Limited Information Strategies for Topological Games

by

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Abstract

I talk a lot about topological games.

TODO: Write this.

Acknowledgments

TODO: Thank people.

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Chapter 1

Introduction

Basic overview of combinatorial games, topological games, limited info strategies, and applications in topology.

Chapter 2

Toplogical Games and Strategies of Perfect and Limited Information

The goal of this paper is to explore the applications of limited information strategies in existing topological games. There are a variety of frameworks for modeling such games, so we establish one within this chapter which we will use for this manuscript.

2.1 Games

Intuitively, the games studied in this paper are two-player games for which each player takes turns making a choice from a set of possible moves. At the conclusion of the game, the choices made by both players are examined, and one of the players is declared the winner of that playthrough.

Games may be modeled mathematically in various ways, but we will find it convenient to think of them in terms defined by Gale and Stewart. [2]

Definition 1. A *game* is a tuple $\langle M, W \rangle$ such that $W \subseteq M^\omega$. M is set of *moves* for the game, and M^ω is the set of all possible *playthroughs* of the game.

W is the set of *winning playthroughs* or *victories* for the first player, and $M^\omega \setminus W$ is the set of victories for the second player. (W is often called the *payoff set* for the first player.)

Within this model, we may imagine two players $\mathscr{A}$ and $\mathscr{B}$ playing a game which consists of *rounds* enumerated for each $n < \omega$. During round n, $\mathscr{A}$ chooses $a_n \in M$, followed by $\mathscr{B}$ choosing $b_n \in M$. The playthrough corresponding to those choices would be the sequence $p = \langle a_0, b_0, a_1, b_1, \ldots \rangle$. If $p \in W$, then $\mathscr{A}$ is the winner of that playthrough, and if $p \notin W$, then $\mathscr{B}$ is the winner. Note that no ties are allowed.

Rather than explicitly defining W, we typically define games by declaring the *rules* that each player must follow and the *winning condition* for the first player. Then a playthrough is in W if either the first player made only *legal moves* which observed the game's rules and the playthrough satisified the winning condition, or the second player made an *illegal move* which contradicted the game's rules.

As an illustration, we could model a game of chess (ignoring stalemates) by letting

$$M = \{\langle p, s\rangle : p \text{ is a chess piece and } s \text{ is a space on the board } \}$$

representing moving a piece p to the space s on the board. Then the rules of chess restict White from moving pieces which belong to Black, or moving a piece to an illegal space on the board.[1] The winning condition could then "inspect" the resulting positions of pieces on the board after each move to see if White attained a checkmate. This winning condition along with the rules implicitly define the set W of winning playthroughs for White.

2.1.1 Infinite and Topological Games

Games never technically end within this model, since playthroughs of the game are infinite sequences. However, for all practical purposes many games end after a finite number of turns.

Definition 2. A game is said to be an *finite game* if for every playthrough $p \in M^\omega$ there exists a round $n < \omega$ such that $[p \upharpoonright n] = \{q \in M^\omega : q \supseteq p \upharpoonright n\}$ is a subset of either W or $M^\omega \setminus W$.

Put another way, a finite game is decided after a finite number of rounds, after which the game's winner could not change even if further rounds were played. Games which are not finite are called *infinite games*.

[1] In practice, M is often defined as the union of two sets, such as white pieces and black pieces in chess. For example, the first player may choose open sets in a topology, while the second player chooses points within the topological space.

As an illustration of an infinite game, we may consider a simple example due to Baker [1].

Game 3. Let $Lim_{A,B}(X)$ denote a game with players $\mathscr{A}$ and $\mathscr{B}$, defined for each subset $A \subset \mathbb{R}$. In round 0, $\mathscr{A}$ chooses a number a_0, followed by $\mathscr{B}$ choosing a number b_0 such that $a_0 < b_0$. In round $n+1$, $\mathscr{A}$ chooses a number a_{n+1} such that $a_n < a_{n+1} < b_n$, followed by $\mathscr{B}$ choosing a number b_{n+1} such that $a_{n+1} < b_{n+1} < b_n$.

