2 < 3
C is 3
Example: $\alpha$-$\beta$ Pruning
Example: $\alpha$-$\beta$ Pruning
Example: $\alpha$-$\beta$ Pruning
Example: α-β Pruning
Example: $\alpha$-$\beta$ Pruning
The \( \alpha \)-\( \beta \) Algorithm

- From Russell and Norvig

\[ \alpha = \text{best score for MAX so far} \]
\[ \beta = \text{best score for MIN so far} \]

\[ \text{game} = \text{game description} \]
\[ \text{state} = \text{current state in game} \]

\begin{verbatim}
function MAX-VALUE(state, game, \( \alpha \), \( \beta \)) returns a utility value
    if CUTOFF-TEST(state) then return EVAL(state)
    for each \( s \) in SUCCESSORS(state) do
        \( \alpha := \text{MAX}(\alpha, \text{MIN-VALUE}(s, game, \alpha, \beta)) \)
        if \( \alpha \geq \beta \) then return \( \alpha \)
    end
    return \( \alpha \)

function MIN-VALUE(state, game, \( \alpha \), \( \beta \)) returns a utility value
    if CUTOFF-TEST(state) then return EVAL(state)
    for each \( s \) in SUCCESSORS(state) do
        \( \beta := \text{MIN}(\beta, \text{MAX-VALUE}(s, game, \alpha, \beta)) \)
        if \( \beta \leq \alpha \) then return \( \beta \)
    end
    return \( \beta \)
\end{verbatim}
The $\alpha$-$\beta$ Algorithm

**function** ALPHA-BETA-SEARCH($state$) **returns** an action

**inputs:** $state$, current state in game

$v \leftarrow$ MAX-VALUE($state$, $-\infty$, $+\infty$)

**return** the action in SUCCESSORS($state$) with value $v$

**function** MAX-VALUE($state$, $\alpha$, $\beta$) **returns** a utility value

**inputs:** $state$, current state in game

- $\alpha$, the value of the best alternative for MAX along the path to $state$
- $\beta$, the value of the best alternative for MIN along the path to $state$

if TERMINAL-TEST($state$) then **return** UTILITY($state$)

$v \leftarrow -\infty$

for $a$, $s$ in SUCCESSORS($state$) do

$v \leftarrow$ MAX($v$, MIN-VALUE($s$, $\alpha$, $\beta$))

if $v \geq \beta$ then **return** $v$

$\alpha \leftarrow$ MAX($\alpha$, $v$)

**return** $v$
The α-β Algorithm

function \textsc{Min-Value}(state, \alpha, \beta) \textbf{returns} a utility value
  inputs: state, current state in game
  \hspace{1em} \alpha, \text{ the value of the best alternative for } \textsc{Max} \text{ along the path to } state
  \hspace{1em} \beta, \text{ the value of the best alternative for } \textsc{Min} \text{ along the path to } state
  if \textsc{Terminal-Test}(state) then return \textsc{Utility}(state)
  \hspace{1em} v \leftarrow +\infty
  for a, s in \textsc{Successors}(state) do
    v \leftarrow \textsc{Min}(v, \textsc{Max-Value}(s, \alpha, \beta))
    if \ v \leq \alpha \ then \ return \ v
    \hspace{1em} \beta \leftarrow \textsc{Min}(\beta, v)
  \hspace{1em} return v
Improving Game Playing

- Increase Depth of Search
- Have better heuristic for game state evaluation

Changing Levels of Difficulty

- Increase Depth of Search
ResourceLimits

- Suppose we have 100 secs, explore $10^4$ nodes/sec
  - $10^6$ nodes per move

- **Standard approach:**
  - **Cutoff test:** Depth limit (perhaps add quiescence search)

- **Evaluation function:**
  - Estimated desirability of position
Evaluation Functions

- Chess, typically linear weighted sum of features
  \[ \text{Eval}(s) = w_1 f_1(s) + w_2 f_2(s) + \ldots + w_n f_n(s) \]

- Example: \( w_1 = 9 \) with
  \[ f_1(s) = \text{(number of white queens)} - \text{(number of black queens)} \]
  etc.
Cutting-Off Search

MinimaxCutoff is identical to MinimaxValue except

1. Terminal? is replaced by Cutoff?
2. Utility is replaced by Eval

Does it work in practice?

\[ b^m = 10^6, b=35 \rightarrow m=4 \]

4-ply lookahead is a hopeless chess player!

