

Limited Information Strategies for Topological Games

by

Steven Clontz

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Approved by

Gary Gruenhage, Chair, Professor of Mathematics
Stewart Baldwin, Professor of Mathematics
Chris Rodger, Professor of Mathematics
Michel Smith, Professor of Mathematics
George Flowers, Dean of the Graduate School

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
Topological 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. [5]

Definition 2.1.1. 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 \mathcal{A} and \mathcal{B} playing a game which consists of *rounds* enumerated for each $n < \omega$. During round n , \mathcal{A} chooses $a_n \in M$, followed by \mathcal{B} choosing $b_n \in M$. The playthrough corresponding to those choices would be the sequence $p = \langle a_0, b_0, a_1, b_1, \dots \rangle$. If $p \in W$, then \mathcal{A} is the winner of that playthrough, and if $p \notin W$, then \mathcal{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 satisfied the winning condition, or the second player made an *illegal move* which contradicted the game's rules. Often, we will consider *legal playthroughs* where both players only made legal moves, in which case only the winning condition need be considered.

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 restrict 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 2.1.2. A game is said to be a *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 $M^\omega \setminus W$. ◇

¹In 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.

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*.

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

Game 2.1.3. Let $Bak_{A,B}(X)$ denote a game with players \mathcal{A} and \mathcal{B} , defined for each subset $A \subset \mathbb{R}$. In round 0, \mathcal{A} chooses a number a_0 , followed by \mathcal{B} choosing a number b_0 such that $a_0 < b_0$. In round $n + 1$, \mathcal{A} chooses a number a_{n+1} such that $a_n < a_{n+1} < b_n$, followed by \mathcal{B} choosing a number b_{n+1} such that $a_{n+1} < b_{n+1} < b_n$.

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

Certainly, \mathcal{A} and \mathcal{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 2.1.4. A *topological game* is a game defined in terms of an arbitrary topological space. \diamond

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 Banach-Mazur and other topological games may be found in Telgarsky's survey on the subject [25].

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

Game 2.1.5. Let $BM_{E,N}(X)$ denote the *Banach-Mazur game* with players \mathcal{E} , \mathcal{N} defined for each topological space X . In round 0, \mathcal{E} chooses a nonempty open set $E_0 \subseteq X$, followed by \mathcal{N} choosing a nonempty open subset $N_0 \subseteq E_0$. In round $n + 1$, \mathcal{E} chooses a nonempty open subset $E_{n+1} \subseteq N_n$, followed by \mathcal{N} choosing a nonempty open subset $N_{n+1} \subseteq E_{n+1}$.

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

For example, if X is a locally compact Hausdorff space, \mathcal{N} can “force” a win by choosing N_0 such that $\overline{N_0}$ is compact, and choosing N_{n+1} such that $N_{n+1} \subseteq \overline{N_n} \subseteq O_{n+1} \subseteq N_n$ (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 2.2.1. A *strategy* for a game $G = \langle M, W \rangle$ is a function from $M^{<\omega}$ to M . \diamond

Definition 2.2.2. An *attack* for a game $G = \langle M, W \rangle$ is a function from ω to M . \diamond

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

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

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

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

◇

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

Definition 2.2.4. 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 \mathcal{A} in the game G , then we write $\mathcal{A} \uparrow G$. Otherwise, we write $\mathcal{A} \nmid G$. ◇

To show that a winning strategy exists for a player (i.e. $\mathcal{A} \uparrow G$), 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. $\mathcal{A} \nmid G$), 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 2.2.5. A game G with players \mathcal{A}, \mathcal{B} is said to be *determined* if either $\mathcal{A} \uparrow G$ or $\mathcal{B} \uparrow G$. 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 [14]. 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

Often, we will build new strategies based on others.

Definition 2.2.6. A strategy τ is a *strengthening* of another strategy σ for a player if whenever the result of the game for σ and an attack a by the opponent is a victory for the player, then the result of the game for τ and a is also a victory for the player. \diamond

Proposition 2.2.7. *If σ is a winning strategy, and τ strengthens σ , then τ is also a winning strategy.* \diamond

2.2.1 Applications of Strategies

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

Proposition 2.2.8. *If X is countable, then $\mathcal{B} \uparrow \text{Bak}_{A,B}(X)$.* \diamond

Proof. Adapted from [1]. Let $X = \{x_0, x_1, \dots\}$. Let $i(a, b)$ be the least integer such that $a < x_{i(a,b)} < b$, if it exists. We define a strategy σ for \mathcal{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 arbitrary, say, $a_0 + 1$.
- $\sigma(\langle a_0, \dots, a_{n+1} \rangle) = x_{i(a_{n+1}, b_n)}$, 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 $\sigma(\langle a_0, \dots, a_{n+1} \rangle)$ is arbitrary, say, $\sigma(\langle a_0, \dots, a_{n+1} \rangle) = \frac{a_{n+1} + b_n}{2}$.

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 \mathcal{B} . Let $a = \langle a_0, a_1, \dots \rangle$ be a legal attack by \mathcal{A} against σ : we will show that the resulting playthrough is

²These 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). [16]

a victory for \mathcal{B} , that is, $\lim_{n \rightarrow \infty} a_n \notin X$. Let $b_n = \sigma(\langle a_0, \dots, a_n \rangle)$. Note that

$$a_0 < a_1 < \dots < \lim_{n \rightarrow \infty} a_n < \dots < b_1 < b_0$$

If $i(a_0, \infty)$ does not exist, then a_0 is greater than every element of X , and thus $\lim_{n \rightarrow \infty} a_n \notin X$. 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 $x_i \leq a_0 < \lim_{n \rightarrow \infty} a_n$.
- $i = i(a_0, \infty)$. Then $x_i = b_0 > \lim_{n \rightarrow \infty} a_n$.
- $i(a_0, \infty) < i < i(a_1, b_0)$. Then $x_i \leq a_1 < \lim_{n \rightarrow \infty} a_n$ or $x_i \geq b_0 > \lim_{n \rightarrow \infty} a_n$.
- $i = i(a_{n+1}, b_n)$ for some $n < \omega$. Then $x_i = b_{n+1} > \lim_{n \rightarrow \infty} a_n$.
- $i(a_{n+1}, b_n) < i < i(a_{n+2}, b_{n+1})$ for some $n < \omega$. Then $x_i \leq a_{n+2} < \lim_{n \rightarrow \infty} a_n$ or $x_i \geq b_{n+1} > \lim_{n \rightarrow \infty} a_n$.

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

More informally, \mathcal{B} can force a win by enumerating the countable set X and playing every legal choice by the end of the game. This yields a classical result.

Corollary 2.2.9. \mathbb{R} is uncountable. ◇

Proof. $\mathcal{A} \uparrow \text{Bak}_{A,B}(\mathbb{R})$, since a_n must converge to some real number. This implies $\mathcal{B} \nmid \text{Bak}_{A,B}(\mathbb{R})$, 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 2.2.10. $\mathcal{E} \not\preceq BM_{E,N}(X)$ if and only if X is a Baire space. [10]

◇

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

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

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

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

◇

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 2.2.12. A k -*tactical strategy* or k -*tactic* is a function $\sigma : M^{\leq k} \rightarrow M$ yielding a corresponding strategy $\sigma \circ \nu_k : M^{<\omega} \rightarrow M$.

A k -*Markov strategy* or k -*mark* is a function $\sigma : M^{\leq k} \times \omega \rightarrow M$ yielding a corresponding strategy $\sigma \circ \mu_k : M^{<\omega} \rightarrow M$.

◇

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-Markov 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. Of course, a limited information strategy σ is *winning* for a player if its corresponding strategy $\sigma \circ \nu_k$ or $\sigma \circ \mu_k$ is winning for that player.

Definition 2.2.13. If a winning k -tactical strategy exists for a player \mathcal{A} in the game G , then we write $\mathcal{A} \underset{k\text{-tact}}{\uparrow} G$. If $k = 1$, then $\mathcal{A} \underset{\text{tact}}{\uparrow} G$.

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

The existence of a winning limited information strategy can characterize a stronger property than the property characterized by a perfect information strategy.

Definition 2.2.14. X is an α -favorable space when $\mathcal{N} \underset{\text{tact}}{\uparrow} BM_{E,N}(X)$. X is a *weakly α -favorable space* when $\mathcal{N} \uparrow BM_{E,N}(X)$. \diamond

Proposition 2.2.15. X is α -favorable $\Rightarrow X$ is weakly α -favorable $\Rightarrow X$ is Baire \diamond

Those arrows may not be reversed. A Bernstein subset of the real line is an example of a Baire space which is not weakly α -favorable, and Gabriel Debs constructed an example of a completely regular space for which \mathcal{N} has a winning 2-tactic, but lacks a winning 1-tactic.

[4]

Chapter 3

Gruenhage's Convergence and Clustering Games

We begin by investigating a game due to Gary Gruenhage.

Game 3.0.16. Let $Gru_{\mathcal{O},P}^{\rightarrow}(X, S)$ denote the *W-convergence game* with players \mathcal{O} , \mathcal{P} , for a topological space X and $S \subseteq X$.

In round n , \mathcal{O} chooses an open neighborhood $O_n \supseteq S$, followed by \mathcal{P} choosing a point $x_n \in \bigcap_{m \leq n} O_m$.

\mathcal{O} wins the game if the points x_n converge to the set S ; that is, for every open neighborhood $U \supseteq S$, $x_n \in U$ for all but finite $n < \omega$.

If $S = \{x\}$ then we write $Gru_{\mathcal{O},P}^{\rightarrow}(X, x)$ for short. \diamond

The “W” in the name merely refers to \mathcal{O} ’s goal: to “win” the game. Gruenhage defined this game in his doctoral dissertation to define a class of spaces generalizing first-countability. [7]

Definition 3.0.17. The spaces X for which $\mathcal{O} \uparrow Gru_{\mathcal{O},P}^{\rightarrow}(X, x)$ for all $x \in X$ are called *W-spaces*. \diamond

In fact, using limited information strategies, one may characterize the first-countable spaces using this game.

Proposition 3.0.18. *X is first countable if and only if $\mathcal{O} \uparrow_{pre} Gru_{\mathcal{O},P}^{\rightarrow}(X, x)$ for all $x \in X$.* \diamond

Proof. The forward implication shows that all first-countable spaces are *W* spaces, and was proven in [7]: if $\{U_n : n < \omega\}$ is a countable base at x , let $\sigma(n) = \bigcap_{m \leq n} U_m$. σ is easily seen to be a winning predetermined strategy.

If X is not first countable at some x , let σ be a predetermined strategy for \mathcal{O} in $\text{Gru}_{\mathcal{O},P}^{\rightarrow}(X, x)$. There exists an open neighborhood U of x which does not contain any $\bigcap_{m \leq n} \sigma(m)$ (otherwise $\{\bigcap_{m \leq n} \sigma(m) : n < \omega\}$ would be a countable base at x). Let x_n be an element of $\bigcap_{m \leq n} \sigma(m) \setminus U$ for all $n < \omega$. Then $\langle x_0, x_1, \dots \rangle$ is a winning counter-attack to σ for \mathcal{P} , so \mathcal{O} lacks a winning predetermined strategy. \square

At first glance, the difficulty of $\text{Gru}_{\mathcal{O},P}^{\rightarrow}(X, S)$ could be increased for \mathcal{O} by only restricting the choices for \mathcal{P} to be within the most recent open set played by \mathcal{O} , rather than all the previously played open sets.

Definition 3.0.19. Let $\text{Gru}_{\mathcal{O},P}^{\rightarrow,*}(X, S)$ denote the *hard W -convergence game* which proceeds as $\text{Gru}_{\mathcal{O},P}^{\rightarrow}(X, S)$, except that \mathcal{P} need only choose $x_n \in O_n$ rather than $x_n \in \bigcap_{m \leq n} O_m$ during each round. \diamond

This seemingly more difficult game for \mathcal{O} is Gruenhage's original formulation. But with perfect information, there is no real difference for \mathcal{O} .

Proposition 3.0.20. $\mathcal{O} \uparrow_{\text{limit}} \text{Gru}_{\mathcal{O},P}^{\rightarrow}(X, S)$ if and only if $\mathcal{O} \uparrow_{\text{limit}} \text{Gru}_{\mathcal{O},P}^{\rightarrow,*}(X, S)$, where \uparrow_{limit} is either \uparrow or \uparrow_{pre} . \diamond

Proof. The backwards implication is immediate.

For the forward implication, let σ be a winning predetermined (perfect information) strategy, and λ be the 0-Markov fog-of-war μ_0 (the identity).

We define a new predetermined (perfect information) strategy τ by

$$\tau \circ \lambda(\langle x_0, \dots, x_{n-1} \rangle) = \bigcap_{m \leq n} \sigma \circ \lambda(\langle x_0, \dots, x_{m-1} \rangle)$$

so that each move by \mathcal{O} according to $\tau \circ \lambda$ is the intersection of \mathcal{O} 's previous moves. Then any attack against $\tau \circ \lambda$ is an attack against $\sigma \circ \lambda$, and since $\sigma \circ \lambda$ is a winning strategy, so is $\tau \circ \lambda$. \square

Put more simply, $\tau(n) = \bigcap_{m \leq n} \sigma(m)$ in the predetermined case, and $\tau(\langle x_0, \dots, x_{n-1} \rangle) = \bigcap_{m \leq n} \sigma(\langle x_0, \dots, x_{m-1} \rangle)$ in the perfect information case. The original proof would have been invalid if λ was required to be, say, the tactical fog-of-war ν_1 , since the value of \mathcal{O} 's own round 1 move $\sigma \circ \nu_1(\langle x_0 \rangle) = \sigma(\langle x_0 \rangle)$ could not be determined from the information she has during round 2: $\nu_1(\langle x_0, x_1 \rangle) = \langle x_1 \rangle$.

Due to the equivalency of the “hard” and “normal” variations of the convergence game in the perfect information case, many authors use them interchangeably. However, it is possible to find spaces for which the games are not equivalent when considering $k + 1$ -tactics and $k + 1$ -marks, as we will soon see.

In addition to the W -convergence games, we will also investigate “clustering” analogs to both variations.

Game 3.0.21. Let $Gru_{\mathcal{O},P}^{\rightsquigarrow}(X, S)$ ($Gru_{\mathcal{O},P}^{\rightsquigarrow,*}(X, S)$) be a variation of $Gru_{\mathcal{O},P}^{\rightarrow}(X, S)$ ($Gru_{\mathcal{O},P}^{\rightarrow,*}(X, S)$) such that x_n need only cluster at S , that is, for every open neighborhood U of S , $x_n \in U$ for infinitely many $n < \omega$. \diamond

This variation seems to make \mathcal{O} 's job easier, but Gruenhage noted that the clustering game is perfect-information equivalent to the convergence game for \mathcal{O} . This can easily be extended for some limited information cases as well.

Proposition 3.0.22. $\mathcal{O} \uparrow_{limit} Gru_{\mathcal{O},P}^{\rightarrow}(X, S)$ if and only if $\mathcal{O} \uparrow_{limit} Gru_{\mathcal{O},P}^{\rightsquigarrow}(X, S)$ where \uparrow_{limit} is any of \uparrow_{pre} , \uparrow_{tact} , \uparrow_{mark} , or \uparrow . \diamond

Proof. For the perfect information case we refer to [7].

In the predetermined (resp. tactical) case, suppose that σ is a winning predetermined (resp. tactical) strategy for \mathcal{O} in $Gru_{\mathcal{O},P}^{\rightsquigarrow}(X, S)$. Let p be a legal attack against σ , and q be a subsequence of p . It's easily seen that q is also a legal attack against σ , so q clusters at S . Since every subsequence of p clusters at S , p converges to S , and σ is a winning predetermined (resp. tactical) strategy for \mathcal{O} in $Gru_{\mathcal{O},P}^{\rightarrow}(X, S)$ as well.

In the final case, note that any Markov strategy σ' for \mathcal{O} may be strengthened to σ defined by $\sigma(x, n) = \bigcap_{m \leq n} \sigma'(x, m)$. So, suppose that σ is a winning Markov strategy for \mathcal{O} in $Gru_{\mathcal{O}, P}^{\rightarrow}(X, S)$ such that $\sigma(x, m) \supseteq \sigma(x, n)$ for all $m \leq n$.