$\mathscr{A}$ wins the game if the sequence $\langle a_n : n < \omega \rangle$ limits to a point in X, and $\mathscr{B}$ wins otherwise.

Certainly, $\mathscr{A}$ and $\mathscr{B}$ will never be in a position without (infinitely many) legal moves available, and provided that A is non-trivial, there is a playthrough such that for all $n < \omega$, the segment (a_n, b_n) intersects both A and $\mathbb{R} \setminus A$. Such a playthrough could never be decided in a finite number of moves, so the winning condition considers the infinite sequence of moves made by the players and declares a victor at the "end" of the game.

Definition 4. A *topological game* is a game defined in terms of an arbitrary topological space.

Topological games are usually infinite games, ignoring trivial examples. One of the earliest examples of a topological game is the Banach-Mazur game, proposed by Stanislaw Mazur as Problem 43 in Stefan Banach's Scottish Book (1935). A more comprehensive history of the Banacy-Mazur and other topological games may be found in Telgarsky's survey on the subject [6].

The original game was defined for subsets of the real line; however, we give a more general definition here.

Game 5. Let $Empty_{E,N}(X)$ denote the *Banach-Mazur game* with players $\mathscr{E}$, $\mathscr{N}$ defined for each topological space X. In round 0, $\mathscr{E}$ chooses a nonempty open set $E_0 \subseteq X$, followed by $\mathscr{N}$ choosing a nonempty open subset $N_0 \subseteq E_0$. In round $n+1$, $\mathscr{E}$ chooses a nonempty open subset $E_{n+1} \subseteq N_n$, followed by $\mathscr{N}$ choosing a nonempty open subset $N_{n+1} \subseteq E_{n+1}$.

$\mathscr{E}$ wins the game if $\bigcap_{n<\omega} E_n = \emptyset$, and $\mathscr{N}$ wins otherwise.

For example, if X is a locally compact Hausdorff space, $\mathscr{N}$ can "force" a win by choosing N_0 such that $\overline{N_0}$ is compact, and choosing N_{n+1} such that $N_{n+1} \subseteq \overline{N_{n+1}} \subseteq O_{n+1} \subseteq N_n$ (possible since N_n is a compact Hausdorff $\Rightarrow$ normal space). Since $\bigcap_{n<\omega} E_n = \bigcap_{n<\omega} N_n$ is the decreasing intersection of compact sets, it cannot be empty.

This concept of when (and how) a player can "force" a win in certain topological games is the focus of this manuscript.

2.2 Strategies

We shall make the notion of forcing a win in a game rigorous by introducing "strategies" and "attacks" for games.

Definition 6. A *strategy* for a game $G = \langle M, W \rangle$ is a function from $M^{<\omega}$ to M.

Definition 7. An *attack* for a game $G = \langle M, W \rangle$ is a function from ω to M.

Intuitively, a strategy is a rule for one of the players on how to play the game based upon the previous (finite) moves of her opponent, while an attack is a fixed strike by an opponent indexed by round number.

Definition 8. The *result* of a game given a strategy σ for the first player and an attack $\langle a_0, a_1, \ldots \rangle$ by the second player is the playthrough

$$\langle \sigma(\emptyset), a_0, \sigma(\langle a_0 \rangle), a_1, \sigma(\langle a_0, a_1 \rangle), \ldots \rangle$$

Likewise, if σ is a strategy for the second player, and $\langle a_0, a_1, \ldots \rangle$ is an attack by the first player, then the result is the playthrough

$$\langle a_0, \sigma(\langle a_0 \rangle), a_1, \sigma(\langle a_0, a_1 \rangle), \ldots \rangle$$

We now may rigorously define the notion of “forcing” a win in a game.

Definition 9. A strategy σ is a *winning strategy* for a player if for every attack by the opponent, the result of the game is a victory for that player.

If a winning strategy exists for a player $\mathscr{A}$ in the game G, then we write $\mathscr{A} \uparrow G$. Otherwise, we write $\mathscr{A} \not\uparrow G$.

To show that a winning strategy exists for a player (i.e. $\mathscr{A} \uparrow G$), we typically begin by defining it and showing that it is *legal*: it only yields moves which are legal according to the rules of the game. Then, we consider an arbitrary legal attack, and prove that the result of the game is a victory for that player.

