Game theory

Nim game, Minimax, Alpha-Beta pruning

beOI Training

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What is game theory?

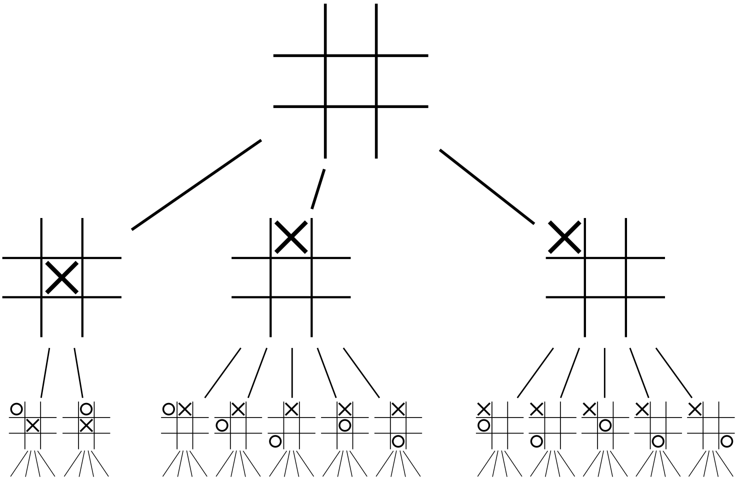
Modelling strategic situations:

- with conflict or cooperation
  - chess, football, pictionary, ...
- decisions based on personal goals
  - beating the opponent, maximizing points, ...
- influenced by the choice patterns of other players
  - if someone plays predictably, you can use it against them
- might involve randomness
  - dice rolls, card draws, ...

Goal: compute choices, optimal strategies, expected gains

Decision trees

A useful tool to examine decisions and their consequences.



Utility vectors and zero-sum games

Utility vectors:

- define the “gains” of an end state
- one entry per player: $(2, 3, -2)$, $(0, 7)$, ...
- determine the choices of players
  - player 1 will choose $(\mathbf{3}, 5)$ over $(\mathbf{2}, 3)$
- but not always!
  - should player 2 choose $(0, \mathbf{6}, 5)$ or $(2, \mathbf{6}, 3)$?

Main focus: two-player zero-sum games:

- only two players: no complicated interactions
- zero-sum: our benefits are the opponent’s losses
  - $(5, -5)$, $(-3, 3)$, $(0, 0)$, ... (or just 5, -3, 0)
- the value of a choice is always well-defined

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Subtraction game: rules

"Jeu des alumettes" in French, ??? in Dutch

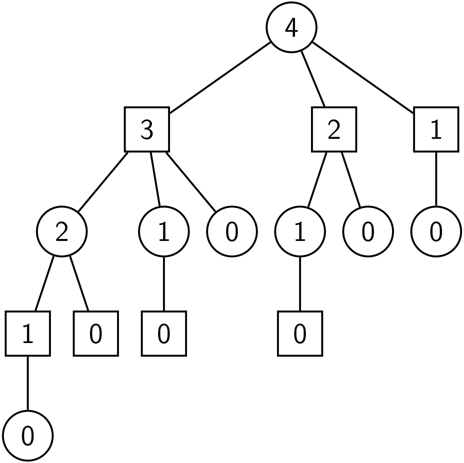
- At the beginning, n matches on the table
- Two players play in alternance
- At each turn they remove $1, 2, \ldots, k$ matches
- The player that takes the last match wins

Example with $k = 3$:

- At the beginning, $n = 8$ matches.
- Player A takes 2; remaining: 6.
- Player B takes 1; remaining: 4.
- Player A takes 3; remaining: 1.
- Player B takes 1 and wins.

