

IMPARTIAL ACHIEVEMENT & AVOIDANCE GAMES FOR GENERATING FINITE GROUPS

DePaul Mathematical Sciences Colloquium

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Joint work with Bret Benesh and Nándor Sieben

Intuitive Definition

Combinatorial Game Theory (CGT) is the study of two-person games satisfying:

- Two players alternate making moves.
- No hidden information.
- No random moves.

Combinatorial games

- Chess
- Go
- Connect Four
- Nim
- Tic-Tac-Toe
- X-Only Tic-Tac-Toe

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Non-combinatorial games

- Battleship (hidden information)
- Rock-Paper-Scissors (non-alternating and random)
- Poker (hidden information and random)

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Partizan

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- Go
- Connect Four
- Tic-Tac-Toe

Impartial

- Nim
- X-Only Tic-Tac-Toe

Comments

- We are interested in impartial games.
- We will require that game sequence is finite and there are no ties.
- When analyzing games, we will assume that both players make optimal moves.
- Player that moves first is called α and second player is called β .
- **Normal Play:** The last player to move wins.
- **Misère Play:** The last player to move loses.

Single-pile Nim

Start with a pile of n stones. Each player chooses at least one stone from the pile. The player that takes the last stone wins. Game is denoted $*n$ (called a **nimber**).



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Multi-pile Nim

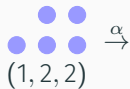
Start with k piles consisting of n_1, \dots, n_k stones, respectively. Each player chooses at least one stone from a single pile. The player that takes the last stone wins. Denoted $*n_1 + \dots + *n_k$.

Example

Let's play $*1 + *2 + *2$. Here's a possible sequence.

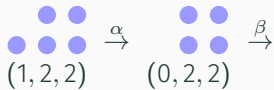
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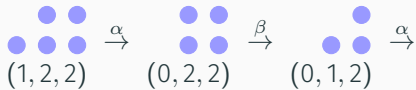
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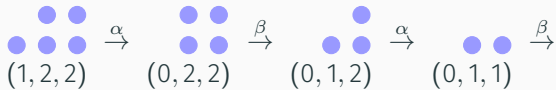
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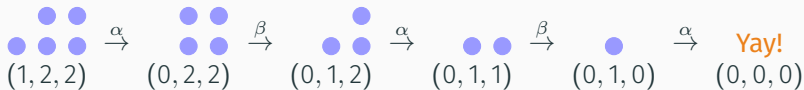
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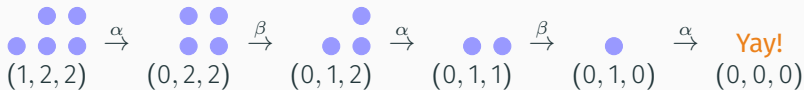
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Question

In general, is there an optimal strategy for either player?

Answer

Short answer is yes: write sizes of piles in binary, do binary addition without carry (XOR), and if possible, hand your opponent a sum of 0. If players make optimal moves, this is only possible for one of the players.

Definition

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From perspective of the player that is about to move, a **P-position** is a **losing position** while an **N-position** is a **winning position**.

Examples

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If G and H are games, then $G + H$ is the game where each player makes a move in one of the games. Set of options:

$$\text{Opt}(G + H) := \{Q + H \mid Q \in \text{Opt}(G)\} \cup \{G + S \mid S \in \text{Opt}(H)\}$$

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Proof



Copy cat.

Definition

$G_1 = G_2$ if and only if $G_1 + G_2$ is a P-position.

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Theorem

$G_1 = G_2$ if and only if $G_1 + H$ and $G_2 + H$ have the same outcome for all H .

Definition

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Examples

- $\text{mex}(\{0, 1, 2, 4, 5\}) = 3$
- $\text{mex}(\{1, 3\}) = 0$
- $\text{mex}(\{0, 1\}) = 2$
- $\text{mex}(\emptyset) = 0$

Definition

If G is a game, then

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This is a recursive definition. We start computing with terminal positions (empty option set).

