COMP250: Artificial Intelligence

7: Monte Carlo Tree Search

Heuristics for search

From session 2: Minimax search

```
procedure MINIMAX(state, currentPlayer)
    if state is terminal then
        return value of state
    else if currentPlayer is maximising then
        bestValue = −∞
        for each possible nextState do
            v = MINIMAX(nextState, 3− currentPlayer)
            bestValue = MAX(bestValue, v)
            if bestValue ≥ 1 then
                break
        return bestValue
    else if currentPlayer is minimising then
        bestValue = +∞
        for each possible nextState do
            v = MINIMAX(nextState, 3− currentPlayer)
            bestValue = MIN(bestValue, v)
            if bestValue ≤ −1 then
                break
        return bestValue
```

Minimax for larger games

- The game tree for noughts and crosses has only a few thousand states
- Most games are too large to search fully
  - Connect 4 has $\approx 10^{13}$ states
  - Chess has $\approx 10^{47}$ states

Depth limiting

- Standard minimax needs to search all the way to **terminal** (game over) states
- **Depth limiting** is a common technique to apply minimax to larger games
- Still evaluate terminal states as $+1$ / 0 / -1
- For nonterminal states at depth d, apply a heuristic evaluation instead of searching deeper
- Evaluation is a number between -1 and $+1$, estimating the probable outcome of the game

1-ply search

- Case $d = 1$
- For each move, evaluate the state resulting from playing that move
- This is computationally fast
- Often easier to design a “which state is better” heuristic than to directly design a “which move to play” heuristic

Designing heuristics

- The **playing strength** of depth limited minimax depends heavily on the design of the **heuristic**
- Good heuristic design requires **in-depth knowledge** of the tactics and strategy of the game
- What if we don't have that knowledge? ...

Monte Carlo evaluation

Expected value

- Let X be a **random variable**
- Let $p(x)$ be the probability that X has value x
- Then the **expected value** of X is

$$\sum_{x} x \cdot p(x)$$

Expected value — example

- A slot machine pays out:
  - \$1 with probability 0.05
  - \$5 with probability 0.03
  - \$10 with probability 0.02
  - Nothing with probability 0.9
- The expected payout is

$$1 \times 0.05 + 5 \times 0.03 + 10 \times 0.02 + 0 \times 0.9 = 0.4$$

  i.e. \$0.40
- What this means: if you play the slot machine N times, on average you will win $N \times \$0.40$

“Randomness” in computing

- Digital computers are **deterministic**, so there’s no such thing as true randomness
  - Cryptographically secure systems use an external source of randomness e.g. atmospheric noise, radioactive decay
- What we actually have are **pseudo-random number generators (PRNGs)**
- A PRNG is an algorithm which gives an **unpredictable** sequence of numbers based on a **seed**
- Sequence is **uniformly distributed**, i.e. all numbers have equal probability
- Seed is generally based on some source of **entropy**, e.g. system clock, mouse input, electronic noise

Monte Carlo methods

- In computing, a **Monte Carlo method** is an algorithm based on **averaging over random samples**
- The **average** over a large number of samples is a good approximation of the **expected value**
- Used for **quickly approximating** quantities over **large domains**
- Generally designed to **converge in the limit**
  - An **infinite** number of samples would give an **exact** answer
  - As the **number of samples** increases, the **accuracy** of the answer improves
- Applications in physics, engineering, finance, weather forecasting, graphics, ...

Monte Carlo evaluation in games

- Based on **random rollouts**

while s is not terminal **do**
  let m be a random legal move from s
  update s by playing m

- The **value** of a rollout is the **value** of the terminal state it reaches (i.e. 1 for a win, -1 for a loss, 0 for a draw)
- Averaging gives the **expected value** of the initial state
- Higher expected value $=$ more chance of winning

Monte Carlo search

- **Flat Monte Carlo search**: 1-ply search with Monte Carlo evaluation
- How about minimax with $d > 1$ and Monte Carlo evaluation?
  - Minimax assumes the evaluation is **deterministic**, but Monte Carlo is not
  - Not commonly used, mainly because there's something better...