If we wish to show that a winning strategy does not exist for a player (i.e. $\mathscr{A} \not\uparrow G$), we often consider an arbitrary legal strategy, and use it to define a legal *counter-attack* for the opponent. If we can prove that the result of the game for that strategy and counter-attack is a victory for the opponent, then a winning strategy does not exist.

Unlike finite games, is not the case that a winning strategy must exist for one of the players in an infinite game.

Definition 10. A game G with players $\mathscr{A}$, $\mathscr{B}$ is said to be *determined* if either $\mathscr{A} \uparrow G$ or $\mathscr{B} \uparrow G$. Otherwise, the game is *undetermined*.

The Borel Determinacy Theorem states that $G = \langle M, W \rangle$ is determined whenever W is a Borel subset of M^ω [4]. It’s an easy corollary that all finite games are determined; W must be clopen.

However, as stated earlier, most topological games are infinite, and many are undetermined for certain spaces constructed using the Axiom of Choice.[2]

[2]These spaces cannot be constructed just only the axioms of ZF. In fact, mathematicians have studied an Axiom of Determinacy which declares that that all Gale-Stewart games are determined (and implies that the Axiom of Choice is false). [5]

2.2.1 Applications of Strategies

The power of studying these infinite-length games can be illustrated by considering the following proposition.

Proposition 11. *If X is countable, then $\mathscr{B} \uparrow Lim_{A,B}(X)$.*

Proof. Adapted from [1]. Let $X = \{x_0, x_1, \dots\}$. Let $i(a, b)$ be the least integer such that $a < x_{i(x,y)} < b$, if it exists. We define a strategy σ for $\mathscr{B}$ such that:

- $\sigma(\langle a_0 \rangle) = x_{i(a_0,\infty)}$. If $i(a_0, \infty)$ does not exist, then the choice of $\sigma(\langle a_0 \rangle)$ is arbitary, say, $a_0 + 1$.

- $\sigma(\langle a_0, ..., a_{n+1} \rangle) = x_{i(a_{n+1},b_n)}$, where $b_n = \sigma(\langle a_0, \dots, a_n \rangle)$. If $i(a_{n+1}, b_n)$ does not exist, then the choice of $\sigma(\langle a_0, ..., a_{n+1} \rangle)$ is arbitrary, say, $\sigma(\langle a_0, ..., a_{n+1} \rangle) = \frac{a_{n+1}+b_n}{2}$.

Observe that σ is a legal strategy according to the rules of the game since $a_0 < \sigma(\langle a_0 \rangle)$ and $a_{n+1} < \sigma(\langle a_0, \dots, a_{n+1} \rangle) < b_n$. We claim this is a winning strategy for $\mathscr{B}$. Let $a = \langle a_0, a_1, \dots \rangle$ be a legal attack by $\mathscr{A}$ against σ: we will show that the resulting playthrough is a victory for $\mathscr{B}$, that is, $\lim_{n\to\infty} a_n \notin X$. Let $b_n = \sigma(\langle a_0, \dots, a_n \rangle)$. Note that

$$a_0 < a_1 < \cdots < \lim_{n\to\infty} a_n < \cdots < b_1 < b_0$$

If $i(a_0, \infty)$ does not exist, then a_0 is greater than every element of X, and thus $\lim_{n\to\infty} a_n \notin X$. A similar argument follows if some $i(a_{n+1}, b_n)$ does not exist.

Otherwise,

$$i(a_0, \infty) < i(a_1, b_0) < i(a_2, b_1) < \dots$$

and for each $i < \omega$, one of the following must hold.

- $i < i(a_0, \infty)$. Then $x_i \le a_0 < \lim_{n\to\infty} a_n$.

- $i = i(a_0, \infty)$. Then $x_i = b_0 > \lim_{n\to\infty} a_n$.