Let p be a legal attack against σ , and q be a subsequence of p . For $m < \omega$, there exists $f(m) \geq m$ such that $q(m) = p(f(m))$. It follows that $q(0) = p(f(0)) \in \sigma(\emptyset, 0) \cap \bigcap_{m \leq f(0)} \sigma(\langle p(m) \rangle, m) \subseteq \sigma(\emptyset, 0)$ and

$$\begin{aligned} q(n+1) = p(f(n+1)) &\in \sigma(\emptyset, 0) \cap \bigcap_{m < f(n+1)} \sigma(\langle p(m) \rangle, m+1) \\ &\subseteq \sigma(\emptyset, 0) \cap \bigcap_{m < n+1} \sigma(\langle p(f(m)) \rangle, f(m)+1) \\ &= \sigma(\emptyset, 0) \cap \bigcap_{m < n+1} \sigma(\langle q(m) \rangle, f(m)+1) \\ &\subseteq \sigma(\emptyset, 0) \cap \bigcap_{m < n+1} \sigma(\langle q(m) \rangle, m+1) \end{aligned}$$

so q is also a legal attack against σ . Since σ is a winning strategy, q clusters at S , and since every subsequence of p clusters at S , p must converge to S . Thus σ is also a winning Markov strategy for \mathcal{O} in $Gru_{\mathcal{O}, P}^{\rightarrow}(X, S)$ as well. \square

Proposition 3.0.23. *For any $x \in X$ and $k < \omega$,*

- $\mathcal{O} \uparrow_{k+1\text{-tact}} Gru_{\mathcal{O}, P}^{\rightarrow}(X, x) \Leftrightarrow \mathcal{O} \uparrow_{\text{tact}} Gru_{\mathcal{O}, P}^{\rightarrow}(X, x)$
- $\mathcal{O} \uparrow_{k+1\text{-mark}} Gru_{\mathcal{O}, P}^{\rightarrow}(X, x) \Leftrightarrow \mathcal{O} \uparrow_{\text{mark}} Gru_{\mathcal{O}, P}^{\rightarrow}(X, x)$

\diamond

Proof. If σ witnesses $\mathcal{O} \uparrow_{k+1\text{-tact}} Gru_{\mathcal{O}, P}^{\rightarrow}(X, x)$, let $\tau(\emptyset) = \sigma(\emptyset)$ and

$$\tau(\langle q \rangle) = \bigcap_{i < k} \sigma(\langle \underbrace{x, \dots, x}_{k-i}, q, \underbrace{x, \dots, x}_{i+1} \rangle)$$

Then τ is easily verified to be a winning tactic, and the proof for the second part is analogous. \square

Two types of questions emerge from these results.

Question 3.0.24. Does $\mathcal{O} \uparrow_{2\text{-tact}} Gru_{\mathcal{O},P}^{\rightarrow}(X, S)$ imply $\mathcal{O} \uparrow_{2\text{-tact}} Gru_{\mathcal{O},P}^{\rightarrow}(X, S)$? What about for $\uparrow_{2\text{-mark}} ?$ \diamond

Question 3.0.25. Could $\mathcal{O} \uparrow_{k+1\text{-tact}} Gru_{\mathcal{O},P}^{\rightarrow}(X, S)$ actually imply $\mathcal{O} \uparrow_{\text{tact}} Gru_{\mathcal{O},P}^{\rightarrow}(X, S)$? What about for $Gru_{\mathcal{O},P}^{\rightarrow}(X, S)$? \diamond

3.1 Fort spaces

In his original paper, Gruenhage suggested the one-point-compactification of a discrete space as an example of a W -space which is not first-countable.

Definition 3.1.1. A *Fort space* $\kappa^* = \kappa \cup \{\infty\}$ is defined for each cardinal κ . Its subspace κ is discrete, and the neighborhoods of ∞ are of the form $\kappa^* \setminus F$ for each $F \in [\kappa]^{<\omega}$. \diamond

Proposition 3.1.2. $\mathcal{O} \uparrow_{\text{tact}} Gru_{\mathcal{O},P}^{\rightarrow}(\kappa^*, \infty)$ for all cardinals κ \diamond

Proof. Let $\sigma(\emptyset) = \sigma(\langle \infty \rangle) = \kappa^*$ and $\sigma(\langle \alpha \rangle) = \kappa^* \setminus \{\alpha\}$. Any legal attack against the tactic σ could not repeat non- ∞ points, so it must converge to ∞ . \square

Corollary 3.1.3. $\mathcal{O} \uparrow Gru_{\mathcal{O},P}^{\rightarrow,*}(\kappa^*, \infty)$ for all cardinals κ \diamond

Proof. Propositions 3.0.20 and 3.1.2. \square

Since it's trivial to show that $\mathcal{O} \uparrow_{\text{pre}} Gru_{\mathcal{O},P}^{\rightarrow}(\kappa^*, \infty)$ if and only if $\kappa \leq \omega$, this closes the question on limited information strategies for $Gru_{\mathcal{O},P}^{\rightarrow}(\kappa^*, \infty)$. However, limited information analysis of the harder $Gru_{\mathcal{O},P}^{\rightarrow,*}(\kappa^*, \infty)$ is more interesting.

Peter Nyikos noted Proposition 3.1.2 and the following in [17].

Theorem 3.1.4. $\mathcal{O} \not\uparrow_{\text{mark}} Gru_{\mathcal{O},P}^{\rightarrow,*}(\omega_1^*, \infty)$. \diamond

This actually can be generalized to any k -Markov strategy with just a little more book-keeping.

Theorem 3.1.5. $\mathcal{O} \not\uparrow_{k\text{-mark}} Gru_{\mathcal{O},P}^{\rightarrow,*}(\omega_1^*, \infty)$. ◇

Proof. Let σ be a k -mark for \mathcal{O} . Since the set

$$D_\sigma = \bigcap_{n < \omega, s \in \omega^{\leq k}} \sigma(s, n)$$

is co-countable, we may choose $\alpha_\sigma \in D_\sigma \cap \omega_1$. Thus, we may choose $n_0 < n_1 < \dots < \omega$ such that

$$\langle n_0, \dots, n_{k-1}, \alpha_\sigma, n_k, \dots, n_{2k-1}, \alpha_\sigma, \dots \rangle$$

is a legal counterattack, which fails to converge to ∞ since α_σ is repeated infinitely often. □

However, while the clustering and convergence variants are equivalent for Markov strategies in the “normal” version of the W game, they are *not* equivalent in the “hard” version.

Theorem 3.1.6. $\mathcal{O} \uparrow_{\text{mark}} Gru_{\mathcal{O},P}^{\rightsquigarrow,*}(\omega_1^*, \infty)$. ◇

Proof. For each $\alpha < \omega_1$ let $A_\alpha = \langle A_\alpha(0), A_\alpha(1), \dots \rangle$ be a countable sequence of finite sets such that $A_\alpha(n) \subset A_\alpha(n+1)$ and $\bigcup_{n < \omega} A_\alpha(n) = \alpha + 1$.

We define the Markov strategy σ by setting

$$\sigma(\emptyset, 0) = \sigma(\langle \infty \rangle, n) = \omega_1^*$$

and for all $\alpha < \omega_1$ setting

$$\sigma(\langle \alpha \rangle, n) = \omega_1^* \setminus A_\alpha(n)$$

Note that for any $\alpha_0 < \dots < \alpha_{k-1}$, there is some $n < \omega$ such that $\{\alpha_0, \dots, \alpha_{k-1}\} \subseteq A_{\alpha_i}(n)$ for all $i < k$. Thus for any legal attack p against σ , the range of p cannot be finite. Since the range of p is infinite, every open neighborhood of ∞ contains infinitely many points of p , so p clusters at ∞ . □

However, knowledge of the round number is critical.

Theorem 3.1.7. $O \not\uparrow_{k\text{-tact}} \text{Gru}_{O,P}^{\rightsquigarrow,*}(\omega_1^*, \infty)$. ◇

Proof. Let σ be a k -tactic for \mathcal{O} in $\text{Gru}_{O,P}^{\rightsquigarrow,*}(\omega_1^*, \infty)$. By the closing-up lemma, the set

$$C_\sigma = \{\alpha < \omega_1 : s \in \alpha^{\leq k} \Rightarrow \omega_1^* \setminus \sigma(s) \subset \alpha\}$$

is closed and unbounded. Let $a_\sigma : \omega_1 \rightarrow C_\sigma$ be an order isomorphism.

Choose $n_0 < \dots < n_{k-1} < \omega$ such that for each $i < k$:

$$a_\sigma(n_i) \in \sigma(\langle a_\sigma(n_0), \dots, a_\sigma(n_{i-1}), a_\sigma(\omega + i), \dots, a_\sigma(\omega + k - 1) \rangle)$$

Finally, observe that the legal counterattack

$$\langle a_\sigma(n_0), \dots, a_\sigma(n_{k-1}), a_\sigma(\omega), \dots, a_\sigma(\omega + k - 1), a_\sigma(n_0), \dots, a_\sigma(n_{k-1}), a_\sigma(\omega), \dots, a_\sigma(\omega + k - 1), \dots \rangle$$

has a range outside the open neighborhood

$$\omega_1^* \setminus \{a_\sigma(n_0), \dots, a_\sigma(n_{k-1}), a_\sigma(\omega), \dots, a_\sigma(\omega + k - 1)\}$$

of ∞ . Thus σ is not a winning k -tactic. □

Once the discrete space is larger than ω_1 , knowing the round number is not sufficient to construct a limited information strategy, due to a similar argument.

Theorem 3.1.8. $O \not\uparrow_{k\text{-mark}} \text{Gru}_{O,P}^{\rightsquigarrow,*}(\omega_2^*, \infty)$. ◇

Proof. Let σ be a k -mark for \mathcal{O} in $\text{Gru}_{O,P}^{\rightsquigarrow,*}(\omega_2^*, \infty)$. By the closing-up lemma, the set

$$C_\sigma = \{\alpha < \omega_2 : s \in \alpha^{<\omega} \Rightarrow \omega_2^* \setminus \sigma \circ \mu_k(s) \subset \alpha\}$$

is closed and unbounded. (Recall that μ_k is the k -Markov fog-of-war which turns perfect information into the last k moves and the round number.) Let $a_\sigma : \omega_2 \rightarrow C_\sigma$ be an order isomorphism.

Choose $\beta_0 < \dots < \beta_{k-1} < \omega_1$ such that for each $i < k$:

$$a_\sigma(\beta_i) \in \bigcap_{n < \omega} \sigma(\langle a_\sigma(\beta_0), \dots, a_\sigma(\beta_{i-1}), a_\sigma(\omega_1 + i), \dots, a_\sigma(\omega_1 + k - 1) \rangle, n)$$

Finally, observe that the legal counterattack

$$\langle a_\sigma(\beta_0), \dots, a_\sigma(\beta_{k-1}), a_\sigma(\omega_1), \dots, a_\sigma(\omega_1 + k - 1), a_\sigma(\beta_0), \dots, a_\sigma(\beta_{k-1}), a_\sigma(\omega_1), \dots, a_\sigma(\omega_1 + k - 1), \dots \rangle$$

has a range outside the open neighborhood

$$\omega_2^* \setminus \{a_\sigma(\beta_0), \dots, a_\sigma(\beta_{k-1}), a_\sigma(\omega_1), \dots, a_\sigma(\omega_1 + k - 1)\}$$

of ∞ . Thus σ is not a winning k -mark. □

3.2 Sigma-products

Knowing the status of W -games in simpler spaces yields insight to larger spaces.

Proposition 3.2.1. *Suppose $S \subseteq Y \subseteq X$, \uparrow is any of \uparrow , $\uparrow_{k\text{-tact}}$, or $\uparrow_{k\text{-mark}}$, and $G(X, S)$ is any of $\text{Gru}_{O,P}^\rightarrow(X, S)$, $\text{Gru}_{O,P}^{\rightarrow,*}(X, S)$, $\text{Gru}_{O,P}^{\rightsquigarrow}(X, S)$, or $\text{Gru}_{O,P}^{\rightsquigarrow,*}(X, S)$.*

Then $\mathcal{O} \uparrow_{\text{limit}} G(X, S)$ implies $\mathcal{O} \uparrow_{\text{limit}} G(Y, S)$. ◇

Proof. Simply intersect the output of the winning strategy in $G(X, S)$ with Y . □

A natural superspace of a Fort space is the sigma-product of a discrete cardinal.

Definition 3.2.2. Let $\Sigma_y \prod_{\alpha < \kappa} X_\alpha$ be a *sigma-product* of X with dimension κ for each $y \in \prod_{\alpha < \kappa} X_\alpha$, the subset of the usual Tychonoff product space $\prod_{\alpha < \kappa} X_\alpha$ such that $x \in \Sigma_y \prod_{\alpha < \kappa} X_\alpha$ if and only if $\{\alpha < \kappa : x(\alpha) \neq y(\alpha)\}$ is countable.

Unless otherwise specified, we assume $0 \in X_\alpha$ for all $\alpha < \kappa$ and $y = \vec{0}$, and write $\Sigma \prod_{\alpha < \kappa} X_\alpha$. \diamond

Proposition 3.2.3. κ^* is homeomorphic to the space

$$\{x \in \Sigma 2^\kappa : x(\alpha) = 0 \text{ for all but one } \alpha < \kappa\}$$

\diamond

Proof. Map $\alpha < \kappa$ to x_α such that

$$x_\alpha(\beta) = \begin{cases} 0 & \beta \neq \alpha \\ 1 & \beta = \alpha \end{cases}$$

and map ∞ to the zero vector $\vec{0}$. \square

Corollary 3.2.4. $\mathcal{O} \uparrow_{k\text{-tact}} Gru_{O,P}^{\vec{\omega},*}(\Sigma \mathbb{R}^{\omega_1}, \vec{0})$, $\mathcal{O} \uparrow_{k\text{-mark}} Gru_{O,P}^{\vec{\omega},*}(\Sigma \mathbb{R}^{\omega_1}, \vec{0})$, and $\mathcal{O} \uparrow_{k\text{-mark}} Gru_{O,P}^{\vec{\omega},*}(\Sigma \mathbb{R}^{\omega_2}, \vec{0})$. \diamond

While this closes the question on tactics and marks for high dimensional sigma- (and Tychonoff-) products of the real line, there is another type of limited information strategy to investigate.

Definition 3.2.5. For a game $G = \langle M, W \rangle$ and *coding strategy* or *code* $\sigma : M^2 \rightarrow M$, the σ -coding fog-of-war $\gamma_\sigma : M^{<\omega} \rightarrow M^{\leq 2}$ is the function defined such that

$$\gamma_\sigma(\emptyset) = \emptyset$$

and

$$\gamma_\sigma(s \frown \langle x \rangle) = \langle \sigma \circ \gamma_\sigma(s), x \rangle$$

For a coding strategy σ , its corresponding strategy is $\sigma \circ \gamma_\sigma$. For a game G , if $\sigma \circ \gamma_\sigma$ is a winning strategy for \mathcal{A} , then σ is a winning coding strategy and we write $\mathcal{A} \uparrow_{\text{code}} G$. \diamond

Intuitively, a σ -coding fog-of-war converts perfect information of the game into the last moves of both the player and her opponent, so a player has a winning coding strategy when she only needs to know the move of her opponent and her own last move. The term “coding” comes from the fact that a player may encode information about the history of the game into her own moves, and use this encoded information in later rounds.

As an example, the existence of a winning coding strategy is necessary for the second player to force a win the Banach-Mazur game.

Theorem 3.2.6. $\mathcal{N} \uparrow BM_{E,N}(X)$ if and only if $\mathcal{N} \underset{\text{code}}{\uparrow} BM_{E,N}(X)$ [4] [6]. \diamond

We are interested in whether the same holds for W games.

The hard and normal versions of the W games are all equivalent with regards to coding strategies since \mathcal{O} may always ensure her new move is a subset of her previous move. For Fort spaces, the question is immediately closed.

Proposition 3.2.7. $\mathcal{O} \underset{\text{code}}{\uparrow} Gru_{\mathcal{O},P}^{\rightarrow}(\kappa^*, \infty)$. \diamond

Proof. Let $\sigma(\emptyset) = \kappa^*$, $\sigma(\langle U, \alpha \rangle) = U \setminus \{\alpha\}$ for $\alpha < \kappa$, and $\sigma(\langle U, \infty \rangle) = U$. \mathcal{P} cannot legally repeat non- ∞ points of the set, so her points converge to ∞ . \square

This trick does not simply extend to the $\Sigma\mathbb{R}^\kappa$ case, however. An open set may only restrict finitely many coordinates of the product, and a point in $\Sigma\mathbb{R}^\kappa$ may have countably infinite non-zero coordinates. Thus, information about the previous non-zero coordinates cannot be directly encoded into the open set.

Circumventing this takes a bit of extra machinery. We proceed by defining a simpler infinite game for each cardinal κ .

Game 3.2.8. Let $PtFin_{F,C}(\kappa)$ denote the *point-finite game* with players \mathcal{F} , \mathcal{C} for each cardinal κ .

In round n , \mathcal{F} chooses $F_n \in [\kappa]^{<\omega}$, followed by \mathcal{C} choosing $C_n \in [\kappa \setminus \bigcup_{m \leq n} F_m]^{\leq \omega}$.

\mathcal{F} wins the game if the collection $\{C_n : n < \omega\}$ is a point-finite cover of its union $\bigcup_{n < \omega} C_n$, that is, each point in $\bigcup_{n < \omega} C_n$ is in C_n only for finitely many $n < \omega$. \diamond

This game has a strong resemblance to a game defined by Scheepers in [21] in relationship to the Banach-Mazur game and studied specifically with finite and countable sets in [22]. Scheeper's game and the results pertaining to it aren't of use here; however, they will be referenced in a later chapter in studying a different topological game.

This game of finite and countable sets is directly applicable to the W games played upon the sigma-product of real lines.