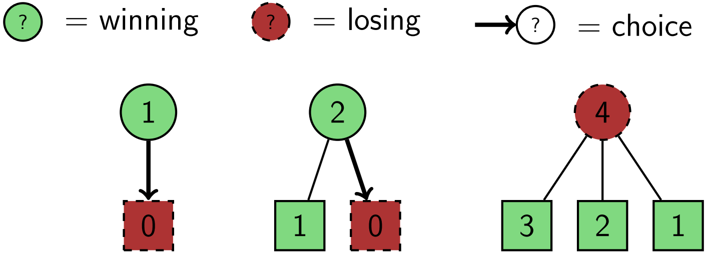
Subtraction game: decision tree

? = “A plays” $\boxed{?}$ = “B plays”

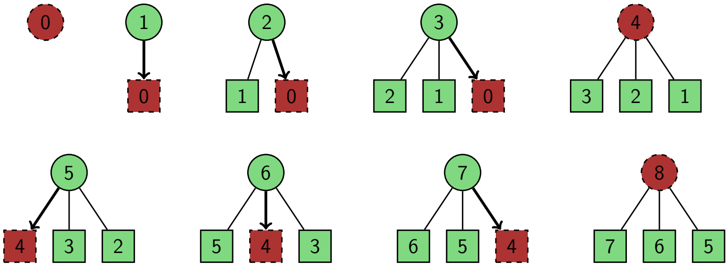


Winning states

- A winning state is a state such that the *current player* has winning strategy
- A state is winning iff one of the moves leads to a losing state for the opponent
- If all the next states are winning for the opponent, then we can't win!



Subtraction game: winning states



Observations:

- All multiples of $4 = k + 1$ are losing states
- All other states are winning because they point to a multiple of $k + 1$

Subtraction game: optimal play

If the number of matches is a multiple of $k+1$:

- all moves are bad;
- if the opponent plays perfectly you will certainly lose.

Otherwise:

- only one move is correct;
- remove matches *so that you leave* a multiple of $k+1$;
- if you play perfectly you will certainly win.

Examples of perfect moves (for $k=3$):

- $1 \to 0 \quad 2 \to 0 \quad 3 \to 0$
- $5 \to 5 \quad 6 \to 4 \quad 7 \to 4$
- $\ldots$

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Nim game: rules

Similar to subtraction game but:

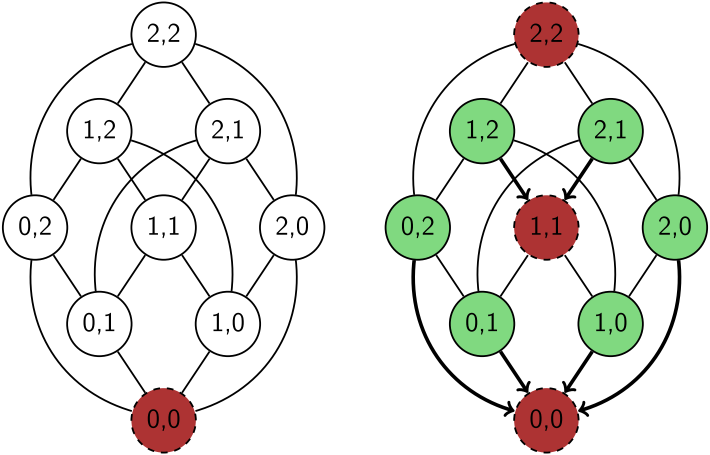
- More than one heap: sizes $(2,3)$, $(2,1,9)$.
- You can remove as many matches as you want but *from a single heap*.
- The player that empties the last heap wins.

Example with three heaps:

- At the beginning, there are three heaps: $(3,5,4)$.
- Player A takes 2 on heap 1; remaining: $(1,5,4)$.
- Player B empties heap 2; remaining: $(1,0,4)$.
- Player A takes 3 on heap 3; remaining: $(1,0,1)$.
- Player B empties heap 1; remaining: $(0,0,1)$.
- Player A empties heap 3 and wins.

Nim game: two heaps

Compute the winning/losing states in a bottom-up way.



(We make no distinction between players anymore.)