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Examples

- $\text{nim}(*0) = \text{mex}(\emptyset) = 0$
- $\text{nim}(*1) = \text{mex}(\{\text{nim}(*0)\}) = \text{mex}(\{0\}) = 1$
- $\text{nim}(*2) = \text{mex}(\{\text{nim}(*0), \text{nim}(*1)\}) = \text{mex}(\{0, 1\}) = 2$
- $\text{nim}(*n) = n$
- $\text{nim}(*1 + *1) = \text{mex}(\{\text{nim}(*1)\}) = \text{mex}(\{1\}) = 0$
- $\text{nim}(*1 + *2) = \text{mex}(\{\text{nim}(*2), \text{nim}(*1), \text{nim}(*1 + *1)\})$
 $= \text{mex}(\{2, 1, 0\}) = 3$

Theorem (Sprague–Grundy)

Every game is equivalent to a single Nim pile: $G = * \text{nim}(G)$

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Big Picture

Fundamental problem in the theory of impartial combinatorial games is the determination of the nim-number of the game.

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Loosely speaking, we can think of nim-numbers as “isomorphism” classes of games.

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Big Picture

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Theorem

2nd player β wins G if and only if $G = *0$.

Let G be a finite (possibly trivial) group.

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Generate Game

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- 1st player chooses any $g_1 \in G$.
- At k th turn, designated player selects $g_k \in G \setminus \{g_1, \dots, g_{k-1}\}$ to create position $\{g_1, \dots, g_k\}$.
- Player wins on the n th turn if $\langle g_1, \dots, g_n \rangle = G$.

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Positions of $\text{GEN}(G)$ are subsets of terminal positions, which are certain generating sets of G .

MATCH-UP



Name: LeBron James

Bret Benesh

Height: 6'8"

6'5"

Weight: 260 lbs

180 lbs

Age: 32 years

>32 years

Salary: \$30.96 million/year

\$0 million/year

Accolades: 3x NBA Champion
4x NBA MVP
2x Olympic gold medalist
11x NBA All-Star

Never had a cavity
Sagittarius

LEBRON VS BRET: GAME ONE

GEN on $S_3 = \{e, (1, 2), (1, 3), (2, 3), (1, 2, 3), (1, 3, 2)\}$



LeBron

P

$\langle P \rangle$

Bret

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GEN on $S_3 = \{e, (1, 2), (1, 3), (2, 3), (1, 2, 3), (1, 3, 2)\}$



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$(1, 2)$	$\{(1, 2, 3), (1, 3, 2), (1, 2)\}$	S_3	

Let G be a finite nontrivial group.

Do Not Generate Game

For the **avoidance game** $\text{DNG}(G)$:

- 1st player chooses $g_1 \in G$ such that $\langle g_1 \rangle \neq G$.
- At the k th turn, designated player selects $g_k \in G \setminus \{g_1, \dots, g_{k-1}\}$ such that $\langle g_1, \dots, g_k \rangle \neq G$ to create position $\{g_1, \dots, g_k\}$.
- Player that cannot select an element without building a generating set is loser.

Positions of $\text{DNG}(G)$ are exactly the non-generating subsets of G and terminal positions are the maximal subgroups of G .

LEBRON VS BRET: GAME TWO

DNG on $S_3 = \{e, (1, 2), (1, 3), (2, 3), (1, 2, 3), (1, 3, 2)\}$



LeBron

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LEBRON VS BRET: GAME THREE

DNG on $D_8 = \langle r, s \rangle = \{e, r, r^2, r^3, s, rs, r^2s, r^3s\}$



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	$\{r^2\}$	\mathbb{Z}_2	r^2
r^3	$\{r^2, r^3\}$	\mathbb{Z}_4	

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LeBron	P	$\langle P \rangle$	Bret
r^3	$\{r^2\}$	\mathbb{Z}_2	r^2
	$\{r^2, r^3\}$	\mathbb{Z}_4	
	$\{r^2, r^3, e\}$	\mathbb{Z}_4	e

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r	$\{r^2, r^2, e, r\}$	\mathbb{Z}_4	