Lemma 3.2.9. $\mathcal{F} \uparrow_{code} PtFin_{F,C}(\kappa)$ implies $\mathcal{O} \uparrow_{code} Gru_{\vec{O},P}(\Sigma\mathbb{R}^\kappa, \vec{0})$. \diamond

Proof. Let σ be a winning coding strategy for \mathcal{F} in $PtFin_{F,C}(\kappa)$ such that $\sigma(\emptyset) \supset \emptyset$ and $\sigma(F, C) \supset F$.

For $F \in [\kappa]^{<\omega}$ and $\epsilon > 0$ let $U(F, \epsilon)$ be the basic open set in \mathbb{R}^κ such that each projection is of the form

$$\pi_\alpha(U(F, \epsilon)) = \begin{cases} (-\epsilon, \epsilon) & \alpha \in F \\ \mathbb{R} & \alpha \notin F \end{cases}$$

Note that $F \supset \emptyset$ and ϵ are uniquely identifiable given $U(F, \epsilon) \cap \Sigma\mathbb{R}^\kappa$.

For each point $x \in \Sigma\mathbb{R}^\kappa$ and $\epsilon > 0$, let $C_\epsilon(x) \in [\kappa]^{\leq\omega}$ such that $\alpha \in C_\epsilon(x)$ if and only if $|x(\alpha)| \geq \epsilon$.

We define the coding strategy τ for \mathcal{O} in $Gru_{\vec{O},P}(\Sigma\mathbb{R}^\kappa, \vec{0})$ as follows:

$$\tau(\emptyset) = U(\sigma(\emptyset), 1) \cap \Sigma\mathbb{R}^\kappa$$

$$\tau(\langle U(F, \epsilon) \cap \Sigma\mathbb{R}^\kappa, x \rangle) = U\left(\sigma(\langle F, C_\epsilon(x) \rangle), \frac{\epsilon}{2}\right) \cap \Sigma\mathbb{R}^\kappa$$

Let $\langle a_0, a_1, a_2, \dots \rangle$ be a legal attack by \mathcal{P} against τ . It then follows that

$$b = \langle C_1(a_0), C_{1/2}(a_1), C_{1/4}(a_2), \dots \rangle$$

is a legal attack by \mathcal{C} against σ . Since σ is a winning strategy, each ordinal in $\bigcup_{n < \omega} C_{2^{-n}}(a_n)$ is in $C_{2^{-n}}(a_n)$ only for finitely many $n < \omega$. Thus for every coordinate $\alpha < \kappa$ it follows that

there exists some $n_\alpha < \omega$ such that $a_n(\alpha) \leq 2^{-n}$ for $n \geq n_\alpha$. We conclude $a_n \rightarrow \vec{0}$, showing that τ is a winning strategy. \square

This lemma simplifies our notation in proving the main result. Intuitively, we aim to show that when κ has cofinality ω , \mathcal{F} can split up the game among ω -many smaller cardinals converging to κ , and when κ has a larger cofinality, \mathcal{F} may exploit the fact that \mathcal{C} may only play within some ordinal smaller than κ .

Theorem 3.2.10. $\mathcal{F} \uparrow_{code} PtFin_{F,C}(\kappa)$ for all cardinals κ . \diamond

Proof. For each cardinal κ and $\lambda < \kappa$, assume σ_λ is a winning strategy for \mathcal{F} in $PtFin_{F,C}(\lambda)$ such that $\sigma_\lambda(\emptyset) \supset \emptyset$ and $\sigma_\lambda(\langle F, C \rangle) \supset F$.

In the case that $\text{cf}(\kappa) = \omega$, let $\langle \kappa_0, \kappa_1, \dots \rangle$ be an increasing sequence of cardinals limiting to κ . Then we define the coding strategy σ for \mathcal{F} as follows:

$$\sigma(\emptyset) = \sigma_{\kappa_0}(\emptyset)$$

$$\sigma(\langle F, C \rangle) = \bigcup_{n \leq |F|} \sigma_{\kappa_n}(\langle F \cap \kappa_n, C \cap \kappa_n \rangle)$$

Then for each legal attack $a = \langle a(0), a(1), \dots \rangle$ by \mathcal{C} against σ and each $n < \omega$, the sequence $b_n = \langle a(n) \cap \kappa_n, a(n+1) \cap \kappa_n, \dots \rangle$ is a legal attack by \mathcal{C} against the winning coding strategy σ_{κ_n} . It follows then that $\{a(i+n) \cap \kappa_n : i < \omega\}$ is a point-finite cover of $\bigcup_{i < \omega} a(i+n) \cap \kappa_n$. We conclude that $\{a(i) : i < \omega\}$ is a point-finite cover of $\bigcup_{i < \omega} a(i)$ and σ is a winning strategy.

It remains to consider the case where $\text{cf}(\kappa) > \omega$. Note that now, for each $C \in [\kappa]^{\leq \omega}$, C is bounded above in κ . So we define the coding strategy σ for \mathcal{F} as follows:

$$\sigma(\emptyset) = \emptyset$$

$$\sigma(\langle F, C \rangle) = \{\sup(C)\} \cup \bigcup_{\alpha \in F} \sigma_{\alpha+1}(\langle F \cap (\alpha+1), C \cap (\alpha+1) \rangle)$$

Then for each legal attack $a = \langle a(0), a(1), \dots \rangle$ by \mathcal{C} against σ and each $n < \omega$, the sequence $b_n = \langle a(n) \cap (\sup(a(n)) + 1), a(n+1) \cap (\sup(a(n)) + 1), \dots \rangle$ is a legal attack by \mathcal{C} against the winning coding strategy $\sigma_{\sup(a(n))+1}$. It follows then that $\{a(i+n) \cap (\sup(a(n)) + 1) : i < \omega\}$ is a point-finite cover of $\bigcup_{i < \omega} a(i+n) \cap (\sup(a(n)) + 1)$. We conclude that $\{a(i) : i < \omega\}$ is a point-finite cover of $\bigcup_{i < \omega} a(i)$ and σ is a winning strategy. \square

Corollary 3.2.11. $\mathcal{O} \uparrow_{code} Gru_{\vec{\mathcal{O}}, P}^{\rightarrow}(\Sigma \mathbb{R}^{\kappa}, \vec{0})$ for all cardinals κ . \diamond

This leaves open the question analogous to Theorem 3.2.6.

Question 3.2.12. Does $\mathcal{O} \uparrow Gru_{\vec{\mathcal{O}}, P}^{\rightarrow}(X, x)$ imply $\mathcal{O} \uparrow_{code} Gru_{\vec{\mathcal{O}}, P}^{\rightarrow}(X, x)$? \diamond

Chapter 4

Bell's Convergence Games

A very recent development related to Gruenhage's convergence and clustering games comes from Jocelyn Bell.

4.1 A Game on Uniform Spaces

Definition 4.1.1. A *uniformity* on a set X is a filter \mathbb{D} of subsets of X^2 , known as \mathbb{D} -*entourages*, such that $\bigcap \mathbb{D} = \Delta = \{\langle x, x \rangle : x \in X\}$ and, for each entourage $D \in \mathbb{D}$:

- There exists $E \in \mathbb{D}$ such that

$$E \circ E = \{\langle x, z \rangle : \exists y \in X (\langle x, y \rangle, \langle y, z \rangle \in E)\} \subseteq D$$

- $D^{-1} = \{\langle y, x \rangle : \langle x, y \rangle \in D\} \in \mathbb{D}$

◇

A set X with a uniformity is called a *uniform space*. As \mathbb{D} is a filter, we also have that $D \cap E \in \mathbb{D}$ for all $E \in \mathbb{D}$, and $F \in \mathbb{D}$ for all $F \supseteq D$. Note that if \mathbb{E} is a filter base satisfying the conditions for a uniformity, then we say \mathbb{E} is a *uniformity base* which may be extended to a uniformity by closing it under the superset operation.

A uniformity is a generalization of a metric.

Definition 4.1.2. For a \mathbb{D} -entourage D and a point $x \in X$, the *D -ball around x* is the set $D[x] = \{y : \langle x, y \rangle \in D\}$. ◇

Definition 4.1.3. If d is a metric for the space X , then the *metric uniformity* for X is generated by the uniformity base $\{D_\epsilon : \epsilon > 0\}$ where $D_\epsilon = \{\langle x, y \rangle : d(x, y) < \epsilon\}$. ◇

Bell first introduced what she called the “proximal game” in [2]. This game was used to prove that the Σ -product of spaces for which \mathcal{D} has a winning strategy is collectionwise normal, as well as to show the collectionwise normality of certain uniform box products.

Game 4.1.4. Let $Bell_{D,P}^{\text{uni}}(X, \mathbb{D})$ denote the *Bell uniform space game* with players \mathcal{D} , \mathcal{P} which proceeds as follows for a uniform space X with uniformity \mathbb{D} . In round 0, \mathcal{D} chooses a \mathbb{D} -entourage D_0 , followed by \mathcal{P} choosing a point $p_0 \in X$. In round $n + 1$, \mathcal{D} chooses a \mathbb{D} -entourage D_{n+1} , followed by \mathcal{P} choosing a point $p_{n+1} \in D_n[p_n]$.

\mathcal{D} wins in the case that either $\langle p_0, p_1, \dots \rangle$ converges with respect to the uniformity \mathbb{D} (there exists $N < \omega$ such that $p(n) \in D[x]$ for $n \geq N$), or $\bigcap_{n < \omega} D_n[p_n] = \emptyset$. \diamond

4.2 Topologizing Bell’s Game

Like metrics, uniformities induce natural topological structures.

Definition 4.2.1. The *uniform topology* induced by a uniformity \mathbb{D} on X declares U open if for each $x \in U$, there exists $D \in \mathbb{D}$ such that $D[x] \subseteq U$. \diamond

Theorem 4.2.2. *The uniform topology induced by a uniformity \mathbb{D} on X is the coarsest topology such that for each $x \in X$ and $D \in \mathbb{D}$, $D[x]$ is a neighborhood (not necessarily open) of x .* \diamond

Proof. Let \mathcal{T} be a topology such that $D[x]$ is a neighborhood of x for each $x \in X$, and let U be open in the uniform topology. For each $x \in U$, there exists $D_x \in \mathbb{D}$ such that $D_x[x] \subseteq U$, and since $D_x[x]$ is a neighborhood of x , there is $U_x \in \mathcal{T}$ such that $x \in U_x \subseteq D_x[x]$. Thus \mathcal{T} contains the uniform topology. \square

The uniform topology for a metric uniformity is simply the usual metric topology, and $D_\epsilon[x]$ is the usual metric ϵ -ball around x .

Definition 4.2.3. A topological space X is *uniformizable* if there exists a uniformity which induces the given topology on X . \diamond

Bell's game may thus be used to characterize the structure of uniformizable spaces.

Definition 4.2.4. A uniformizable space X is *proximal* if there exists a compatible uniformity \mathbb{D} such that $\mathcal{D} \uparrow Bell_{D,P}^{\text{uni}}(X, \mathbb{D})$. \diamond

However, since the focus of this manuscript is on topological spaces, it will be useful to recharacterize the proximal property in terms of a topological game. This may be attained by considering a few known results on uniform spaces. See e.g. [26] for proofs.

Theorem 4.2.5. *Every uniform topology is $T_{3\frac{1}{2}}$, and every $T_{3\frac{1}{2}}$ topology is uniformizable.* \diamond

Theorem 4.2.6. *The union of all uniformities which induce a particular topology is itself a uniformity and induces the same topology.* \diamond

Definition 4.2.7. The *universal uniformity* for a uniformizable topology is the uniformity finer than all uniformities which induce the given topology. \diamond

Definition 4.2.8. For a uniformizable space X , a *universal entourage* D is a \mathbb{D} -entourage of the universal uniformity \mathbb{D} . \diamond

Theorem 4.2.9. *For every uniformizable space, if D is a neighborhood of the diagonal Δ such that there exist neighborhoods D_n of Δ with $D \supseteq D_0$ and $D_n \supseteq D_{n+1} \circ D_{n+1}$, then D is a universal entourage.* \diamond

Theorem 4.2.10. *Every neighborhood of the diagonal is a universal entourage for paracompact uniformizable spaces.* \diamond

Definition 4.2.11. An *open symmetric \mathbb{D} -entourage* D is a \mathbb{D} -entourage which is open in the product topology induced by \mathbb{D} and where $D = D^{-1}$. \diamond

Theorem 4.2.12. *For every \mathbb{D} -entourage D , there exists an open symmetric \mathbb{D} -entourage $U \subseteq D$.* \diamond

We will simply use the word *entourage* to refer to open symmetric universal entourages. Note that if D is an entourage, then $D[x]$ is an open neighborhood of x .

Definition 4.2.13. For every entourage D , let $\frac{1}{2^n}D$ denote entourages for $n < \omega$ such that $\frac{1}{1}D = D$ and $\frac{1}{2^{n+1}}D \circ \frac{1}{2^{n+1}}D \subseteq \frac{1}{2^n}D$. \diamond

The proof of the following is routine.

Proposition 4.2.14. *If X is a uniformizable space, then for all $x \in X$ and entourages D :*

$$x \in \frac{1}{2}D[y] \text{ and } y \in \frac{1}{2}D[z] \Rightarrow x \in D[z]$$

and

$$\frac{1}{2}D[x] \subseteq \overline{\frac{1}{2}D[x]} \subseteq D[x]$$

\diamond

The natural adaptation of Bell's game simply replaces the \mathbb{D} -entourages of the uniform space with the (open symmetric universal) entourages of a uniformizable space.

Game 4.2.15. Let $Bell_{D,P}^{\rightarrow,*}(X)$ denote the *hard Bell convergence game* with players \mathcal{D} , \mathcal{P} which proceeds as follows for a uniformizable space X . In round 0, \mathcal{D} chooses an entourage D_0 , followed by \mathcal{P} choosing a point $p_0 \in X$. In round $n + 1$, \mathcal{D} chooses an entourage D_{n+1} , followed by \mathcal{P} choosing a point $p_{n+1} \in D_n[p_n]$.

\mathcal{D} wins in the case that either $\langle p_0, p_1, \dots \rangle$ converges in X , or $\bigcap_{n < \omega} D_n[p_n] = \emptyset$. \mathcal{P} wins otherwise. \diamond

Like $Gru_{O,P}^{\rightarrow,*}(X, x)$, \mathcal{D} may choose to intersect her plays with her previous plays given perfect information. Since this cannot be guaranteed with limited information, a simpler variation for \mathcal{D} may also be considered, which will be the focus of this chapter.

Game 4.2.16. Let $Bell_{D,P}^{\rightarrow}(X)$ denote the *Bell convergence game* with players \mathcal{D} , \mathcal{P} which proceeds analogously to $Bell_{D,P}^{\rightarrow,*}(X)$, except for the following. Let $E_n = \bigcap_{m \leq n} D_m$, where

D_n is the entourage played by \mathcal{D} in round n . Then \mathcal{P} must ensure that $p_{n+1} \in E_n[p_n]$, and \mathcal{D} wins when either $\langle p_0, p_1, \dots \rangle$ converges in X or $\bigcap_{n < \omega} E_n[p_n] = \emptyset$. \diamond

These games are all essentially equivalent with respect to perfect information for \mathcal{D} .

Theorem 4.2.17. $\mathcal{D} \uparrow Bell_{D,P}^{\rightarrow,*}(X)$ if and only if $\mathcal{D} \uparrow Bell_{D,P}^{\rightarrow}(X)$ if and only if X is proximal. \diamond

Proof. If $\mathcal{D} \uparrow Bell_{D,P}^{\rightarrow,*}(X)$, then we immediately see that $\mathcal{D} \uparrow Bell_{D,P}^{\rightarrow}(X)$. If σ is a winning strategy for \mathcal{D} in $Bell_{D,P}^{\rightarrow}(X)$, then τ defined by $\tau(s) = \bigcap_{t \leq s} \sigma(t)$ is easily seen to be a winning strategy for \mathcal{D} in $Bell_{D,P}^{\rightarrow,*}(X)$.

If $\mathcal{D} \uparrow Bell_{D,P}^{\rightarrow,*}(X)$, then $\mathcal{D} \uparrow Bell_{D,P}^{\text{uni}}(X, \mathbb{D})$ where \mathbb{D} is the universal uniformity, showing X is proximal. Finally, if X is proximal, then there exists a winning strategy σ for $Bell_{D,P}^{\text{uni}}(X, \mathbb{D})$ where \mathbb{D} is a uniformity inducing the topology on X . Then a winning strategy for \mathcal{D} in $Bell_{D,P}^{\rightarrow,*}(X)$ may be constructed by converting every \mathbb{D} -entourage into a smaller open symmetric universal entourage. \square

Bell showed the following results in [2].

Theorem 4.2.18. If X is metrizable, then $\mathcal{D} \uparrow_{pre} Bell_{D,P}^{\rightarrow}(X)$. \diamond

Theorem 4.2.19. If $\mathcal{D} \uparrow Bell_{D,P}^{\rightarrow}(X)$, then $\mathcal{O} \uparrow Gru_{\vec{O},P}^{\rightarrow}(X, x)$ for all $x \in X$. Thus proximal spaces are W spaces. \diamond

Theorem 4.2.20. Proximal spaces are collectionwise normal. \diamond

Theorem 4.2.21. Every closed subspace of a proximal space is proximal. \diamond

Theorem 4.2.22. Every Σ -product of proximal spaces is proximal. \diamond

Since the empty intersection winning condition of her game can obfuscate things, Bell suggested that \mathcal{D} “absolutely wins” her uniform space game if the points played by \mathcal{P} always converge, inspiring the following game.