Nim game: the search of a losing criterion

For two heaps, we can see that losing states have heaps of equal size:

- if they are $\neq$, you can make them $=$;
  - $(5,2) \to (2,2) \quad (3,7) \to (3,3) \quad (4,0) \to (0,0)$
- if they are $=$, they will always become $\neq$;
  - $(2,2) \to (1,2),(0,2),(2,1),(2,0)$
- the game always ends at $(0,0)$.

What about more heaps? Any idea?
Examples of losing states: $(0,0,0)$, $(0,1,1)$, $(1,2,3)$, $(1,4,5)$, $(1,6,7)$, $(2,4,6)$, $(3,5,6)$, $(1,1,3,3)$, $(1,3,5,7)$, $(2,3,6,7)$, $(4,5,6,7)$, $(3,3,4,4)$, ...

Nim game: key invariant

A state $(n_1, \ldots, n_l)$ is losing iff $n_1 \oplus \cdots \oplus n_l = 0$. **WHAT?**

For example: $(3, 5, 6)$ is losing because

$$3_{10} \oplus 5_{10} \oplus 6_{10} = 011_2 \oplus 101_2 \oplus 110_2 = 000_2$$

We call this the *nim-sum*.

We need to prove this:

- The ending situation has a zero nim-sum (clear).
- During one move:
  - When the nim-sum is zero, we cannot keep it zero.
  - When the nim-sum is not zero, we can make it zero.

Nim game: losing situation

"When the nim-sum is zero, we cannot keep it zero."

- Before the move: $n_1 \oplus \cdots \oplus n_l = 0$
- We take matches from heap i: $n_i \to n_i'$
- After the move:

$$\begin{aligned}
n_1 \oplus & \cdots \oplus n_i' \oplus \cdots \oplus n_l \\
&= n_1 \oplus \cdots \oplus (n_i \oplus n_i \oplus n_i') \oplus \cdots \oplus n_l \\
&= (n_1 \oplus \cdots \oplus n_i' \oplus \cdots \oplus n_l) \oplus (n_i \oplus n_i') \\
&= n_i \oplus n_i' \\
&\neq 0
\end{aligned}$$

Nim game: winning situation

"When the nim-sum is not zero, we can make it zero."

- Before the move: $n_1 \oplus \cdots \oplus n_l = s \neq 0$
- If we can replace some n_i with $n_i \oplus s$, we win!
- But it has to verify $n_i \oplus s < n_i$ (we cannot add matches).
- Let `1<<j` be the largest bit in s. We just have to take n_i that contains the bit `1<<j`. This implies $n_i \oplus s < n_i$.
- Example: state $(7, 8, 13)$.

$$7_{10} \oplus 8_{10} \oplus 13_{10} = 0111_2 \oplus 1000_2 \oplus 1101_2 = 00\mathbf{1}0_2$$

Only $7_{10} = 01\mathbf{1}1_2$ has the required bit.

$$01\mathbf{1}1_2 \oplus 00\mathbf{1}0_2 = 01\mathbf{0}1_2 = 5_{10} < 7_{10}$$

Next state: $(5, 8, 13)$.

Win/lose games: general conclusions

Frequent properties of simple win-or-lose games:

- Few losing states, many winning states
  - because one losing child is enough
- Losing states defined by a specific property
  - n divisible by $k+1$, $n_1 \oplus \cdots \oplus n_l = 0$, ...
- The property can always be *restored* when broken
  - this defines the winning strategy
- But it can never be *kept* by a move
  - the losing player can never turn the game around

Exercise: solve this subtraction/Nim mashup.

- Several heaps with sizes $(n_1, \ldots, n_l)$.
- You can $1, 2, \ldots, k$ matches from a single heap.

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Minimax principles

Minimax example

Minimax implementation

Minimax with DP

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Very large search spaces

Alpha-beta definition

Alpha-beta example

Alpha-beta implementation

Sources of figures

- https://commons.wikimedia.org/wiki/File:Tic-tac-toe-game-tree.svg