- 4-ply ≈ human novice
- 8-ply ≈ typical PC, human master
- 12-ply ≈ Deep Blue, Kasparov
Quiescence search

- Quiescence search: Study moves that are noisy
- They appear good, but moves around them - bad
- Investigate them with a localized leaf search
- Attempt to identify delaying tactics and change the seemingly-good value of the node
- A very natural extension of mini-max
- Simply run search again at a leaf node until that leaf node becomes quiet
- As with iterative deepening, running time of the algorithm won’t increase by more than a constant
Real Deterministic Games

- **Checkers:** Chinook ended 40-year-reign of human world champion Marion Tinsley in 1994.
  - Used a precomputed endgame database
  - Defining perfect play for all positions involving 8 or fewer pieces on the board - a total of 444 billion positions.

- **Chess:** Deep Blue defeated human world champion Kasparov in a six-game match in 1997.
  - Deep Blue searches 200 million positions per second
  - Uses very sophisticated evaluation
  - Undisclosed methods for extending some lines of search up to 40 ply.
Move Ordering

- Best possible pruning is achieved if the best move is searched first at each level of the tree.
- Problem: If we knew the best move, we would not need to search!
- Thus, we employ move ordering heuristics, which search the best move first.
- **Example:** In Chess, search capturing moves before non-capturing moves.
- **What we want:** domain independent techniques.
Example: Poor Move Ordering
Example: Good Move Ordering
Principal Variation Move

- As it is a search algorithm, can apply Iterative Deepening to Mini-Max
- At each level, we thus find a move path we expect us and the opponent to take
- At the next stage, search it first!
  - Called **Principal Variation** move
- Even though Iterative Deepening takes some time, PV-move can greatly improve overall performance!
Other Heuristics

• **Killer Moves**: Remember move that produced a cut on this level of the tree
  – If we encounter it again, search it first!
  – Normally remember two moves per level

• **History Heuristic**: Same as Killer Moves, want to remember moves that produce cuts
  – Want to use info on all levels of tree
  – Hold array of counters, increment based on level cut occurred at
  – Details outside scope of this talk
Real Deterministic Games

- **Othello**: Human champions refuse to compete against computers, who are too good.
Things to Remember: Games

- Games are fun to work on!
- They illustrate several important points about AI
- Perfection is unattainable
- Must approximate paths and solutions
- Good idea to think about what to think about
Two Player to Multi-Player Games

• Mini-Max: Originally envisioned for Chess
  – Two player, deterministic, perfect information game

• What if we want to play a multi-player game?
  – Instead of two players, we have $N$ players, where $N > 2$
  – Examples: Chinese Checkers, Poker

• New challenges, requiring new techniques!
Qualities of Multi-Player Games

• In two player zero sum games, your gain is reflected in equal loss for opponent
  – No longer true for multi-player game
  – Loss spread between multiple opponents

• *Coalitions* may arise during play

• More opponent turns occur between perspectives
Extending Mini-Max to Multi-Player Games

• Problem: Mini-Max operates using a single value
  – Worked for two player games, as opponent's gain is our loss

• Single score very valuable – Allows pruning
  – Would like to keep pruning to speed up the search

• Simple solution: All opponents minimize our score
  – So, MAX-MIN-MIN, MAX-MIN-MIN-MIN, etc

• Called the Paranoid Algorithm
Paranoid Algorithm

Sample Paranoid Tree (Red MAX, Blue MIN)
function integer paranoid(node, depth):
    if node is terminal or depth <= 0 then
        return heuristic value of node
    else
        if node is max then
            \( val = -\infty \)
            for all child of node do
                \( val = \max(val, \text{paranoid}(\text{child}, \text{depth} - 1)) \)
            end for
        else
            \( val = \infty \)
            for all child of node do
                \( val = \min(val, \text{paranoid}(\text{child}, \text{depth} - 1)) \)
            end for
        end if
    end if
    return val
end if
Paranoid Algorithm

• Algorithm *exact same* as Mini-Max in many implementations

• Pros
  – Easy to implement and understand
  – Subject to \( \alpha-\beta \) pruning on MAX/MIN borders
  – Not for phases between MIN nodes