Monte Carlo Tree Search

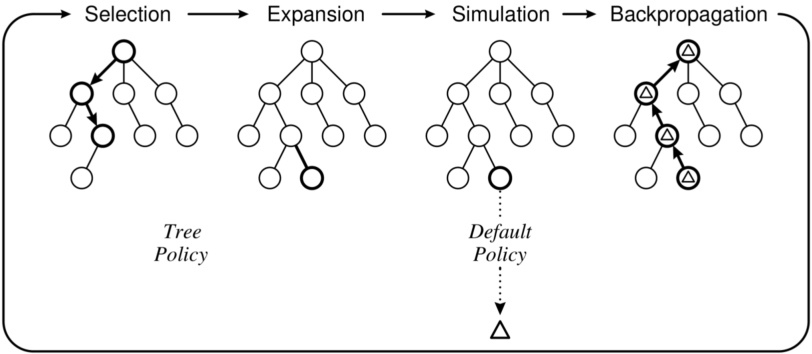
Monte Carlo Tree Search (MCTS)

- Like Monte Carlo evaluation, based on **rollouts**
- First few rollouts are **random**
- However, statistics from these rollouts are used to **bias** future rollouts
- Bias rollouts towards **plausible** lines of play, i.e. where each player is trying to play the best move

The MCTS algorithm

- MCTS builds a **tree**
- Initially, the tree consists of a single **root node**
- Each rollout has four stages:
  - **Selection**: Starting from the root, descend the tree by choosing moves. Continue until we reach a node which does not yet have children for all legal moves.
  - **Expansion**: Choose a random legal move for which the current node does not have a child node. Add this new node to the tree.
  - **Simulation**: Perform a Monte Carlo rollout, playing random moves until a terminal state is reached.
  - **Backpropagation**: For each node visited during **selection** and **expansion**, update the node's statistics based on the result of the simulation.
- Perform many rollouts, then use the statistics at the top level of the tree to choose the best move

The MCTS algorithm



Selection policy

- Selection must balance:
  - **Exploitation** of moves that are known to be good
  - **Exploration** of moves that have not often been tried
- This can be modelled as a **multi-armed bandit problem**

Multi-armed bandits

- We have a row of one-armed bandits (slot machines)
- We **do not know** the payout probabilities of any of them, and they're all different
- How to maximise our winnings?
- Again must balance
  - **Exploitation** of machines that are known to have a high expected payout
  - **Exploration** of machines that have not been tried often, to get a better estimate of their expected payout

Upper Confidence Bound (UCB)

- For each machine m, record:
  - n_m: the number of plays of this machine
  - V_m: the total winnings from playing this machine
  - $n = \sum_m n_m$, total number of plays across all machines
- At each stage, play the machine for which

$$\frac{V_m}{n_m} + c\sqrt{\frac{\log n}{n_m}}$$

is largest

  - $\frac{V_m}{n_m}$ is the **exploitation** part: average payout from this machine so far
  - $\sqrt{\frac{\log n}{n_m}}$ is the **exploration** part: large if n_m is small
  - c is a parameter for adjusting the balance between exploitation and exploration

UCB demo

http://orangehelicopter.com/academic/bandits.html?ucb

Upper Confidence Bound for Trees (UCT)

- Use UCB as the selection policy
- In each node x, record:
  - n_x: the number of visits to this node
  - V_x: the total value of rollouts through this node
- From node p, choose the child q such that

$$\frac{V_q}{n_q} + c\sqrt{\frac{\log n_p}{n_q}}$$

is largest

UCT demo

Benefits of MCTS

- "Vanilla" MCTS is **game independent**
- But if game-specific heuristics are available, they can be used to **enhance** MCTS
- MCTS is **anytime**
  - Can stop it after **any** amount of computation (within reason) and get a reasonably good answer
  - Compare with minimax: $O(e^d)$ for depth d
- Does not suffer from **horizon effect**
  - Minimax at depth d cannot "see" what happens $d + 1$ moves in the future
  - MCTS can build the tree as deep as it likes
  - Selects which parts of the tree to expand more deeply

MCTS for games of imperfect information