

# Combinatorial Games

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## Combinatorial Games

- ▶ Turn-based competitive multi-player games
- ▶ Can be a simple win-or-lose game, or can involve points
- ▶ Everyone has perfect information
- ▶ Each turn, the player changes the current “state” using a valid “move”
- ▶ At some states, there are no valid moves
  - The current player immediately loses at these states

# Outline

Simple Games

Minimax Algorithm

Nim Game

Grundy Numbers (Nimbers)

## Combinatorial Game Example

- ▶ Settings: There are  $n$  stones in a pile. Two players take turns and remove 1 or 3 stones at a time. The one who takes the last stone wins. Find out the winner if both players play perfectly
- ▶ State space: Each state can be represented by the number of remaining stones in the pile
- ▶ Valid moves from state  $x$ :  $x \rightarrow (x - 1)$  or  $x \rightarrow (x - 3)$ , as long as the resulting number is nonnegative
- ▶ State 0 is the losing state

## Example (continued)

- ▶ No cycles in the state transitions
  - Can solve the problem bottom-up (DP)
- ▶ A player wins if there is a way to force the opponent to lose
  - Conversely, we lose if there is no such a way
- ▶ State  $x$  is a winning state (W) if
  - $(x - 1)$  is a losing state,
  - OR  $(x - 3)$  is a losing state
- ▶ Otherwise, state  $x$  is a losing state (L)

## Example (continued)

- ▶ DP table for small values of  $n$ :

$n$	0	1	2	3	4	5	6	7
W/L	L	W	L	W	L	W	L	W

- ▶ See a pattern?
- ▶ Let's prove our conjecture

## Example (continued)

- ▶ Conjecture: If  $n$  is odd, the first player wins. If  $n$  is even, the second player wins.
- ▶ Holds true for the base case  $n = 0$
- ▶ In general,
  - If  $n$  is odd, we can remove one stone and give the opponent an even number of stones
  - If  $n$  is even, no matter what we choose, we have to give an odd number of stones to the opponent

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## More Complex Games

- ▶ Settings: a competitive zero-sum two-player game
  - ▶ Zero-sum: if the first player's score is  $x$ , then the other player gets  $-x$
  - ▶ Each player tries to maximize his/her own score
  - ▶ Both players play perfectly
- 
- ▶ Can be solved using a *minimax* algorithm

## Minimax Algorithm

- ▶ Recursive algorithm that decides the best move for the current player at a given state
- ▶ Define  $f(S)$  as the optimal score of the current player who starts at state  $S$
- ▶ Let  $T_1, T_2, \dots, T_m$  be states can be reached from  $S$  using a single move
- ▶ Let  $T$  be the state that minimizes  $f(T_i)$
- ▶ Then,  $f(S) = -f(T)$ 
  - Intuition: minimizing the opponent's score maximizes my score

## Memoization

- ▶ (Not *memorization* but *memoization*)
- ▶ A technique used to avoid repeated calculations in recursive functions
- ▶ High-level idea: take a note (memo) of the return value of a function call. When the function is called with the same argument again, return the stored result
- ▶ Each subproblem is solved at most once
  - Some may not be solved at all!

## Recursive Function without Memoization

```
int fib(int n)
{
    if(n <= 1) return n;
    return fib(n - 1) + fib(n - 2);
}
```

- How many times is `fib(1)` called?

## Memoization using `std::map`

```
map<int, int> memo;  
int fib(int n)  
{  
    if(memo.count(n)) return memo[n];  
    if(n <= 1) return n;  
    return memo[n] = fib(n - 1) + fib(n - 2);  
}
```

- How many times is `fib(1)` called?

## Minimax Algorithm Pseudocode

- ▶ Given state  $S$ , want to compute  $f(S)$
- ▶ If we know  $f(S)$  already, return it
- ▶ Set return value  $x \leftarrow -\infty$
- ▶ For each valid next state  $T$ :
  - Update return value  $x \leftarrow \max\{x, -f(T)\}$
- ▶ Write a memo  $f(S) = x$  and return  $x$

## Possible Extensions

- ▶ The game is not zero-sum
  - Each player wants to maximize his own score
  - Each player wants to maximize the difference between his score and the opponent's
- ▶ There are more than two players
- ▶ All of above can be solved using a similar idea

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## Nim Game

- ▶ Settings: There are  $n$  piles of stones. Two players take turns. Each player chooses a pile, and removes any number of stones from the pile. The one who takes the last stone wins. Find out the winner if both players play perfectly
- ▶ Can't really use DP if there are many piles, because the state space is huge