• Cons
  – Views all opponents as a coalition – leads to bad play
  – Limited look-ahead for perspective player
  – Need to have multiple MIN phases in a row
Max-N Algorithm

- 1986: Luckhardt and Irani
- Addresses coalition problem of Paranoid
- Keeps *tuple* of scores, not one value
- Assumption: Players maximize their *own* score
  - No consideration for other players

- Heuristic returns value for each player
  - i.e. [6, 3, 8] for three-player game

- $N$th player maximizes $N$th value
Max-N Algorithm

Sample Max-N Tree
Max-N Algorithm

function integer[] max-n(node, depth):
    if node is terminal or depth <= 0 then
        return heuristic value of node
    else
        val = −∞
        tuple = []
        for all child of node do
            val = max(val, max-n(child; depth − 1)[node.player])
            if val changed
                tuple = max-n(child; depth-1)
            end if
        end for
        return tuple
    end if
Max-N Algorithm

• In terms of raw Mini-Max, very simple extension

• Pros
  – Players “look out for number one”
  – More realistic play
  – Perspective player can see more opportunities
  – Reason: Possibilities are not excluded as readily

• Cons
  – Pruning is very complicated, and not as good
  – Can be worse than Paranoid due to decreased search depth
Best-Reply Search

• Relatively new: 2011 (Schadd and Winands)
• *All* opponents considered to be *one* player
  – They only get ONE turn between them

• Only opponent with best move is thought to act
• Return to MAX-MIN-MAX-MIN...
• Essentially a return to Mini-Max algorithm
  • With a very *powerful* opponent!!
Best-Reply Search

Sample BRS Tree (one level)
function integer best-reply(node, depth):
    if node is terminal or depth <= 0 then
        return heuristic value of node
    else
        if node is max then
            val = −∞
            for all child of node do
                val = max(val, best-reply(child; depth − 1))
            end for
        else
            val = ∞
            for all opponents do
                for all opponent’s child at node do
                    val = min(val; best-reply(child; depth − 1))
                end for
            end for
        end if
    end if
Best-Reply Search

• Attempt to get “best of both worlds”

• Pros
  – Balance between coalition and free-for-all
  – Allows $\alpha$-$\beta$ pruning
  – Significant lookahead for perspective player

• Cons
  – Illegal game states analyzed
  – Not applicable to some games
  – This is the domain of some current research (2015)
Adaptive Data Structures

- Other, completely unrelated field
- Concerned with record access frequency
- Problem:
  - Elements in data structure accessed with different frequency
- Solution:
  - Change the structure of the data structure as elements queried
- Can use list, tree or others
ADS – Move to Front Rule

Order of access: 3, 1, 1, 4, ...
Order of access: R3, R1, R1, ...
Our contribution, usable with the BRS

ADS operations are constant, and small

We use an ADS that contains opponents

When an opponent is found to have the most minimizing move, we query the ADS

ADS moves over time to relative opponent threats

When grouping moves, do it in the order of the ADS

Improves move ordering, leading to better pruning!
The Threat-ADS Heuristic

BRS with Threat-ADS (one level)
function integer brs_threat_ads(node, depth):
    if node is terminal or depth <= 0 then
        return heuristic value of node
    else
        if node is max then
            \( val = -\infty \)
            for all child of node do
                \( val = \max(val, \text{best-reply}(\text{child}; depth - 1)) \)
            end for
        else
            \( val = \infty \)
            for all opponents in ADS do
                for all opponent’s child at node do
                    \( val = \min(val; \text{best-reply}(\text{child}; depth - 1)) \)
                end for
            end for
            ADS.update(val.opponent)
        end if
    end if
Experimental Framework

- Game needed to test Threat-ADS heuristic
- Needs:
  - BRS must be applicable
  - Game should be simple to implement
- Use established games Focus and Chinese Checkers
- Also develop the Virus Game
Virus Game

• Turn based game with N players
• Played on 2D board
• Goal is to eliminate all other players
• Turn: Player “infects” a square they are adjacent to
• All nearby squares, according to a configured pattern, are given to that player
Experimental Configuration