Definition 4.2.23. Let $Bell_{\vec{D},P}^{\rightarrow}(X)$ denote the *absolute Bell convergence game* which proceeds analogously to $Bell_{\vec{D},P}^{\rightarrow}(X)$, except that \mathcal{D} must always ensure that $\langle p_0, p_1, \dots \rangle$ converges in X in order to win. \diamond

Definition 4.2.24. A uniformizable space X is *absolutely proximal* if $\mathcal{D} \uparrow Bell_{\vec{D},P}^{\rightarrow}(X)$. \diamond

4.3 Characterizing Corson compactness

Gruenhage and the author showed in [3] that Bell's uniform space game yields an internal characterization of Corson compact spaces, answering a question of Nyikos in [18]. We include a proof of this result using the topological version of the game instead.

Definition 4.3.1. A compact space is *Corson compact* if it is homeomorphic to a compact subset of a Σ -product of real lines. \diamond

Nyikos observed the following in [18].

Proposition 4.3.2. *Corson compact spaces are proximal.* \diamond

Proof. The real line is metrizable and thus proximal, and closed subsets of Σ -products of proximal spaces are proximal. \square

A result of Gruenhage [8] gives a useful game characterization of Corson compactness.

Theorem 4.3.3. *A compact space is Corson compact if and only if $\mathcal{O} \uparrow Gru_{\vec{O},P}^{\rightarrow}(X^2, \Delta)$.* \diamond

Thus our desired result will follow if we may show that a winning strategy in $Bell_{\vec{D},P}^{\rightarrow}(X)$ may be used to construct a winning strategy in $Gru_{\vec{O},P}^{\rightarrow}(X^2, \Delta)$. However, due to the secondary winning condition for \mathcal{D} in $Bell_{\vec{D},P}^{\rightarrow}(X)$, it will be more convenient if we may use a winning strategy for \mathcal{D} in $Bell_{\vec{D},P}^{\rightarrow}(X)$ instead.

Definition 4.3.4. A uniformizable space X is *uniformly locally compact* if there exists an entourage D such that $\overline{D[x]}$ is compact for all x . \diamond

Of course, any compact uniformizable space is uniformly locally compact. However, note that a space may be locally compact without being uniformly locally compact.

Theorem 4.3.5. *A uniformizable space is uniformly locally compact if and only if it is locally compact and paracompact. [13]* \diamond

As an example, ω_1 with the linear order topology is locally compact, but not paracompact or uniformly locally compact.

Theorem 4.3.6. *If X is a uniformly locally compact space, then $\mathcal{D} \uparrow Bell_{D,P}^{\rightarrow}(X)$ if and only if $\mathcal{D} \uparrow Bell_{D,P}^{\rightarrow}(X)$.* \diamond

Proof. Let L be an entourage such that $\overline{L[x]}$ is compact for all x . Let σ be a strategy witnessing $\mathcal{D} \uparrow Bell_{D,P}^{\rightarrow}(X)$. Without loss of generality, we may assume $\sigma(t) \subseteq L$ and that $t \supseteq s$ implies $\sigma(t) \subseteq \frac{1}{4}\sigma(s)$. Note then that $\overline{\sigma(t)[x]} \subseteq \overline{L[x]}$ is compact.

Let $\tau(t) = \frac{1}{2}\sigma(t)$. If p attacks τ in $Bell_{D,P}^{\rightarrow}(X)$, then

$$p(n+1) \in \tau(p \upharpoonright n)[p(n)] = \frac{1}{2}\sigma(p \upharpoonright n)[p(n)]$$

and for

$$x \in \overline{\sigma(p \upharpoonright (n+1))[p(n+1)]} \subseteq \overline{\frac{1}{4}\sigma(p \upharpoonright n)[p(n+1)]} \subseteq \frac{1}{2}\sigma(p \upharpoonright n)[p(n+1)]$$

we can conclude $x \in \sigma(p \upharpoonright n)[p(n)]$. Thus

$$\sigma(p \upharpoonright (n+1))[p(n+1)] \subseteq \overline{\sigma(p \upharpoonright (n+1))[p(n+1)]} \subseteq \sigma(p \upharpoonright n)[p(n)]$$

Finally, note that since τ yields subsets of σ , p also attacks the winning strategy σ in $Bell_{D,P}^{\rightarrow}(X)$, but since the intersection of a descending chain of nonempty compact sets is nonempty, we have

$$\bigcap_{n < \omega} \sigma(p \upharpoonright n)[p(n)] = \bigcap_{n < \omega} \overline{\sigma(p \upharpoonright n)[p(n)]} \neq \emptyset$$

We conclude that p converges. \square

Lemma 4.3.7. *If $\mathcal{D} \uparrow Bell_{D,P}^{\rightarrow}(X)$, then $\mathcal{O} \uparrow Gru_{O,P}^{\rightarrow}(X, H)$ for all compact H in X .* \diamond

Proof. Let σ be a winning strategy for \mathcal{D} in $Bell_{D,P}^{\rightarrow}(X)$ game such that $p \supsetneq q$ implies $\sigma(p) \subseteq \frac{1}{4}\sigma(q)$. For any sequence t , let $o_t = \{\langle n, t(2n+1) \rangle : 2n+1 \in \text{dom}(t)\}$ be the subsequence of t consisting of its odd-indexed terms. We proceed by constructing a winning strategy for \mathcal{O} in $Gru_{O,P}^{\rightarrow}(X, H)$. Since $\mathcal{O} \uparrow Gru_{O,P}^{\rightarrow}(X, H)$ if and only if $\mathcal{O} \uparrow Gru_{O,P}^{\sim}(X, H)$, the result will follow.

We begin by defining a tree $T(\emptyset)$, during which we will define a number $m_\emptyset < \omega$ and points $h_{\emptyset,i}, h_{\emptyset,i,j}$ for $i, j < m_\emptyset$ which yield an open set

$$\bigcup_{i,j < m_\emptyset} \frac{1}{4}\sigma(\langle h_{\emptyset,i} \rangle)[h_{\emptyset,i,j}] = \bigcup_{\emptyset \smallfrown \langle i, h_{\emptyset,i,j} \rangle \in \max(T(\emptyset))} \frac{1}{4}\sigma(o_\emptyset \smallfrown \langle h_{\emptyset,i} \rangle)[h_{\emptyset,i,j}]$$

containing H . \mathcal{O} will use this as the initial move in her winning strategy for $Gru_{O,P}^{\sim}(X, H)$.

- Choose $m_\emptyset < \omega$, $h_{\emptyset,i} \in H$ for $i < m_\emptyset$, and $h_{\emptyset,i,j} \in H \cap \overline{\frac{1}{4}\sigma(\emptyset)[h_{\emptyset,i}]}$ for $i, j < m_\emptyset$ such that

$$\left\{ \frac{1}{4}\sigma(\emptyset)[h_{\emptyset,i}] : i < m_\emptyset \right\}$$

is a cover for H and such that for each $i < m_\emptyset$

$$\left\{ \frac{1}{4}\sigma(\langle h_{\emptyset,i} \rangle)[h_{\emptyset,i,j}] : j < m_\emptyset \right\}$$

is a cover for $H \cap \overline{\frac{1}{4}\sigma(\emptyset)[h_{\emptyset,i}]}$.

- Let $\langle i, h_{\emptyset,i,j} \rangle$ and its initial segments be in $T(\emptyset)$ for $i, j < m_\emptyset$.

It follows that

$$\left\{ \frac{1}{4} \sigma(o_\emptyset \frown \langle h_{\emptyset,i} \rangle) [h_{\emptyset,i,j}] : \emptyset \frown \langle i, h_{\emptyset,i}, j \rangle \in \max(T(a)) \right\}$$

covers H .

Now suppose that a is a partial attack by \mathcal{P} in $\text{Gru}_{\mathcal{O},P}^{\rightsquigarrow}(X, H)$ for which we have defined a tree $T(a)$. We will define $T(a \frown \langle x \rangle) \supseteq T(a)$ for each $x \in X$, and whenever $x \in \frac{1}{4} \sigma(o_s \frown \langle h_{s,i} \rangle) [h_{s,i,j}]$ for some $s \frown \langle i, h_{s,i}, j \rangle \in \max(T(a))$, we will set $t = s \frown \langle i, h_{s,i}, j, x \rangle$ and define a number $m_t < \omega$ and points $h_{t,k}, h_{t,k,l}$ for $k, l < m_t$ to yield an open set

$$\bigcup_{t \frown \langle k, h_{t,k}, l \rangle \in \max(T(a \frown \langle x \rangle))} \frac{1}{4} \sigma(o_t \frown \langle h_{t,k} \rangle) [h_{t,k,l}]$$

which will be the next open neighborhood of H in \mathcal{O} 's winning strategy for $\text{Gru}_{\mathcal{O},P}^{\rightsquigarrow}(X, H)$.

- We will extend the nodes $s \frown \langle i, h_{s,i}, j \rangle \in \max(T(a))$ such that $x \in \frac{1}{4} \sigma(o_s \frown \langle h_{s,i} \rangle) [h_{s,i,j}]$. For each such $s \frown \langle i, h_{s,i}, j \rangle$, set $t = s \frown \langle i, h_{s,i}, j, x \rangle$.
- Note that whenever $o_s \frown \langle h_{s,i} \rangle$ is a legal partial attack against σ , then

$$x \in \frac{1}{4} \sigma(o_s \frown \langle h_{s,i} \rangle) [h_{s,i,j}] \subseteq \frac{1}{4} \sigma(o_s) [h_{s,i,j}]$$

and

$$h_{s,i,j} \in \overline{\frac{1}{4} \sigma(o_s) [h_{s,i}]} \subseteq \frac{1}{2} \sigma(o_s) [h_{s,i}]$$

implies

$$x \in \sigma(o_s) [h_{s,i}]$$

and thus $o_s \frown \langle h_{s,i}, x \rangle = o_t$ is also a legal partial attack against σ .

- Choose $m_t < \omega$, $h_{t,k} \in H \cap \overline{\frac{1}{4}\sigma(o_s \frown \langle h_{s,i} \rangle)[h_{s,i,j}]}$ for $k < m_t$, and $h_{t,k,l} \in H \cap \overline{\frac{1}{4}\sigma(o_t)[h_{t,k}]}$ for $k, l < m_t$ such that

$$\left\{ \frac{1}{4}\sigma(o_t)[h_{t,k}] : k < m_t \right\}$$

is a cover for $H \cap \overline{\frac{1}{4}\sigma(o_s \frown \langle h_{s,i} \rangle)[h_{s,i,j}]}$ and such that for each $k < m_t$

$$\left\{ \frac{1}{4}\sigma(o_t \frown \langle h_{t,k} \rangle)[h_{t,k,l}] : l < m_t \right\}$$

is a cover for $H \cap \overline{\frac{1}{4}\sigma(o_t)[h_{t,k}]}$.

- Note that whenever o_t is a legal partial attack against σ , then

$$h_{t,k} \in \overline{\frac{1}{4}\sigma(o_s \frown \langle h_{s,i} \rangle)[h_{s,i,j}]} \subseteq \frac{1}{2}\sigma(o_s \frown \langle h_{s,i} \rangle)[h_{s,i,j}]$$

and

$$x \in \frac{1}{4}\sigma(o_s \frown \langle h_{s,i} \rangle)[h_{s,i,j}]$$

implies

$$h_{t,k} \in \sigma(o_s \frown \langle h_{s,i} \rangle)[x]$$

and thus $o_t \frown \langle h_{t,k} \rangle$ is a legal partial attack against σ .

- Include all initial segments of $t \frown \langle k, h_{t,k}, l \rangle$ in $T(a \frown \langle x \rangle)$ for $k, l < m_t$.

This completes the construction of $T(a \frown \langle x \rangle)$. Note that since

$$\left\{ \frac{1}{4}\sigma(o_s \frown \langle h_{s,i} \rangle)[h_{s,i,j}] : s \frown \langle i, h_{s,i}, j \rangle \in \max(T(a)) \right\}$$

covers H , then since

$$\left\{ \frac{1}{4}\sigma(o_t \frown \langle h_{t,k} \rangle)[h_{t,k,l}] : s \frown \langle i, h_{s,i}, j, x, k, h_{t,k}, l \rangle \in \max(T(a \frown \langle x \rangle)) \setminus \max(T(a)) \right\}$$

covers $H \cap \frac{1}{4}\sigma(o_s \smallfrown \langle h_{s,i} \rangle)[h_{s,i,j}]$, we have that

$$\left\{ \frac{1}{4}\sigma(o_t \smallfrown \langle h_{t,k} \rangle)[h_{t,k,l}] : t \smallfrown \langle k, h_{t,k}, l \rangle \in \max(T(a \smallfrown \langle x \rangle)) \right\}$$

covers H .

We define a strategy τ for \mathcal{O} in $Gru_{\vec{O},P}^{\omega}(X, H)$ such that:

$$\tau(a) = \bigcup_{s \smallfrown \langle i, h_{s,i}, j \rangle \in \max(T(a))} \frac{1}{4}\sigma(o_s \smallfrown \langle h_{s,i} \rangle)[h_{s,i,j}]$$

If p is a legal attack by \mathcal{P} against τ , then let $T(p) = \bigcup_{n < \omega} T(p \upharpoonright n)$. We note $T(p)$ is an infinite tree (for each $n < \omega$, a node of $T(p \upharpoonright n)$ was extended) with finite levels:

- \emptyset has exactly m_\emptyset successors $\langle i \rangle$.
- $s \smallfrown \langle i \rangle$ has exactly one successor $s \smallfrown \langle i, h_{s,i} \rangle$
- $s \smallfrown \langle i, h_{s,i} \rangle$ has exactly m_s successors $s \smallfrown \langle i, h_{s,i}, j \rangle$
- $s \smallfrown \langle i, h_{s,i}, j \rangle$ has either no successors or exactly one successor $s \smallfrown \langle i, h_{s,i}, j, x \rangle$
- $t = s \smallfrown \langle i, h_{s,i}, j, x \rangle$ has exactly m_t successors $t \smallfrown \langle k \rangle$

Hence $T(p)$ has an infinite branch

$$q' = \langle i_0, h_0, j_0, x_0, i_1, h_1, j_1, x_1, \dots \rangle$$

Let $q = o_{q'} = \langle h_0, x_0, h_1, x_1, \dots \rangle$. Note that by the construction of $T(p)$, q is a legal attack on the winning strategy σ in $Bell_{\vec{D},P}^{\rightarrow}(X)$, so it must converge. Since every other term of q is in H , it must converge to H . Then since o_q is a subsequence of p , p must cluster at H . \square

Theorem 4.3.8. *A compact space is Corson compact if and only if $\mathcal{D} \upharpoonright Bell_{\vec{D},P}^{\rightarrow}(X)$.* \diamond

Proof. If $\mathcal{D} \upharpoonright Bell_{\vec{D},P}^{\rightarrow}(X)$, then $\mathcal{D} \upharpoonright Bell_{\vec{D},P}^{\rightarrow}(X^2)$. As X^2 is (uniformly locally) compact, $\mathcal{D} \upharpoonright Bell_{\vec{D},P}^{\rightarrow}(X^2)$. Thus $\mathcal{O} \upharpoonright Gru_{\vec{O},P}^{\rightarrow}(X^2, \Delta)$, showing that X is Corson compact. \square

4.4 Limited information results

One may generalize many of the results originally shown by Bell [2] and Nyikos [18] by considering limited information strategies.

Theorem 4.4.1. *Let $k < \omega$. For all $x \in X$:*

- $\mathcal{D} \uparrow_{2k\text{-tact}} Bell_{D,P}^{\rightarrow}(X) \Rightarrow \mathcal{O} \uparrow_{k\text{-tact}} Gru_{O,P}^{\rightarrow}(X, x)$
- $\mathcal{D} \uparrow_{2k\text{-mark}} Bell_{D,P}^{\rightarrow}(X) \Rightarrow \mathcal{O} \uparrow_{k\text{-mark}} Gru_{O,P}^{\rightarrow}(X, x)$
- $\mathcal{D} \uparrow Bell_{D,P}^{\rightarrow}(X) \Rightarrow \mathcal{O} \uparrow Gru_{O,P}^{\rightarrow}(X, x)$

◇

Proof. The perfect-information result was originally shown by Bell. Let L_k represent either the k -tactical fog-of-war ν_k , the k -Markov fog-of-war μ_k , or the identity id .