## Nim Game Example

- ▶ Starts with heaps of 3, 4, 5 stones
  - We will call them heap A, heap B, and heap C
- ▶ Alice takes 2 stones from A:  $(1, 4, 5)$
- ▶ Bob takes 4 from C:  $(1, 4, 1)$
- ▶ Alice takes 4 from B:  $(1, 0, 1)$
- ▶ Bob takes 1 from A:  $(0, 0, 1)$
- ▶ Alice takes 1 from C and wins:  $(0, 0, 0)$

## Solution to Nim

- ▶ Given heaps of size  $n_1, n_2, \dots, n_m$
- ▶ The first player wins if and only if the *nim-sum*  
 $n_1 \oplus n_2 \oplus \dots \oplus n_m$  is nonzero ( $\oplus$  is bitwise XOR operator)
- ▶ Why?
  - If the nim-sum is zero, then whatever the current player does, the nim-sum of the next state is nonzero
  - If the nim-sum is nonzero, it is possible to force it to become zero (not obvious, but true)

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## Playing Multiple Games at Once

- Suppose that multiple games are played at the same time. At each turn, the player chooses a game and make a move. You lose if there is no possible move. We want to determine the winner

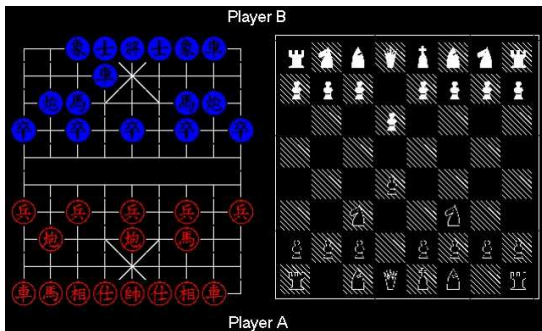


Figure from <http://sps.nus.edu.sg/~limchuwe/cgt/>

## Grundy Numbers (Nimbers)

- ▶ For each game, we compute its *Grundy number*
- ▶ The first player wins if and only if the XOR of all the Grundy numbers is nonzero
  - For example, the Grundy number of a one-pile version of the nim game is equal to the number of stones in the pile (we will see this again later)
- ▶ Let's see how to compute the Grundy numbers for general games

## Grundy Numbers

- ▶ Let  $S$  be a state, and  $T_1, T_2, \dots, T_m$  be states can be reached from  $S$  using a single move
- ▶ The Grundy number  $g(S)$  of  $S$  is the smallest nonnegative integer that doesn't appear in  $\{g(T_1), g(T_2), \dots, g(T_m)\}$ 
  - Note: the Grundy number of a losing state is 0
  - Note: I made up the notation  $g(\cdot)$ . Don't use it in other places

## Grundy Numbers Example

- ▶ Consider a one-pile nim game
- ▶  $g(0) = 0$ , because it is a losing state
- ▶ State 0 is the only state reachable from state 1, so  $g(1)$  is the smallest nonnegative integer not appearing in  $\{g(0)\} = \{0\}$ .  
Thus,  $g(1) = 1$
- ▶ Similarly,  $g(2) = 2$ ,  $g(3) = 3$ , and so on
- ▶ Grundy numbers for this game is then  $g(n) = n$ 
  - That's how we got the nim-sum solution



## Another Example

- ▶ Let's consider a variant of the game we considered before; only 1 or 2 stones can be removed at each turn
- ▶ Now we're going to play many copies of this game at the same time
- ▶ Grundy number table:

$n$	0	1	2	3	4	5	6	7
$g(n)$	0	1	2	0	1	2	0	1

## Another Example (continued)

- ▶ Grundy number table:

$n$	0	1	2	3	4	5	6	7
$g(n)$	0	1	2	0	1	2	0	1

- ▶ Who wins if there are three piles of stones  $(2, 4, 5)$ ?
- ▶ What if we start with  $(5, 11, 13, 16)$ ?
- ▶ What if we start with  $(10^{100}, 10^{200})$ ?

## Tips for Solving Game Problems

- ▶ If the state space is small, use memoization
- ▶ If not, print out the result of the game for small test data and look for a pattern
  - This actually works really well!
- ▶ Try to convert the game into some nim-variant
- ▶ If multiple games are played at once, use Grundy numbers