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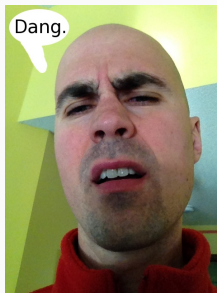
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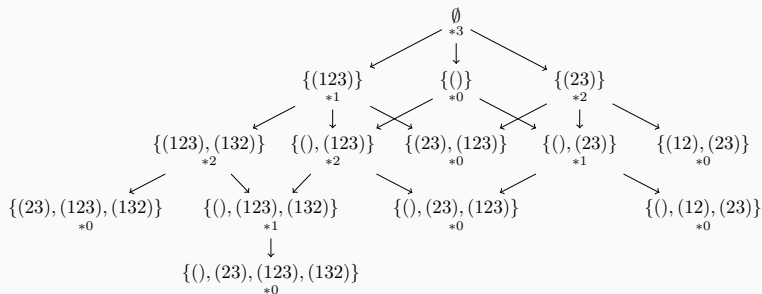
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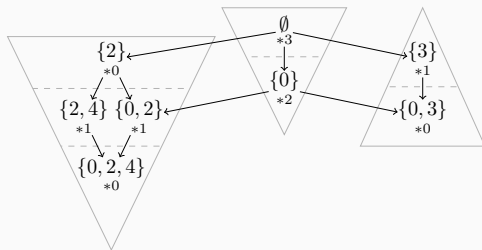
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- 1988: Barnes establishes **element-based criteria** for who wins DNG, assorted GEN results.
- 2014: Ernst and Sieben determine nim-numbers (and hence outcomes) for cyclic, dihedral, abelian.
- 2016: Benesh, Ernst, and Sieben establish **subgroup-based criteria** for the determination of nim-numbers (and hence outcomes) for DNG, characterize **spectrum of nim-numbers for DNG**, determine nim-numbers for GEN and DNG for a variety of groups including generalized dihedral, symmetric, and alternating groups.

REPRESENTATIVE GAME TREES

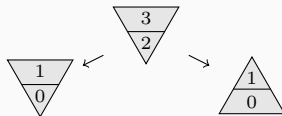


Representative game tree for $\text{GEN}(S_3) = *3$

STRUCTURE DIAGRAMS

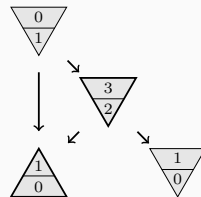
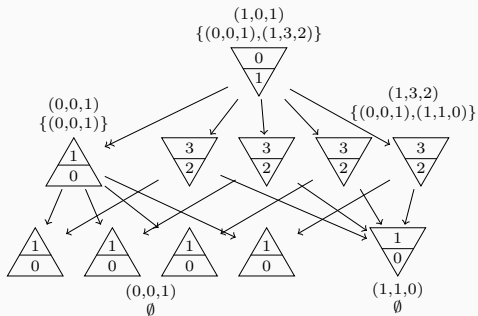
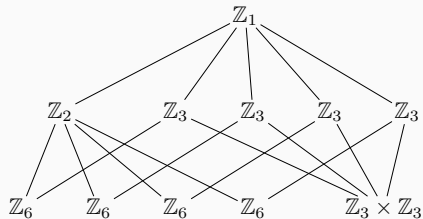


$\text{DNG}(\mathbb{Z}_6)$



Structure diagram

SIMPLIFIED STRUCTURE DIAGRAMS

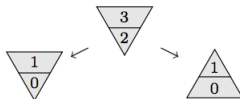


$DNG(\mathbb{Z}_6 \times \mathbb{Z}_3)$

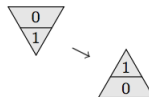
SIMPLIFIED STRUCTURE DIAGRAMS



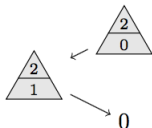
(a) $\text{DNG}(\mathbb{D}_{4k})$



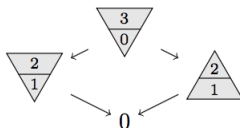
(b) $\text{DNG}(\mathbb{D}_{2k+1})$



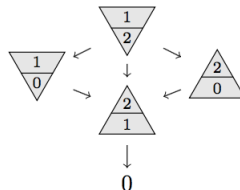
(c) $\text{DNG}(\mathbb{D}_{4k+2})$



(d) $\text{GEN}(\mathbb{D}_{4k})$



(e) $\text{GEN}(\mathbb{D}_{2k+1})$



(f) $\text{GEN}(\mathbb{D}_{4k+2})$

Simplified structure diagrams for dihedral groups

Theorem (Ernst, Sieben)

If $n \geq 2$, then $\text{nim}(\text{GEN}(\mathbb{Z}_n)) = \text{nim}(\text{DNG}(\mathbb{Z}_n)) + 1$.