Let $\sigma \circ L_{2k}$ be a winning strategy for \mathcal{D} in $Bell_{D,P}^{\rightarrow}(X)$. We define the strategy $\tau \circ L_k$ for \mathcal{O} in $Gru_{O,P}^{\rightarrow}(X, x)$ such that

$$\tau \circ L_k(t) = \sigma \circ L_{2k}(\langle x, t(0), \dots, x, t(|t| - 1) \rangle)[x] \cap \sigma \circ L_{2k}(\langle x, t(0), \dots, x, t(|t| - 1), x \rangle)[x]$$

Let p attack τ such that $p(n) \in \bigcap_{m \leq n} \tau \circ L_k(p \upharpoonright m)$. Consider the attack q against the winning strategy $\sigma \circ L_{2k}$ such that $q(2n) = x$ and $q(2n+1) = p(n)$. Let $D_n = \sigma \circ L_{2k}(q \upharpoonright n)$ and $E_n = \bigcap_{m \leq n} D_m$.

Certainly, $x \in E_{2n}[x] = E_{2n}[q(2n)]$ for any $n < \omega$. Note also for any $n < \omega$ that

$$\begin{aligned} p(n) &\in \bigcap_{m \leq n} \tau \circ L_k(p \upharpoonright m) \\ &= \bigcap_{m \leq n} (\sigma \circ L_{2k}(\langle x, p(0), \dots, x, p(m-1) \rangle)[x] \cap \sigma \circ L_{2k}(\langle x, p(0), \dots, x, p(m-1), x \rangle)[x]) \\ &= \bigcap_{m \leq n} (D_{2m}[x] \cap D_{2m+1}[x]) = \bigcap_{m \leq 2n+1} D_m[x] = E_{2n+1}[x] \end{aligned}$$

so by the symmetry of E_{2n+1} , $x \in E_{2n+1}[p(n)] = E_{2n+1}[q(2n+1)]$. Also, $q(2n+1) = p(n) \in E_{2n}[x] = E_{2n}[q(2n)]$ and $p(n) \in E_{2n+1}[x] \Rightarrow q(2n+2) = x \in E_{2n+1}[p(n)] = E_{2n+1}[q(2n+1)]$, making q a legal attack.

Then as $x \in \bigcap_{n < \omega} E_n[q(n)] \neq \emptyset$, and σ is a winning strategy, the attack q converges. Since $q(2n) = x$, q must converge to x . Thus its subsequence p converges to x , and $\tau \circ L_k$ is a winning strategy for \mathcal{O} in $\text{Gru}_{\mathcal{O},P}^{\rightarrow}(X, x)$. \square

Theorem 4.4.2. *Let $X \cup \{\infty\}$ be a uniformizable space with points in X isolated, and $k < \omega$. Then*

- $\mathcal{O} \uparrow_{k\text{-tact}} \text{Gru}_{\mathcal{O},P}^{\rightarrow}(X \cup \{\infty\}, \infty) \Leftrightarrow \mathcal{D} \uparrow_{k\text{-tact}} \text{Bell}_{D,P}^{\rightarrow}(X \cup \{\infty\})$
- $\mathcal{O} \uparrow_{k\text{-mark}} \text{Gru}_{\mathcal{O},P}^{\rightarrow}(X \cup \{\infty\}, \infty) \Leftrightarrow \mathcal{D} \uparrow_{k\text{-mark}} \text{Bell}_{D,P}^{\rightarrow}(X \cup \{\infty\})$
- $\mathcal{O} \uparrow \text{Gru}_{\mathcal{O},P}^{\rightarrow}(X \cup \{\infty\}, \infty) \Leftrightarrow \mathcal{D} \uparrow \text{Bell}_{D,P}^{\rightarrow}(X \cup \{\infty\})$

\diamond

Proof. The perfect-information result is due to Nyikos. Let L_k represent either the k -tactical fog-of-war ν_k , the k -Markov fog-of-war μ_k , or the identity id .

The right-to-left implications have already been shown. For any open neighborhood U of ∞ , $D(U) = \Delta \cup U^2$ is an entourage of X .

Let $\sigma \circ L_k$ be a winning strategy for $\text{Gru}_{\mathcal{O},P}^{\rightarrow}(X \cap \{\infty\}, \infty)$. We then define the strategy $\tau \circ L_k$ such that

$$\tau \circ L_k(t) = D(\sigma \circ L_k(t))$$

Let p attack τ such that $\bigcap_{n < \omega} \tau \circ L_k(p \upharpoonright n)[p(n)] \neq \emptyset$.

If $\infty \in \bigcap_{n < \omega} \tau \circ L_k(p \upharpoonright n)[p(n)]$, it follows that p is a legal attack on $\sigma \circ L_k$. Since $\sigma \circ L_k$ is a winning strategy, it follows that $p \rightarrow \infty$.

Otherwise, $\infty \notin \tau \circ L_k(p \upharpoonright N)[p(N)]$ for some $N < \omega$, and then $\tau \circ L_k(p \upharpoonright N)[p(N)] = \{p(N)\}$ implies $p \rightarrow p(N)$.

Thus $\tau \circ L_k$ is a winning strategy for $\text{Gru}_{\mathcal{O},P}^{\rightarrow}(X \cup \{\infty\}, \infty)$. \square

Corollary 4.4.3. *Let $X \cup \{\infty\}$ be a uniformizable space such that X is discrete, and $k < \omega$.*

Then

- $\mathcal{D} \uparrow_{k+1\text{-tact}} Bell_{D,P}^{\rightarrow}(X \cup \{\infty\}) \Leftrightarrow \mathcal{D} \uparrow_{tact} Bell_{D,P}^{\rightarrow}(X \cup \{\infty\})$
- $\mathcal{D} \uparrow_{k+1\text{-mark}} Bell_{D,P}^{\rightarrow}(X \cup \{\infty\}) \Leftrightarrow \mathcal{D} \uparrow_{mark} Bell_{D,P}^{\rightarrow}(X \cup \{\infty\})$

◇

Proof. The equivalencies hold for $Gru_{O,P}^{\rightarrow}(X, x)$. □

A close result may be obtained for arbitrary uniformizable spaces.

Proposition 4.4.4. *For any uniformizable space X and $k < \omega$,*

- $\mathcal{D} \uparrow_{k+2\text{-tact}} Bell_{D,P}^{\rightarrow}(X) \Leftrightarrow \mathcal{D} \uparrow_{2\text{-tact}} Bell_{D,P}^{\rightarrow}(X)$
- $\mathcal{D} \uparrow_{k+2\text{-mark}} Bell_{D,P}^{\rightarrow}(X) \Leftrightarrow \mathcal{D} \uparrow_{2\text{-mark}} Bell_{D,P}^{\rightarrow}(X)$

◇

Proof. If σ is a winning $k + 2$ -tactic, then define τ by

$$\tau(s) = \bigcap_{t \in \text{range}(s) < k+2} \sigma(t)$$

If σ is a winning $k + 2$ -mark, then define τ by

$$\tau(s, n) = \bigcap_{\substack{t \in \text{range}(s) < k+2 \\ m \leq (k+2)n}} \sigma(t, m)$$

In either case, the proof that τ is a winning limited information strategy is routine. □

Theorem 4.4.5. *Let X be a uniformizable space and H be a closed subset of X . If $k < \omega$, then*

- $\mathcal{D} \uparrow_{k\text{-tact}} Bell_{D,P}^{\rightarrow}(X) \Leftrightarrow \mathcal{D} \uparrow_{k\text{-tact}} Bell_{D,P}^{\rightarrow}(H)$

- $\mathcal{D} \uparrow_{k\text{-mark}} Bell_{D,P}^{\rightarrow}(X) \Leftrightarrow \mathcal{D} \uparrow_{k\text{-mark}} Bell_{D,P}^{\rightarrow}(H)$
- $\mathcal{D} \uparrow Bell_{D,P}^{\rightarrow}(X) \Leftrightarrow \mathcal{D} \uparrow Bell_{D,P}^{\rightarrow}(H)$

◇

Proof. The perfect-information result was originally shown by Bell. Let L_k represent either the k -tactical fog-of-war ν_k , the k -Markov fog-of-war μ_k , or the identity id .

Let $\sigma \circ L_k$ be a winning strategy for \mathcal{D} in $Bell_{D,P}^{\rightarrow}(X)$. We define the strategy $\tau \circ L_k$ for \mathcal{D} in $Bell_{D,P}^{\rightarrow}(H)$ as follows:

$$\tau \circ L(p \upharpoonright n) = \sigma \circ L(p \upharpoonright n) \cap H^2$$

Let p attack $\tau \circ L_k$. p also attacks the winning strategy $\sigma \circ L_k$, so either

$$\bigcap_{n < \omega} \left(\bigcap_{m \leq n} \tau \circ L(p \upharpoonright m) \right) [p(n)] \subseteq \bigcap_{n < \omega} \left(\bigcap_{m \leq n} \sigma \circ L(p \upharpoonright m) \right) [p(n)] = \emptyset$$

or $p : \omega \rightarrow H$ converges in X , and thus converges in H as H is closed. □

Bell showed the following to obtain a result of Mary Ellen Rudin [20] as a corollary.

Theorem 4.4.6. *A Σ -product of proximal spaces is proximal.* ◇

Corollary 4.4.7. *A Σ -product of metrizable spaces is collectionwise normal.* ◇

A sketch of the proof: \mathcal{D} may use the winning strategies for the proximal spaces coordinate-wise to ensure that either every coordinate converges, or one coordinate intersects to the empty set. But in order to do this throughout the entire game, perfect information is used in a non-trivial way to remember all coordinates for which \mathcal{D} played a point with non-zero value in that coordinate. But for countable products, this memory may be replaced with knowledge of the round number.

Lemma 4.4.8. *Let D_α be an entourage of X_α for $\alpha < \kappa$. Then $P_\alpha(D_\alpha) = \{\langle x, y \rangle : \langle x(\alpha), y(\alpha) \rangle \in D_\alpha\}$ is an entourage of $\prod_{\alpha < \kappa} X_\alpha$.* ◇

Proof. Let $D_\alpha \supseteq U_0$ and $U_{n+1} \circ U_{n+1} \subseteq U_n$ for neighborhoods U_n of the diagonal of X_α . Then note that $P_\alpha(U_n)$ is a neighborhood of the diagonal of $\prod_{\alpha < \kappa} X_\alpha$. Thus as $P_\alpha(D_\alpha) \supseteq P_\alpha(U_0)$ and $P_\alpha(U_{n+1}) \circ P_\alpha(U_{n+1}) \subseteq P_\alpha(U_n)$, we conclude $P_\alpha(D_\alpha)$ is an entourage. \square

Theorem 4.4.9. *If $\mathcal{D} \uparrow_{k\text{-mark}} Bell_{D,P}^\rightarrow(X_i)$ for $i < \omega$, then $\mathcal{D} \uparrow_{k\text{-mark}} Bell_{D,P}^\rightarrow(\prod_{i < \omega} X_i)$.* \diamond

Proof. Let σ_i be a winning k -mark for \mathcal{D} in $Bell_{D,P}^\rightarrow(X_i)$. For $s \in (\prod_{i < \omega} X_i)^{\leq \omega}$, let $s_i \in X_i^{\leq \omega}$ such that $s(j)(i) = s_i(j)$ for $j \in \text{dom}(s)$. Recall that ν_k removes all but the last k elements of a finite sequence, and for an countably infinite sequence p , let $p \upharpoonright^k n = \nu_k(p \upharpoonright n)$.

Define the k -mark τ for \mathcal{D} in $Bell_{D,P}^\rightarrow(\prod_{i < \omega} X_i)$ by

$$\tau(s, n) = \bigcap_{i \leq n} P_i(\sigma_i(s_i, n))$$

and let $p \in (\prod_{i < \omega} X_i)^\omega$ be a legal attack against τ , so the following must hold for $m, n < \omega$:

$$p(n+1) \in \left(\bigcap_{j \leq n} \tau(p \upharpoonright^k j, j) \right) [p(n)] = \left(\bigcap_{i \leq j \leq n} P_i(\sigma_i(p_i \upharpoonright^k j, j)) \right) [p(n)]$$

$$p_m(m+n+1) \in \left(\bigcap_{j \leq n} \sigma_m(p_m \upharpoonright^k (m+j), m+j) \right) [p_m(m+n)]$$

For $m < \omega$, attack σ_m with $q_m \in X_m^\omega$ defined by $q_m(n) = p_m(m+n)$. Note that

$$q_m(n+1) = p_m(m+n+1) \in \left(\bigcap_{j \leq n} \sigma_m(p_m \upharpoonright^k (m+j), m+j) \right) [p_m(m+n)]$$

$$\subseteq \left(\bigcap_{j \leq n} \sigma_m(q_m \upharpoonright^k (j), j) \right) [q_m(n)]$$

so q_m is a legal attack.

If for some $m < \omega$,

$$\emptyset = \left(\bigcap_{n < \omega} \sigma_m(q_m \upharpoonright^k n, n) \right) [q_m(n)] \supseteq \left(\bigcap_{n < \omega} \sigma_m(p_m \upharpoonright^k (m+n), n) \right) [p_m(m+n)]$$

$$\begin{aligned}
&\supseteq \left(\bigcap_{n < \omega} \sigma_m(p_m \upharpoonright^k (m+n), m+n) \right) [p_m(m+n)] \\
&= \left(\bigcap_{m \leq n < \omega} \sigma_m(p_m \upharpoonright^k n, n) \right) [p_m(n)]
\end{aligned}$$

then

$$\begin{aligned}
&\bigcap_{n < \omega} \left(\bigcap_{j \leq n} \tau(p \upharpoonright^k j, j) \right) [p(n)] = \bigcap_{n < \omega} \left(\bigcap_{i \leq j \leq n} P_i(\sigma_i(p_m \upharpoonright^k j, j)) \right) [p(n)] \\
&\subseteq \bigcap_{m \leq n < \omega} \left(\bigcap_{m \leq j \leq n} P_m(\sigma_m(p_m \upharpoonright^k j, j)) \right) [p(n)] \subseteq \bigcap_{m \leq n < \omega} \left(\bigcap_{m \leq n} P_m(\sigma_m(p_m \upharpoonright^k n, n)) \right) [p(n)] \\
&= \bigcap_{m \leq n < \omega} \left(\bigcap_{m \leq n} P_m(\sigma_m(p_m \upharpoonright^k n, n)[p_m(n)]) \right) = \bigcap_{m \leq n < \omega} P_m(\sigma_m(p_m \upharpoonright^k n, n)[p_m(n)]) \\
&= P_m \left(\bigcap_{m \leq n < \omega} \sigma_m(p_m \upharpoonright^k n, n)[p_m(n)] \right) = P_m(\emptyset) = \emptyset
\end{aligned}$$

Otherwise for all $m < \omega$, q_m converges to some $x_m \in X_m$, then p_m converges to $x_m \in X_m$ and thus p converges. This shows that τ is a winning k -mark. \square

Chapter 5

Gruenhage's Locally Finite Games

A variation of $Gru_{\vec{O},P}(X, x)$, also due to Gruenhage, may be used to characterize various covering properties, particularly for locally compact spaces. We assume all spaces are T_1 .

5.1 Characterizations using $Gru_{K,P}(X)$, $Gru_{K,L}(X)$

Game 5.1.1. Let $Gru_{K,P}(X)$ denote the *Gruenhage compact/point game* with players \mathcal{K} , \mathcal{P} . During round n , \mathcal{K} chooses a compact subset K_n of X , followed by \mathcal{P} choosing a point $p_n \in X$ such that $p_n \notin \bigcup_{m \leq n} K_m$.

\mathcal{K} wins the game if the collection $\{\{p_n\} : n < \omega\}$ is locally finite in the space, and \mathcal{P} wins otherwise. \diamond

This game is often formulated by requiring that the collection $\{\{p_n\} : n < \omega\}$ be discrete. With the knowledge of at least the latest move of the opponent, \mathcal{K} may guarantee that if $\{\{p_n\} : n < \omega\}$ is locally finite then it is also discrete, since she may require $p_n \in K_{n+1}$. Thus this formulation is essentially equivalent to the usual formulation for all existing applications.

We may relate this game to $Gru_{\vec{O},P}(X, x)$ as follows:

Theorem 5.1.2. *If X is locally compact, then for $k < 2$:*

- $\mathcal{K} \uparrow Gru_{K,P}(X)$ if and only if $\mathcal{O} \uparrow Gru_{\vec{O},P}(X^*, \infty)$.
- $\mathcal{K} \uparrow_{k\text{-mark}} Gru_{K,P}(X)$ if and only if $\mathcal{O} \uparrow_{k\text{-mark}} Gru_{\vec{O},P}(X^*, \infty)$.
- $\mathcal{K} \uparrow_{k\text{-tact}} Gru_{K,P}(X)$ if and only if $\mathcal{O} \uparrow_{k\text{-tact}} Gru_{\vec{O},P}(X^*, \infty)$.

\diamond

Proof. Let L be any of $\nu_0, \nu_1, \mu_0, \mu_1$, or the identity. For any sequence s of points in X^* , let s' be the subsequence of non- ∞ points in s .

If $\sigma \circ L$ is a winning strategy for \mathcal{K} in $\text{Gru}_{K,P}(X)$, let $\tau \circ L$ be a strategy for \mathcal{O} in $\text{Gru}_{\vec{\mathcal{O}},P}(X^*, \infty)$ such that $\tau(L(s)) = X^* \setminus \sigma(L(s)')$. Then for any legal attack p against τ , p' is a legal attack against σ . (The proof of this claim uses the fact that $k < 2$.) If p' is a finite sequence, then p converges to ∞ . Otherwise, the set $\{p'(n) : n < \omega\}$ is locally finite in X , so $\{p'(n) : n < \omega\}$ is a closed discrete subset of X . Then for every neighborhood U of ∞ , $X \setminus U$ is contained in a compact set, so it cannot contain a closed discrete subset. Thus p' and p converge to ∞ .