- $i(a_0, \infty) < i < i(a_1, b_0)$. Then $x_i \leq a_1 < \lim_{n\to\infty} a_n$ or $x_i \geq b_0 > \lim_{n\to\infty} a_n$.
- $i = i(a_{n+1}, b_n)$ for some $n < \omega$. Then $x_i = b_{n+1} > \lim_{n\to\infty} a_n$.
- $i(a_{n+1}, b_n) < i < i(a_{n+2}, b_{n+1})$ for some $n < \omega$. Then $x_i \leq a_{n+2} < \lim_{n\to\infty} a_n$ or $x_i \geq b_{n+1} > \lim_{n\to\infty} a_n$.

In any case, $x_i \neq \lim_{n\to\infty} a_n$, and thus $\lim_{n\to\infty} a_n \notin X$. □

This yields a classical result.

Corollary 12. *$\mathbb{R}$ is uncountable.*

Proof. $\mathscr{A} \uparrow Lim_{A,B}(\mathbb{R})$, since a_n must converge to some real number. This implies $\mathscr{B} \not\uparrow Lim_{A,B}(\mathbb{R})$, and thus $\mathbb{R}$ is not countable. □

Infinite games thus provide a rich framework for considering questions in set theory and topology. In general, the presence or absence of a winning strategy for a player in a topological game characterizes a property of the topological space in question.

Theorem 13. *$\mathscr{E} \not\uparrow Empty_{E,N}(X)$ if and only if X is a Baire space. [3]*

2.2.2 Limited Information Strategies

So far we have assumed both players enjoy *perfect information*, and may develop strategies which use all of the previous moves of the opponent as input.

Definition 14. For a game $G = \langle M, W \rangle$, the *k-tactical fog-of-war* is the function $\nu_k : M^{<\omega} \to M^{\leq k}$ defined by

$$\nu_k(\langle m_0, \ldots, m_{n-1} \rangle) = \langle m_{n-k}, \ldots, m_{n-1} \rangle$$

and the *k-Marköv fog-of-war* is the function $\mu_k : M^{<\omega} \to (M^{\leq k} \times \omega)$ defined by

$$\mu_k(\langle m_0, \ldots, m_{n-1} \rangle) = \langle \langle m_{n-k}, \ldots, m_{n-1} \rangle, n \rangle$$

Essentially, these fogs-of-war represent a limited memory: ν_k filters out all but the last k moves of the opponent, and μ_k filters out all but the last k moves of the opponent and the round number.

We call strategies which do not require full recollection of the opponent's moves *limited information strategies*.

Definition 15. A *k-tactical strategy* or *k-tactic* is a limited information strategy of the form $\sigma \circ \nu_k$.

A *k-Markröv strategy* or *k-mark* is a limited information strategy of the form $\sigma \circ \mu_k$.

k-tactics and k-marks may then only use the last k moves of the opponent, and in the latter case, also the round number.

The k is usually omitted when $k = 1$. A (1-)tactic is called a *stationary strategy* by some authors. 0-tactics are not usually interesting (such strategies would be constant functions); however, we will discuss 0-Markröv strategies, called *predetermined strategies* since such a strategy only uses the round number and does not rely on knowing which moves the opponent will make.

Definition 16. If a winning k-tactical strategy exists for a player $\mathscr{A}$ in the game G, then we write $\mathscr{A} \underset{k\text{-tact}}{\uparrow} G$. If $k = 1$, then $\mathscr{A} \underset{\text{tact}}{\uparrow} G$.

If a winning k-Markröv strategy exists for a player $\mathscr{A}$ in the game G, then we write $\mathscr{A} \underset{k\text{-mark}}{\uparrow} G$. If $k = 1$, then $\mathscr{A} \underset{\text{mark}}{\uparrow} G$, and if $k = 0$, then $\mathscr{A} \underset{\text{pre}}{\uparrow} G$.

Definition 17. X is an *α-favorable space* when $\mathscr{N} \underset{\text{tact}}{\uparrow} \mathit{Empty}_{E,N}(X)$. X is a *weakly α-favorable space* when $\mathscr{N} \uparrow \mathit{Empty}_{E,N}(X)$.

Observation 18. *X is α-favorable $\Rightarrow$ X is weakly α-favorable $\Rightarrow$ X is Baire*

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