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If $n \geq 2$, then

$$\text{DNG}(\mathbb{Z}_n) = \begin{cases} *1, & n = 2 \\ *1, & n \equiv_2 1 \\ *0, & n \equiv_4 0 \\ *3, & n \equiv_4 2 \end{cases}$$

and

$$\text{GEN}(\mathbb{Z}_n) = \begin{cases} *2, & n = 2 \\ *2, & n \equiv_2 1 \\ *1, & n \equiv_4 0 \\ *4, & n \equiv_4 2 \end{cases}$$

Theorem (Ernst, Sieben)

For $n \geq 3$, we have

$$\text{DNG}(\mathbb{D}_n) = \begin{cases} *3, & n \equiv_2 1 \\ *0, & n \equiv_2 0 \end{cases}$$

and

$$\text{GEN}(\mathbb{D}_n) = \begin{cases} *3, & n \equiv_2 1 \\ *0, & n \equiv_4 0 \\ *1, & n \equiv_4 2 \end{cases}$$

Theorem (Ernst, Sieben)

If G is a finite nontrivial abelian group, then

$$\text{DNG}(G) = \begin{cases} *1, & G \text{ is nontrivial of odd order} \\ *1, & G = \mathbb{Z}_2 \\ *3, & G = \mathbb{Z}_2 \times \mathbb{Z}_{2k+1} \text{ with } k \geq 1 \\ *0, & \text{else} \end{cases}$$

$$\text{GEN}(G) = \begin{cases} *2, & |G| \text{ is odd and } d(G) \leq 2 \\ *1, & |G| \text{ is odd and } d(G) \geq 3 \\ *2, & G = \mathbb{Z}_2 \\ *1, & G = \mathbb{Z}_{4k} \text{ with } k \geq 1 \\ *4, & G = \mathbb{Z}_{4k+2} \text{ with } k \geq 1 \\ *1, & G = \mathbb{Z}_2 \times \mathbb{Z}_2 \times \mathbb{Z}_m \times \mathbb{Z}_k \text{ for } m, k \text{ odd} \\ *0, & \text{else} \end{cases}$$

Theorem (Ernst, Sieben)

- If G is any finite nontrivial group, then $\text{DNG}(G)$ is $*0$, $*1$, or $*3$.

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Conjecture (In Progress)

If $|G|$ is even, then $\text{GEN}(G)$ is one of $*0$, $*1$, $*2$, $*3$, $*4$.

Theorem (Benesh, Ernst, Sieben)

Let G be a finite nontrivial group.

- If all maximal subgroups are even, then $\text{DNG}(G) = *0$.
- If all maximal subgroups are odd, then $\text{DNG}(G) = *1$.
- If mixed maximal subgroups, then
 - If the even maximals cover G , then $\text{DNG}(G) = *0$.
 - If the even maximals do not cover G , then $\text{DNG}(G) = *3$.

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Using our “checklist” criteria, we have completely characterized DNG for nilpotent, generalized dihedral, generalized quaternion, symmetric, Coxeter, alternating, and some Rubik’s cube groups.

Big Picture for DNG

- The players just race to fill up one maximal subgroup M .
- **The beginning of the game is a struggle to determine M .**
- α wants $|M|$ to be odd.
- β wants $|M|$ to be even.

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- **The beginning of the game is a struggle to determine M .**
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Strategy

- α wants to pick an element not in any maximal subgroups of even order.
- β wants to pick an involution.

What's left to work on?

- Wrap up spectrum of GEN?
- Wrap up characterization of GEN for nilpotent groups?
- Are there nice results for products and quotients?
- Is it possible to characterize the nim-numbers of GEN in terms of covering conditions by maximal subgroups similar to what we did for DNG?
- What about other “closure systems”? We are currently tinkering with convex hulls of finitely many points in the plane.

Thanks!