If $\sigma \circ L$ is a winning strategy for \mathcal{O} in $\text{Gru}_{\vec{\mathcal{O}},P}(X^*, \infty)$, let $\tau \circ L$ be a strategy for \mathcal{K} in $\text{Gru}_{K,P}(X)$ such that $\tau(L(s)) = X \setminus \sigma(L(s))$. Then for any legal attack p against τ , p is a legal attack against σ , so the sequence p converges to ∞ . For any point $x \in X$ distinct from the $p(n)$, we may choose a neighborhood U_x of x in X missing every point in $p(n)$. For every $n < \omega$, we may choose a neighborhood $U_{p(n)}$ of $p(n)$ in X which misses every distinct $p(m)$. Thus $\{p(n) : n < \omega\}$ is a locally finite collection. \square

The reason why $\text{Gru}_{\vec{\mathcal{O}},P}(X^*, \infty)$ and $\text{Gru}_{K,P}(X)$ are not completely equivalent is due to the fact that \mathcal{P} may hide information from \mathcal{O} by playing ∞ . These moves cannot trivially be ignored using a k -limited information strategy for $k \geq 2$, since \mathcal{P} may ensure that only one “useful” move may be seen by \mathcal{K} at a time by playing k ∞ s between each non- ∞ .

Applications of limited information strategies for \mathcal{K} are already known; see [9].

Theorem 5.1.3. *The following are equivalent for a locally compact space X :*

- X is metacompact
- $\mathcal{K} \uparrow_{\text{tact}} \text{Gru}_{K,P}(X)$.

\diamond

Theorem 5.1.4. *The following are equivalent for a locally compact space X :*

- X is σ -metacompact

- $\mathcal{K} \uparrow_{\text{mark}} Gru_{K,P}(X)$.

◇

In addition, it's trivial to show the following.

Proposition 5.1.5. *The following are equivalent for any space X :*

- X is compact

- $\mathcal{K} \uparrow_{0\text{-tact}} Gru_{K,P}(X)$.

◇

Proof. A 0-tactic is seeded with zero information about the moves of the opponent or the round number, so it must be a constant function valued at X . □

A similar game may be considered by allowing the second player to choose compact sets rather than points, which also provided in [9] a game-theoretic characterization of a covering property for locally compact spaces.

Game 5.1.6. Let $Gru_{K,L}(X)$ denote the *Gruenhage compact/compact game* with players \mathcal{K}, \mathcal{L} . This game proceeds analogously to $Gru_{K,P}(X)$, except the second player \mathcal{L} chooses compact sets L_n missing $\bigcup_{m \leq n} K_m$, and \mathcal{K} wins if the collection $\{L_n : n < \omega\}$ is locally finite. ◇

As above, this formulation is equivalent to requiring $\{L_n : n < \omega\}$ be discrete when considering strategies for \mathcal{K} which use at least the latest move of \mathcal{L} .

Theorem 5.1.7. *The following are equivalent for a locally compact space X :*

- X is paracompact

- $\mathcal{K} \uparrow Gru_{K,L}(X)$.

◇

5.2 Predetermined strategies for $Gru_{K,P}(X)$, $Gru_{K,L}(X)$

Adding knowledge of the round number to a tactic changes the characterization from metacompact to σ -metacompact. In fact, the analogous result holds for 0-tactics to 0-marks, known as predetermined strategies since they rely only on the round number and not the moves of the opponent.

Theorem 5.2.1. *If X is a locally compact Lindelöf space, then $\mathcal{K} \uparrow_{pre} G_{K,L}(X)$.* \diamond

Proof. For each $x \in X$, let U_x be an open neighborhood of x with $\overline{U_x}$ compact. Then as X is Lindelöf, choose $x_n \in X$ for $n < \omega$ such that $\{U_{x_n} : n < \omega\}$ covers X . Define the predetermined strategy σ for \mathcal{K} by $\sigma(n) = \overline{U_{x_n}}$.

Let $L : \omega \rightarrow \mathcal{K}(X)$ legally attack σ , so $L(n) \cap \bigcup_{m \leq n} \sigma(m) = \emptyset$. For each $x \in X$, choose $n < \omega$ with $x \in U_{x_n}$. Then U_{x_n} is a neighborhood of x which intersects finitely many $L(n)$, so $\{L(n) : n < \omega\}$ is locally finite. \square

Definition 5.2.2. A space X is **hemicompact** if there exist compact sets K_n for $n < \omega$ such that every compact set in X is a subset of some K_n . \diamond

Theorem 5.2.3. *If $\mathcal{K} \uparrow_{pre} Gru_{K,P}(X)$, then X is hemicompact.* \diamond

Proof. Let σ be a winning predetermined strategy for \mathcal{K} in $Gru_{K,P}(X)$. If $C \in \mathcal{K}(X)$ is compact, then for each $x \in C$ let U_x be an open neighborhood of x which intersects finitely many $\sigma(n)$. Thus there exists an open neighborhood of C which intersects finitely many $\sigma(n)$. \square

Corollary 5.2.4. *The following are equivalent for any locally compact space X :*

- X is Lindelöf.
- X is σ -compact.
- X is hemicompact.

- $\mathcal{K} \uparrow_{pre} Gru_{K,P}(X)$.
- $\mathcal{K} \uparrow_{pre} Gru_{K,L}(X)$.

◇

5.3 Compactly generated spaces

Definition 5.3.1. A space X is *compactly generated* if a set is closed if and only if its intersection is closed in every compact subspace. Such spaces are also known as *k-spaces*.

◇

All locally compact spaces are *k-spaces*. As will be shown, the games $Gru_{K,P}(X)$, $Gru_{K,L}(X)$ are equivalent for \mathcal{K} 's predetermined strategies in Hausdorff *k-spaces*.

Definition 5.3.2. A space X is a k_ω -space if there exist compact sets K_n for $n < \omega$ such that a set is closed if and only if its intersection is closed in every subspace K_n .

◇

Theorem 5.3.3. If X is a Hausdorff hemicompact *k-space*, then $\mathcal{K} \uparrow_{pre} Gru_{K,L}(X)$.

◇

Proof. Let K_n witness hemicompactness for X . Define the predetermined strategy σ for \mathcal{K} by $\sigma(n) = K_n$.

Let $L : \omega \rightarrow \mathcal{K}(X)$ be a legal attack against σ , and let $L_\omega = \bigcup_{n < \omega} L(n)$. For each compact set (TODO FINISH)

□

Corollary 5.3.4. The following are equivalent for any Hausdorff *k-space* X :

- X is hemicompact.
- X is k_ω .
- $\mathcal{K} \uparrow_{pre} Gru_{K,P}(X)$.
- $\mathcal{K} \uparrow_{pre} Gru_{K,L}(X)$.

◇

Chapter 6

Menger's Game and Rothberger's Game

In 1924 Karl Menger introduced a covering property generalizing σ -compactness [15].

Definition 6.0.5. A space X is Menger if for every sequence $\langle \mathcal{U}_0, \mathcal{U}_1, \dots \rangle$ of open covers of X there exists a sequence $\langle \mathcal{F}_0, \mathcal{F}_1, \dots \rangle$ such that $\mathcal{F}_n \subseteq \mathcal{U}_n$, $|\mathcal{F}_n| < \omega$, and $\bigcup_{n < \omega} \mathcal{F}_n$ is a cover of X . \diamond

Proposition 6.0.6. X is σ -compact $\Rightarrow X$ is Menger $\Rightarrow X$ is Lindelöf. \diamond

None of these implications may be reversed; the irrationals are a simple example of a Lindelöf space which is not Menger, and we'll see several examples of Menger spaces which are not σ -compact.

It can be shown via a non-trivial proof that the following game can be used to characterize the Menger property.

Definition 6.0.7. For each cover \mathcal{U} of X , $S \subseteq X$ is \mathcal{U} -finite if there exists a finite subcollection of \mathcal{U} which covers S . \diamond

Of course, a compact space is \mathcal{U} -finite for all open covers \mathcal{U} .

Game 6.0.8. Let $Men_{C,F}(X)$ denote the *Menger game* with players \mathcal{C} , \mathcal{F} . In round n , \mathcal{C} chooses an open cover \mathcal{U}_n , followed by \mathcal{F} choosing a \mathcal{U}_n -finite subset F_n of X .

\mathcal{F} wins the game if $X = \bigcup_{n < \omega} F_n$, and \mathcal{C} wins otherwise. \diamond

Theorem 6.0.9. A space X is Menger if and only if $\mathcal{C} \nmid Men_{C,F}(X)$ [11]. \diamond

The typical characterization of the Menger game involves \mathcal{F} choosing a finite subcollection \mathcal{F}_n of \mathcal{U}_n , but it is easy to see that the characterization given above is equivalent, and will be convenient for use in our proofs.

6.1 Markov strategies

To the author's knowledge, no other direct work has been done on limited information strategies pertaining to the Menger game, although as we'll see there are results which can be sharpened when considering them. However, we immediately see that tactics are not of any real interest.

Proposition 6.1.1. *X is compact if and only if $\mathcal{F} \uparrow_{tact} Men_{C,F}(X)$ if and only if $\mathcal{F} \uparrow_{k-tact} Men_{C,F}(X)$.* \diamond

Proof. If σ is a winning k -tactic, then for each open cover \mathcal{U} , σ defeats the attack $\langle \mathcal{U}, \mathcal{U}, \dots \rangle$. Then

$$\bigcup_{i \leq k} \sigma(\underbrace{\langle \mathcal{U}, \dots, \mathcal{U} \rangle}_i) = X$$

and X is \mathcal{U} -finite. \square

Essentially, because \mathcal{C} may repeat the same finite sequence of open covers, \mathcal{F} needs to be seeded with knowledge of the round number to prevent being trapped in a loop.

If \mathcal{F} 's memory of \mathcal{C} 's past moves is bounded, then there is no need to consider more than the two most recent moves. The intuitive reason is that \mathcal{C} could simply play the same cover repeatedly until \mathcal{F} 's memory is exhausted, in which case \mathcal{F} would only ever see the change from one cover to another.

Theorem 6.1.2. *There exists $k < \omega$ such that $F \uparrow_{(k+2)\text{-mark}} Men_{C,F}(X)$ if and only if $F \uparrow_{2\text{-mark}} Men_{C,F}(X)$.* \diamond

Proof. Let σ be a winning $(k+2)$ -mark. We define the 2-mark τ as follows:

$$\begin{aligned} \tau(\langle \mathcal{U} \rangle, 0) &= \bigcup_{m < k+2} \sigma(\underbrace{\langle \mathcal{U}, \dots, \mathcal{U} \rangle}_{m+1}, m) \\ \tau(\langle \mathcal{U}, \mathcal{V} \rangle, n+1) &= \bigcup_{m < k+2} \sigma(\underbrace{\langle \mathcal{U}, \dots, \mathcal{U} \rangle}_{k+1-m}, \underbrace{\langle \mathcal{V}, \dots, \mathcal{V} \rangle}_{m+1}, (n+1)(k+2) + m) \end{aligned}$$

Let $\langle \mathcal{U}_0, \mathcal{U}_1, \dots \rangle$ be an attack by \mathcal{C} against τ . Then consider the attack

$$\langle \underbrace{\mathcal{U}_0, \dots, \mathcal{U}_0}_{k+2}, \underbrace{\mathcal{U}_1, \dots, \mathcal{U}_1}_{k+2}, \dots \rangle$$

by \mathcal{C} against σ . Since σ is a winning $(k+2)$ -mark,

$$\begin{aligned} X &= \bigcup_{m < k+2} \sigma(\langle \underbrace{\mathcal{U}_0, \dots, \mathcal{U}_0}_{m+1} \rangle, m) \cup \bigcup_{n < \omega} \bigcup_{m < k+2} \sigma(\langle \underbrace{\mathcal{U}_n, \dots, \mathcal{U}_n}_{k+1-m}, \underbrace{\mathcal{U}_{n+1}, \dots, \mathcal{U}_{n+1}}_{m+1} \rangle, (n+1)(k+2) + m) \\ &= \tau(\langle \mathcal{U}_0 \rangle, 0) \cup \bigcup_{n < \omega} \tau(\langle \mathcal{U}_n, \mathcal{U}_{n+1} \rangle, n+1) \end{aligned}$$

Thus τ is a winning 2-mark. □

A natural question arises: is there an example of a space X for which $\mathcal{F} \uparrow_{2\text{-mark}} \text{Men}_{C,F}(X)$ but $\mathcal{F} \not\uparrow_{\text{mark}} \text{Men}_{C,F}(X)$? We quickly see that perhaps the simplest example of a Lindelöf non- σ -compact space has this property.

Definition 6.1.3. For any cardinal κ , let $\kappa^\dagger = \kappa \cup \{\infty\}$ denote the *one-point Lindelöfication* of discrete κ , where points in κ are isolated, and the neighborhoods of ∞ are the co-countable sets containing it. ◇

Theorem 6.1.4. $F \not\uparrow_{\text{mark}} \text{Men}_{C,F}(\omega_1^\dagger)$. ◇

Proof. This result will later follow from the fact that ω_1^\dagger is not a σ -compact space (all its compact subsets are finite).

For now, let σ be a Markov strategy for \mathcal{F} . For each $\alpha < \omega_1$, let \mathcal{U}_α be the open cover $\{\{\beta\} : \beta < \alpha\} \cup \{\omega_1^\dagger \setminus \alpha\}$ of ω_1^\dagger , and set $F(\alpha, n)$ to be the finite set $\alpha \cap \sigma(\langle \mathcal{U}_\alpha \rangle, n)$.

If $P_n = \{\beta : \beta < \alpha < \omega_1 \Rightarrow \beta \in F(\alpha, n)\}$, then $P_n \subseteq F(\sup(P_n) + 1, n)$. Thus P_n is finite for $n < \omega$. Choose $\beta \in \omega_1 \setminus \bigcup_{n < \omega} P_n$ and $\alpha_n > \beta$ such that $\beta \notin F(\alpha_n, n)$. Then \mathcal{C} may attack σ with $\langle \mathcal{U}_{\alpha_0}, \mathcal{U}_{\alpha_1}, \dots \rangle$, and it follows that $\beta \notin \bigcup_{n < \omega} F(\alpha_n, n)$ and $\beta \notin \bigcup_{n < \omega} \sigma(\langle \mathcal{U}_{\alpha_n} \rangle, n)$. □

The greatest advantage of a strategy which has knowledge of two or more previous moves of the opponent, versus only knowledge of the most recent move, is the ability to react to

changes from one round to the next. It's this ability to react that will give \mathcal{F} her winning 2-Markov strategy in the Menger game on ω_1^\dagger .

For inspiration, we turn to a game whose n -tactics were studied by Marion Scheepers in [21] which has similar goals to the Menger game when played upon κ^\dagger .

Game 6.1.5. Let $Fill_{C,F}^{\cup,\subseteq}(\kappa)$ denote the *strict union filling game* with two players \mathcal{C} , \mathcal{F} . In round 0, \mathcal{C} chooses $C_0 \in [\kappa]^{\leq \omega}$, followed by \mathcal{F} choosing $F_0 \in [\kappa]^{< \omega}$. In round $n + 1$, \mathcal{C} chooses $C_{n+1} \in [\kappa]^{\leq \omega}$ such that $C_{n+1} \supset C_n$, followed by \mathcal{F} choosing $F_{n+1} \in [\kappa]^{< \omega}$.

\mathcal{F} wins the game if $\bigcup_{n < \omega} F_n \supseteq \bigcup_{n < \omega} C_n$; otherwise, \mathcal{C} wins. \diamond

In $Men_{C,F}(\kappa^\dagger)$, \mathcal{C} essentially chooses a countable set to not include in her neighborhood of ∞ , followed by \mathcal{F} choosing a finite subset of this complement to cover during each round. Thus, \mathcal{F} need only be concerned with the *intersection* of the countable sets chosen by \mathcal{C} in $Men_{C,F}(\kappa^\dagger)$, rather than the union as in $Fill_{C,F}^{\cup,\subseteq}(\kappa)$.

Another difference: Scheepers required that \mathcal{C} always choose strictly growing countable sets. The reasoning is clear: if the goal is to study tactics, then \mathcal{C} cannot be allowed to trap \mathcal{F} in a loop by repeating the same moves. But by eliminating this requirement, the study can then turn to Markov strategies, bringing the game further in line with the Menger game played upon κ^\dagger .

We introduce a few games to make the relationship between Scheepers's $Fill_{C,F}^{\cup,\subseteq}(\kappa)$ and $Men_{C,F}(\kappa^\dagger)$ more precise.