- One player: BRS with Threat-ADS
- Others: Random (Interested in tree pruning)
- Take *Node Count* over first few turns of the game
  - Count each node expanded, but not those pruned
- Average over 50 games
- Run for each of three games mentioned
- Run over a variety of configurations
  - Varying number of players
  - Varying starting state
# Results (Initial Board State)

<table>
<thead>
<tr>
<th>Game</th>
<th>Threat-ADS?</th>
<th>Avg. Node Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Virus Game</td>
<td>No</td>
<td>264,000</td>
</tr>
<tr>
<td>Virus Game</td>
<td>Yes</td>
<td>237,000</td>
</tr>
<tr>
<td>Focus</td>
<td>No</td>
<td>6,859,000</td>
</tr>
<tr>
<td>Focus</td>
<td>Yes</td>
<td>6,443,000</td>
</tr>
<tr>
<td>Chinese Checkers</td>
<td>No</td>
<td>3,485,000</td>
</tr>
<tr>
<td>Chinese Checkers</td>
<td>Yes</td>
<td>3,070,000</td>
</tr>
</tbody>
</table>
## Results (Midgame Board State)

<table>
<thead>
<tr>
<th>Game</th>
<th>Threat-ADS?</th>
<th>Avg. Node Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Virus Game</td>
<td>No</td>
<td>307,000</td>
</tr>
<tr>
<td>Virus Game</td>
<td>Yes</td>
<td>275,000</td>
</tr>
<tr>
<td>Focus</td>
<td>No</td>
<td>14,460,000</td>
</tr>
<tr>
<td>Focus</td>
<td>Yes</td>
<td>13,050,000</td>
</tr>
<tr>
<td>Chinese Checkers</td>
<td>No</td>
<td>8,170,000</td>
</tr>
<tr>
<td>Chinese Checkers</td>
<td>Yes</td>
<td>7,680,000</td>
</tr>
</tbody>
</table>
Monte-Carlo Methods

• * Entirely* different way of looking at game playing
  – Applicable to two player and multi-player games

• No game heuristics required!

• Driven by *random game playing*
  – Strong when no good heuristic is available
  – Big example in research is Go

• Very simple example:
  – Play 50 random games for each move
  – Pick one with highest winrate
Monte-Carlo Tree Search

- Simple example above
  - Works for easy games
  - Look-ahead is useful
- Apply random game playing to game tree search
- Navigate:
  - From root to unvisited node
  - Then play random game(s)
- Path guided by exploration/exploitation balance
- At end of time, pick most promising move
- Very powerful: Relatively new compared to Mini-Max
**UCT Algorithm**

- Dominant Monte-Carlo Tree Search technique (2015)
- Starting from root:
  - If there is an unvisited child, pick it
  - Otherwise, pick child that maximizes \( \text{UCTValue} \)
    \[
    \text{UCTVal} = \text{winrate} + \sqrt{\ln(\text{parent.visits})/\text{visits}}
    \]
  - Repeat until an unvisited child is found
- Propagate winrate back up to root
- Repeat until time is up
- Pick move that has *highest winrate*
function integer uct(node, depth):
    for time-steps do
        position = root
        while position is explored
            val = −∞
            for child of position
                !– Unexplored node check here--!
                val = max(val, UCTValue(child))
                position = val.node
            end for
        end while
        Play random game(s) at child
        while position is not root
            update win-rate for player at node
            position = position.parent
        end while
    end for
Multi-Player UCT Algorithm

- **Very easy to extend**
  - We do not have to maintain heuristic values
  - UCT handles N-player games in its base form

- For the player making the move
  - Simply record winrate at each node
  - Assume player will pick move most likely to lead to win

- No change from previous algorithm
More on UCT Value

- UCTValue has two parts
- Winrate is self-explanatory
  - Value between 0.0 and 1.0 indicating proportion of wins
- Second part: $\text{sqrt}(\ln(\text{parent.visits})/\text{visits})$
- Specifics not important, but also between 0.0 and 1.0
- Goes *up* the less this child has been explored in relation to its parent
- Achieves exploration/exploitation balance!
- Sometimes constants usually added to tweak this
Applications of UCT

• Best performance available for Go
  – Top player is currently Zen
  – Defeated 9-dan player with three stone handicap

• Applied to wide range of games
  – Poker
  – Settlers of Catan
  – Magic: The Gathering