Game 6.1.6. Let $Fill_{C,F}^{\cup,\subseteq}(\kappa)$ denote the *union filling game* which proceeds analogously to $Fill_{C,F}^{\cup,\subseteq}(\kappa)$, except that \mathcal{C} 's restriction in round $n + 1$ is reduced to $C_{n+1} \supseteq C_n$. \diamond

Game 6.1.7. Let $Fill_{C,F}^{1,\subseteq}(\kappa)$ denote the *initial filling game* which proceeds analogously to $Fill_{C,F}^{\cup,\subseteq}(\kappa)$, except that \mathcal{F} wins whenever $\bigcup_{n < \omega} F_n \supseteq C_0$. \diamond

Game 6.1.8. Let $Fill_{C,F}^\cap(\kappa)$ denote the *intersection filling game* which proceeds analogously to $Fill_{C,F}^{1,\subseteq}(\kappa)$, except that \mathcal{C} may choose any $C_n \in [\kappa]^{\leq \omega}$ each round, and \mathcal{F} wins whenever $\bigcup_{n < \omega} F_n \supseteq \bigcap_{n < \omega} C_n$. \diamond

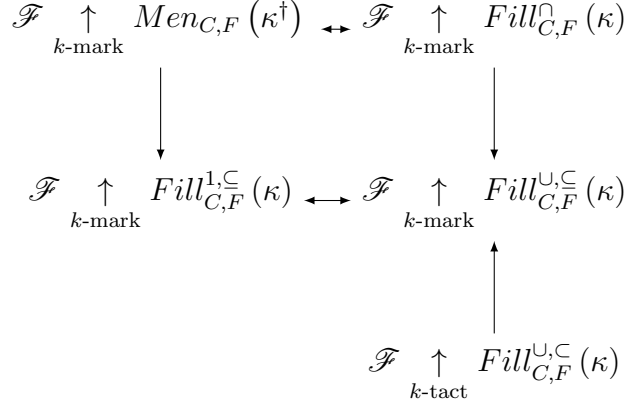


Figure 6.1: Diagram of Filling/Menger game implications

Theorem 6.1.9. *For any cardinal $\kappa > \omega$ and integer $k < \omega$, Figure 6.1 holds.* \diamond

Proof. $\mathcal{F} \uparrow_{k\text{-mark}} Men_{C,F}(\kappa^\dagger) \Rightarrow \mathcal{F} \uparrow_{k\text{-mark}} Fill_{C,F}^\cap(\kappa)$: Let σ be a winning k -mark for \mathcal{F} in $Men_{C,F}(\kappa^\dagger)$. Let $\mathcal{U}(C)$ (resp. $\mathcal{U}(s)$) convert each countable subset C of κ (resp. finite sequence s of such subsets) into the open cover $[C]^1 \cup \{\kappa^\dagger \setminus C\}$ (resp. finite sequence of such open covers). Then τ defined by

$$\tau(s^\frown \langle C \rangle, n) = C \cap \sigma(\mathcal{U}(s^\frown \langle C \rangle), n)$$

is a winning k -mark for \mathcal{F} in $Fill_{C,F}^\cap(\kappa)$.

$\mathcal{F} \uparrow_{k\text{-mark}} Fill_{C,F}^\cap(\kappa) \Rightarrow \mathcal{F} \uparrow_{k\text{-mark}} Men_{C,F}(\kappa^\dagger)$: Let σ be a winning k -mark for \mathcal{F} in $Fill_{C,F}^\cap(\kappa)$. Let $C(\mathcal{U})$ (resp. $C(s)$) convert each open cover \mathcal{U} of κ^\dagger (resp. finite sequence s of such covers) into a countable set C which is the complement of some neighborhood of ∞ in \mathcal{U} (resp. finite sequence of such countable sets). Then τ defined by

$$\tau(s^\frown \langle \mathcal{U} \rangle, n) = (\kappa^\dagger \setminus C(\mathcal{U})) \cup \sigma(C(s^\frown \langle \mathcal{U} \rangle), n)$$

is a winning k -mark for \mathcal{F} in $Men_{C,F}(\kappa^\dagger)$.

$\mathcal{F} \uparrow_{k\text{-mark}} \text{Fill}_{C,F}^\cap(\kappa) \Rightarrow \mathcal{F} \uparrow_{k\text{-mark}} \text{Fill}_{C,F}^{1;\subseteq}(\kappa)$: Let σ be a winning k -mark for \mathcal{F} in $\text{Fill}_{C,F}^\cap(\kappa)$. σ is also a winning k -mark for \mathcal{F} in $\text{Fill}_{C,F}^{1;\subseteq}(\kappa)$.

$\mathcal{F} \uparrow_{k\text{-mark}} \text{Fill}_{C,F}^{1;\subseteq}(\kappa) \Rightarrow \mathcal{F} \uparrow_{k\text{-mark}} \text{Fill}_{C,F}^{\cup;\subseteq}(\kappa)$: Let σ be a winning k -mark for \mathcal{F} in $\text{Fill}_{C,F}^{1;\subseteq}(\kappa)$. For each finite sequence s , let $t \preceq s$ mean t is a final subsequence of s . Then τ defined by

$$\tau(s \smallfrown \langle C \rangle, n) = \bigcup_{t \preceq s, m \leq n} \sigma(t \smallfrown \langle C \rangle, m)$$

is a winning k -mark for \mathcal{F} in $\text{Fill}_{C,F}^{\cup;\subseteq}(\kappa)$.

$\mathcal{F} \uparrow_{k\text{-mark}} \text{Fill}_{C,F}^{\cup;\subseteq}(\kappa) \Rightarrow \mathcal{F} \uparrow_{k\text{-mark}} \text{Fill}_{C,F}^{1;\subseteq}(\kappa)$: Let σ be a winning k -mark for \mathcal{F} in $\text{Fill}_{C,F}^{\cup;\subseteq}(\kappa)$. σ is also a winning k -mark for \mathcal{F} in $\text{Fill}_{C,F}^{1;\subseteq}(\kappa)$.

$\mathcal{F} \uparrow_{k\text{-tact}} \text{Fill}_{C,F}^{\cup;\subseteq}(\kappa) \Rightarrow \mathcal{F} \uparrow_{k\text{-mark}} \text{Fill}_{C,F}^{\cup;\subseteq}(\kappa)$: Let σ be a winning k -tactic for \mathcal{F} in $\text{Fill}_{C,F}^{\cup;\subseteq}(\kappa)$. For each countable subset C of κ , let $C + n$ be the union of C with the n least ordinals in $\kappa \setminus C$. Then τ defined by

$$\tau(\langle C_0, \dots, C_i \rangle, n) = \sigma(\langle C_0 + (n - i), \dots, C_i + n \rangle)$$

is a winning k -mark for \mathcal{F} in $\text{Fill}_{C,F}^{\cup;\subseteq}(\kappa)$. □

While we have not proven a direct implication between the Menger game and Scheeper's original filling game, Scheepers introduced the statement $S(\kappa)$ relating to the almost-compatability of functions from countable subsets of κ into ω which may be applied to both.

Definition 6.1.10. For two functions f, g we say f is μ -almost compatible with g ($f \parallel_\mu^* g$) if $|\{x \in \text{dom}(f) \cap \text{dom}(g) : f(x) \neq g(x)\}| < \mu$. If $\mu = \omega$ then we say f, g are **almost compatible** ($f \parallel^* g$). ◇

Definition 6.1.11. $S(\kappa)$ states that there exist functions $f_A : A \rightarrow \omega$ for each $A \in [\kappa]^{\leq \omega}$ such that $|\{\alpha \in A : f_A(\alpha) \leq n\}| < \omega$ for all $n < \omega$ and $f_A \parallel^* f_B$ for all $A, B \in [\kappa]^\omega$.¹ ◇

¹This is equivalent to the original characterization given in [21]: there exist injections $g_A : A \rightarrow \omega$ such that $g_A \parallel^* g_B$ for all $A, B \in [\kappa]^\omega$ and $A \subset B$.

Scheepers went on to show that $S(\kappa)$ implies $\mathcal{F} \uparrow_{2\text{-tact}} \text{Fill}_{C,F}^{\cup,\subseteq}(\kappa)$. This proof, along with the following facts, give us inspiration for finding a winning 2-Markov strategy in the Menger game played on κ^\dagger .

Theorem 6.1.12. $S(\omega_1)$ and $\kappa > 2^\omega \Rightarrow \neg S(\kappa)$ are theorems of ZFC . $S(2^\omega)$ is a theorem of $ZFC + CH$ and consistent with $ZFC + \neg CH$. \diamond

Proof. For $S(\omega_1)$, look at pg. 70 of [12]; this of course implies $S(2^\omega)$ under CH . $\neg S((2^\omega)^+)$ is shown by a cardinality argument in [21]. The consistency result under $ZFC + \neg CH$ is a lemma for the main theorem in [21]. \square

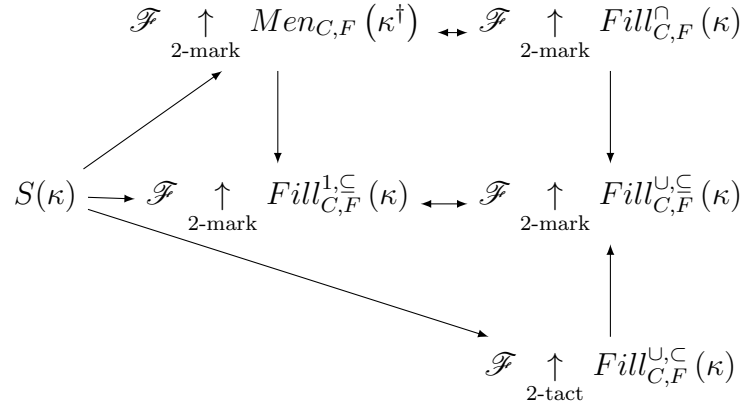


Figure 6.2: Diagram of Filling/Menger game implications with $S(\kappa)$

Theorem 6.1.13. $S(\kappa)$ implies the game-theoretic results in Figure 6.2. \diamond

Proof. Since $S(\kappa) \Rightarrow \mathcal{F} \uparrow_{2\text{-tact}} \text{Fill}_{C,F}^{\cup,\subseteq}(\kappa)$ was a main result of [21], it is sufficient to show that $S(\kappa) \Rightarrow \mathcal{F} \uparrow_{2\text{-mark}} \text{Fill}_{C,F}^\cap(\kappa)$.

Let f_A for $A \in [\kappa]^{\leq \omega}$ witness $S(\kappa)$. We define the 2-mark σ as follows:

$$\sigma(\langle A \rangle, 0) = \{\alpha \in A : f_A(\alpha) \leq 0\}$$

$$\sigma(\langle A, B \rangle, n+1) = \{\alpha \in A \cap B : f_B(\alpha) \leq n+1 \text{ or } f_A(\alpha) \neq f_B(\alpha)\}$$

For any attack $\langle A_0, A_1, \dots \rangle$ by \mathcal{C} and $\alpha \in \bigcap_{n < \omega} A_n$, either $f_{A_n}(\alpha)$ is constant for all n , or $f_{A_n}(\alpha) \neq f_{A_{n+1}}(\alpha)$ for some n ; either way, α is covered. \square

Corollary 6.1.14. $\mathcal{F} \xrightarrow[2\text{-mark}]{\uparrow} Men_{C,F}(\omega_1^\dagger)$. \diamond

6.2 Menger game derived covering properties

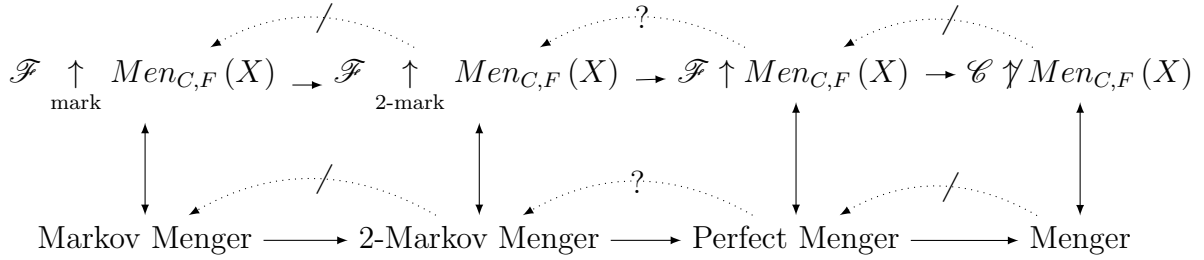


Figure 6.3: Diagram of covering properties related to the Menger game

Limited information strategies for the Menger game naturally define a spectrum of covering properties, see Figure 6.3. However, we do not know if the middle two properties are actually distinct.

Question 6.2.1. Does there exist a space X such that $\mathcal{F} \xrightarrow{\uparrow} Men_{C,F}(X)$ but $\mathcal{F} \not\xrightarrow[2\text{-mark}]{\uparrow} Men_{C,F}(X)$? \diamond

We are also interested in non-game-theoretic characterizations of these covering properties. It has been known for some time that for metrizable spaces, winning Menger spaces are exactly the σ -compact spaces, shown first by Telgarsky in [24] and later directly by Scheepers in [23].

In the interest of generality, we will first characterize the Markov Menger spaces without any separation axioms.

Definition 6.2.2. A subset Y of X is *relatively compact* to X if for every open cover of X , there exists a finite subcollection which covers Y . \diamond

For example, any bounded subset of Euclidean space is relatively compact whether it is closed or not. Actually, relative compactness can be thought of as an analogue of boundedness for regular spaces.

Proposition 6.2.3. *For regular spaces, Y is relatively compact to X if and only if \overline{Y} is compact in X .*² \diamond

Proof. For any space, any subset of a compact set is relatively compact.

Assume Y is relatively compact, let \mathcal{U} be an open cover of \overline{Y} , and define $x \in V_x \subseteq \overline{V_x} \subseteq U_x \in \mathcal{U}$ for each $x \in X$. Then if we take a subcollection $\mathcal{F} = \{V_{x_i} : i < n\}$ covering Y by relative compactness, then $\{U_{x_i} : i < n\}$ is a finite subcollection of \mathcal{U} covering \overline{Y} , showing compactness. \square

We now begin the process of factoring out Scheeper's proof to reveal the limited information implications at work.

Lemma 6.2.4. *Let $\sigma(\mathcal{U}, n)$ be a Markov strategy for F in $\text{Men}_{C,F}(X)$, and \mathfrak{C} collect all open covers of X . Then the set*

$$R_n = \bigcap_{\mathcal{U} \in \mathfrak{C}} \sigma(\mathcal{U}, n)$$

is relatively compact to X . If σ is a winning Markov strategy, then $\bigcup_{n < \omega} R_n = X$. \diamond

Proof. First, for every open cover $\mathcal{U} \in \mathfrak{C}$, $R_n \subseteq \sigma(\mathcal{U}, n)$ is covered by a finite subcollection of \mathcal{U} .

Suppose that $x \notin R_n$ for any $n < \omega$. Then for each n , pick $\mathcal{U}_n \in \mathfrak{C}$ such that $x \notin \sigma(\mathcal{U}_n, n)$. Then \mathcal{C} may counter σ with the attack $\langle \mathcal{U}_0, \mathcal{U}_1, \dots \rangle$. \square

Definition 6.2.5. A σ -relatively-compact space is the countable union of relatively compact subsets. \diamond

²It should be noted that some authors define relative compactness in this way, but such a definition creates pathological implications for non-regular spaces. For example, the singleton containing the particular point of an infinite space with the particular point topology would not be relatively compact since its closure is not compact, even though it is finite.

Corollary 6.2.6. *The following are equivalent:*

- X is σ -relatively-compact
- $F \uparrow_{pre} Men_{C,F}(X)$
- $F \uparrow_{mark} Men_{C,F}(X)$

◇

Proof. If $X = \bigcup_{n < \omega} R_n$ for R_n relatively compact, then $\sigma(n) = R_n$ is a winning predetermined strategy, which yields a winning Markov strategy. The previous lemma finishes the proof. □

Corollary 6.2.7. *Let X be a regular space. The following are equivalent:*

- X is σ -compact
- X is σ -relatively-compact
- $F \uparrow_{pre} Men_{C,F}(X)$
- $F \uparrow_{mark} Men_{C,F}(X)$

◇

For Lindelöf spaces, metrizability is characterized by regularity and second-countability, the latter of which was essentially used by Scheepers in this way:

Lemma 6.2.8. *Let X be a second-countable space. $\mathcal{F} \uparrow Men_{C,F}(X)$ if and only if $\mathcal{F} \uparrow_{mark} Men_{C,F}(X)$.* ◇

Proof. Let σ be a strategy for \mathcal{F} , and note that it's sufficient to consider playthroughs with only basic open covers.

So if \mathcal{U}_t is a basic open cover for $t < s \in \omega^{<\omega}$, and \mathcal{V} is any basic open cover, we may choose a finite subcollection $\mathcal{F}(s, \mathcal{V})$ of \mathcal{V} such that

$$\sigma(\langle \mathcal{U}_{s \upharpoonright 1}, \dots, \mathcal{U}_s, \mathcal{V} \rangle) \subseteq \bigcup \mathcal{F}(s, \mathcal{V})$$

Note that there are only countably-many finite collections of basic open sets. Thus we may choose basic open covers $\mathcal{U}_{s \smallfrown \langle n \rangle}$ for $n < \omega$ such that for any basic open cover \mathcal{V} , there exists $n < \omega$ where $\mathcal{F}(s, \mathcal{V}) = \mathcal{F}(s, \mathcal{U}_{s \smallfrown \langle n \rangle})$.

Let $t : \omega \rightarrow \omega^{<\omega}$ be a bijection. We define the Marköv strategy τ as follows:

$$\tau(\langle \mathcal{V} \rangle, n) = \bigcup \mathcal{F}(t(n), \mathcal{V})$$

Suppose there exists a counter-attack $\langle \mathcal{V}_0, \mathcal{V}_1, \dots \rangle$ of basic open covers which defeats τ . Then there exists $f : \omega \rightarrow \omega$ such that, letting $t(m_n) = f \upharpoonright n$:

$$\begin{aligned} x &\notin \tau(\langle \mathcal{V}_{m_n} \rangle, m_n) \\ &= \bigcup \mathcal{F}(f \upharpoonright n, \mathcal{V}_{m_n}) \\ &= \bigcup \mathcal{F}(f \upharpoonright n, \mathcal{U}_{f \upharpoonright (n+1)}) \\ &\supseteq \sigma(\langle \mathcal{U}_{f \upharpoonright 1}, \dots, \mathcal{U}_{f \upharpoonright (n+1)} \rangle) \end{aligned}$$

Thus $\langle \mathcal{U}_{f \upharpoonright 1}, \mathcal{U}_{f \upharpoonright 2}, \dots \rangle$ is a successful counter-attack by \mathcal{C} against the perfect information strategy σ . □

Corollary 6.2.9. *Let X be a second-countable space. The following are equivalent:*

- X is σ -relatively-compact
- $F \upharpoonright_{pre} Men_{C,F}(X)$
- $F \upharpoonright_{mark} Men_{C,F}(X)$
- $F \upharpoonright Men_{C,F}(X)$

◇

Corollary 6.2.10. *Let X be a metrizable space. The following are equivalent:*

- X is σ -compact
- X is σ -relatively-compact
- $F \uparrow_{pre} Men_{C,F}(X)$
- $F \uparrow_{mark} Men_{C,F}(X)$
- $F \uparrow Men_{C,F}(X)$

◇

Proof. Each property implies Lindelöf, so X may be assumed to be regular and second-countable. □

6.3 Robustly Lindelöf

To help describe $\mathcal{F} \uparrow_{2\text{-mark}} Men_{C,F}(X)$ topologically, we introduce a subset variant of the Menger game and a related covering property.

Game 6.3.1. Let $Men_{C,F}(X, Y)$ denote the *Menger subspace game* which proceeds analogously to the Menger game, except that \mathcal{F} wins whenever $\bigcup_{n < \omega} \mathcal{F}_n$ is a cover for $Y \subseteq X$.

◇

Note of course that $Men_{C,F}(X, X) = Men_{C,F}(X)$.

Definition 6.3.2. A subset Y of X is *relatively robustly Menger* if there exist functions $r_{\mathcal{V}} : Y \rightarrow \omega$ for each open cover \mathcal{V} of X such that for all open covers \mathcal{U}, \mathcal{V} and numbers $n < \omega$, the following sets are \mathcal{V} -finite:

$$c(\mathcal{V}, n) = \{x \in Y : r_{\mathcal{V}}(x) \leq n\}$$

$$p(\mathcal{U}, \mathcal{V}, n+1) = \{x \in Y : n < r_{\mathcal{U}}(x) < r_{\mathcal{V}}(x)\}$$

◇

Definition 6.3.3. A space X is *robustly Menger* if it is relatively robustly Menger to itself.

◇

Proposition 6.3.4. All σ -relatively-compact spaces are robustly Menger.

◇

Proof. If $X = \bigcup_{n < \omega} R_n$, then for all \mathcal{U} , let $r_{\mathcal{U}}(x)$ be the least n such that $x \in R_n$. Then $c(\mathcal{V}, n) = \bigcup_{m \leq n} R_m$ and $p(\mathcal{U}, \mathcal{V}) = \emptyset$. □

Theorem 6.3.5. If $Y \subseteq X$ is relatively robustly Menger, then $\mathcal{F} \uparrow_{2\text{-mark}} \text{Men}_{C,F}(X, Y)$. ◇

Proof. We define the Markov strategy σ as follows. Let $\sigma(\langle \mathcal{U} \rangle, 0) = c(\mathcal{U}, 0)$, and let $\sigma(\langle \mathcal{U}, \mathcal{V} \rangle, n+1) = c(\mathcal{V}, n+1) \cup p(\mathcal{U}, \mathcal{V}, n+1)$.

For any attack $\langle \mathcal{U}_0, \mathcal{U}_1, \dots \rangle$ by \mathcal{C} and $x \in Y$, one of the following must occur:

- $r_{\mathcal{U}_0}(x) = 0$ and thus $x \in c(\mathcal{U}_0, 0) \subseteq \sigma(\langle \mathcal{U}_0 \rangle, 0)$.
- $r_{\mathcal{U}_0}(x) = N+1$ for some $N \geq 0$ and:

- For all $n \leq N$,

$$r_{\mathcal{U}_{n+1}}(x) \leq N+1$$

and thus $x \in c(\mathcal{U}_{N+1}, N+1) \subseteq \sigma(\langle \mathcal{U}_N, \mathcal{U}_{N+1} \rangle, N+1)$.

- For some $n \leq N$,

$$r_{\mathcal{U}_n}(x) \leq n$$

and thus $x \in c(\mathcal{U}_{n+1}, n+1) \subseteq \sigma(\langle \mathcal{U}_n, \mathcal{U}_{n+1} \rangle, n+1)$.

- For some $n \leq N$,

$$n < r_{\mathcal{U}_n}(x) \leq N+1 < r_{\mathcal{U}_{n+1}}(x)$$

and thus $x \in p(\mathcal{U}_n, \mathcal{U}_{n+1}, n+1) \subseteq \sigma(\langle \mathcal{U}_n, \mathcal{U}_{n+1} \rangle, n+1)$

□

Theorem 6.3.6. $S(\kappa)$ implies κ^\dagger is robustly Menger, and thus $\mathcal{F} \uparrow_{2\text{-mark}} \text{Men}_{C,F}(\kappa^\dagger)$. \diamond

Proof. Let f_A for $A \in [\kappa]^{\leq \omega}$ witness $S(\kappa)$ and fix $A(\mathcal{U}) \in [\kappa]^{\leq \omega}$ for each open cover \mathcal{U} such that $\kappa^\dagger \setminus A(\mathcal{U})$ is contained in some element of \mathcal{U} . Then let $r_{\mathcal{U}}(x) = 0$ for $x \in \kappa^\dagger \setminus A(\mathcal{U})$, and $r_{\mathcal{U}}(\alpha) = f_{A(\mathcal{U})}(\alpha)$ for $\alpha \in A(\mathcal{U})$.

It follows that

$$c(\mathcal{U}, n) = (\kappa^\dagger \setminus A(\mathcal{U})) \cup \{\alpha \in A(\mathcal{U}) : f_{A(\mathcal{U})}(\alpha) \leq n\}$$

is \mathcal{U} -finite, $\bigcup_{n < \omega} c(\mathcal{U}, n) = X$, and

$$p(\mathcal{U}, \mathcal{V}, n+1) = \{\alpha \in A(\mathcal{U}) \cap A(\mathcal{V}) : n < f_{A(\mathcal{U})}(\alpha) < f_{A(\mathcal{V})}(\alpha)\}$$

is finite. \square

We may also consider common (non-regular) counterexamples which are finer than the usual Euclidean line.

Definition 6.3.7. Let $R_{\mathbb{Q}}$ be the real line with the topology generated by open intervals with or without the rationals removed. \diamond

Theorem 6.3.8. $R_{\mathbb{Q}}$ is non-regular and non- σ -compact, but is second-countable and σ -relatively-compact. \diamond

Proof. Compact sets in $R_{\mathbb{Q}}$ can be shown to not contain open intervals, and thus are nowhere dense in nonmeager \mathbb{R} , so $R_{\mathbb{Q}}$ is not σ -compact. The usual base of intervals with rational endpoints (with or without rationals removed) witnesses second-countability.

To see that $R_{\mathbb{Q}}$ is σ -relatively compact, consider $[a, b] \setminus \mathbb{Q}$. Let \mathcal{U} be a cover of $R_{\mathbb{Q}}$, and let \mathcal{U}' fill in the missing rationals for any open set in \mathcal{U} . There is a finite subcover $\mathcal{V}' \subseteq \mathcal{U}'$ for $[a, b]$ since \mathcal{U}' contains open sets from the Euclidean topology. Let $\mathcal{V} = \{V \setminus \mathbb{Q} : V \in \mathcal{V}'\}$: this

is a finite refinement of \mathcal{U} covering $[a, b] \setminus \mathbb{Q}$, so $[a, b] \setminus \mathbb{Q}$ is relatively compact. It follows then that $R_{\mathbb{Q}} \setminus \mathbb{Q}$ is σ -relatively-compact, and since \mathbb{Q} is countable, $R_{\mathbb{Q}}$ is σ -relatively-compact. Non-regularity follows since regular and σ -relatively-compact implies σ -compact. \square

Definition 6.3.9. Let R_{ω} be the real line with the topology generated by open intervals with countably many points removed. \diamond

Theorem 6.3.10. R_{ω} is non-regular, non-second-countable, and non- σ -relatively-compact, but $\mathcal{F} \uparrow \text{Men}_{C,F}(R_{\omega})$. \diamond

Proof. The closure of any open set is its closure in the usual Euclidean topology, so R_{ω} is not regular. If $S \supseteq \{s_n : n < \omega\}$ for s_n discrete, then $U_m = R_{\omega} \setminus \{s_n : m < n < \omega\}$ yields an infinite cover $\{U_m : m < \omega\}$ with no finite subcollection covering S , showing that all relatively compact sets are finite, and R_{ω} is not σ -relatively-compact.

Define the winning strategy σ for \mathcal{F} in $\text{Men}_{C,F}(R_{\omega})$ as follows: let $\sigma(\mathcal{U}_0, \dots, \mathcal{U}_{2n}) = [-n, n] \setminus C_n$ for some countable $C_n = \{c_{n,m} : m < \omega\}$, and let $\sigma(\mathcal{U}_0, \dots, \mathcal{U}_{2n+1}) = \{c_{i,j} : i, j < n\}$. Non-second-countable follows since second-countable and $\mathcal{F} \uparrow \text{Men}_{C,F}(X)$ implies σ -relatively-compact. \square

We will soon see that, assuming $S(2^{\omega})$, \mathcal{F} has a winning 2-Marköv strategy for $\text{Men}_{C,F}(R_{\omega})$ as well.

Proposition 6.3.11. Let \uparrow_{limit} be either $\uparrow_{k\text{-mark}}$ or \uparrow . If $X = \bigcup_{i < \omega} X_i$ and $\mathcal{F} \uparrow_{\text{limit}} \text{Men}_{C,F}(X, X_i)$ for $i < \omega$, then $\mathcal{F} \uparrow_{\text{limit}} \text{Men}_{C,F}(X)$ \diamond

Proof. Let L be the k -Markov fog-of-war μ_k (resp. the identity), and let σ_i be a k -Markov strategy (resp. perfect information strategy) for \mathcal{F} in $\text{Men}_{C,F}(X, X_i)$.

We define the k -Markov strategy (resp. perfect information strategy) σ for $\text{Men}_{C,F}(X)$ as follows:

$$\sigma \circ L(\langle \mathcal{U}_0, \dots, \mathcal{U}_n \rangle) = \bigcup_{i \leq n} \sigma_i \circ L(\langle \mathcal{U}_i, \dots, \mathcal{U}_n \rangle)$$

Let $\langle \mathcal{U}_0, \mathcal{U}_1, \dots \rangle$ be a successful counter-attack by \mathcal{C} against σ . Then there exists $x \in X_i$ for some $i < \omega$ such that x is not covered by $\bigcup_{n < \omega} \sigma \circ L(\langle \mathcal{U}_0, \dots, \mathcal{U}_n \rangle)$. It follows that x is not covered by $\bigcup_{n < \omega} \sigma_i \circ L(\langle \mathcal{U}_i, \dots, \mathcal{U}_{i+n} \rangle)$, and $\langle \mathcal{U}_i, \mathcal{U}_{i+1}, \dots \rangle$ is a successful counter-attack by \mathcal{C} against σ_i . \square

Theorem 6.3.12. *If $S(2^\omega)$, then $\mathcal{F} \uparrow_{2\text{-mark}} \text{Men}_{C,F}(R_\omega)$.* \diamond

Proof. It's sufficient to show that $[0, 1] \subseteq R_\omega$ is relatively robustly Menger. Let f_A witness $S(2^\omega)$ for $A \in [[a, b]]^{\leq \omega}$. For each open cover \mathcal{U} , let $A_\mathcal{U}$ be such that $[0, 1] \setminus A_\mathcal{U}$ is \mathcal{U} -finite. Let $r_\mathcal{U}(x) = 0$ if $x \in [0, 1] \setminus A_\mathcal{U}$ and $r_\mathcal{U}(x) = f_{A_\mathcal{U}}(x)$ otherwise.

It follows then that

$$c(\mathcal{U}, n) = [0, 1] \setminus \{x \in A_\mathcal{U} : f_{A_\mathcal{U}}(x) > n\}$$

is \mathcal{U} -finite and

$$p(\mathcal{U}, \mathcal{V}, n+1) = \{x \in A_\mathcal{U} \cap A_\mathcal{V} : n < f_{A_\mathcal{U}}(x) < f_{A_\mathcal{V}}(x)\}$$

is finite. \square

6.4 Rothberger game

We conclude this chapter with some results on another variation of the Menger property and game.

Definition 6.4.1. A space X is Rothberger if for every sequence $\langle \mathcal{U}_0, \mathcal{U}_1, \dots \rangle$ of open covers of X there exists a sequence $\langle S_0, S_1, \dots \rangle$ such that $S_n \in \mathcal{U}_n$ and $\{S_n : n < \omega\}$ is a cover of X . \diamond

Game 6.4.2. Let $\text{Roth}_{C,S}(X)$ denote the Rothberger game with players \mathcal{C} , \mathcal{S} . In round n , \mathcal{C} chooses an open cover \mathcal{U}_n , followed by \mathcal{S} choosing a subset S_n of X contained in some open set in \mathcal{U}_n . \mathcal{S} wins the game if $X = \bigcup_{n < \omega} S_n$, and \mathcal{C} wins otherwise. \diamond

Theorem 6.4.3. *X is Rothberger if and only if $\mathcal{C} \nVdash \text{Roth}_{C,S}(X)$. [19]*

◇

(TODO: cite)

Theorem 6.4.4. *Let X be a compact T_2 space. The following are equivalent:*

- *X is Rothberger*
- *X is scattered*
- *$\mathcal{S} \uparrow \text{Roth}_{C,S}(X)$*
- *$\mathcal{C} \nVdash \text{Roth}_{C,S}(X)$*

◇

Another game exists which is “perfect information equivalent” to the Rothberger game.

Game 6.4.5. Let $\text{Roth}_{P,O}(X)$ denote the *alternate Rothberger game* with players \mathcal{P} , \mathcal{O} . In round n , \mathcal{P} chooses a point $p_n \in X$, followed by \mathcal{O} choosing a neighborhood O_n of p_n . \mathcal{P} wins if $X = \bigcup_{n < \omega} O_n$; \mathcal{O} wins otherwise.

◇

(TODO: cite Galvin (Indeterminacy of Point Open Games?))

Theorem 6.4.6. *$\mathcal{P} \uparrow \text{Roth}_{P,O}(X)$ if and only if $\mathcal{S} \uparrow \text{Roth}_{C,S}(X)$; $\mathcal{O} \uparrow \text{Roth}_{P,O}(X)$ if and only if $\mathcal{C} \uparrow \text{Roth}_{C,S}(X)$.*

◇

An analogous relationship exists for the winning limited information strategies.

Theorem 6.4.7. $P \uparrow_{pre} Roth_{P,O}(X)$ if and only if $S \uparrow_{mark} Roth_{C,S}(X)$; $O \uparrow_{mark} Roth_{P,O}(X)$ if and only if $C \uparrow_{pre} Roth_{C,S}(X)$. \diamond

Proof. TODO \square

As it turns out, \mathcal{S} requires a lot of structure on X in order to guarantee victory with a Markov strategy in the Rothberger game.

Definition 6.4.8. TODO: almost countable \diamond

Theorem 6.4.9. For any space X , the following are equivalent:

- $S \uparrow_{mark} Roth_{C,S}(X)$
- $P \uparrow_{pre} Roth_{P,O}(X)$
- X is almost countable

\diamond

Proof. TODO \square

Theorem 6.4.10. For any T_1 space X , the following are equivalent:

- $S \uparrow_{mark} Roth_{C,S}(X)$
- $P \uparrow_{pre} Roth_{P,O}(X)$
- X is almost countable
- X is countable

\diamond

Let $\kappa \cup \{\infty\}$ be a “weak Lindelöf-ication” of discrete $\kappa > \omega$ such that open neighborhoods of ∞ contain $\kappa \setminus \omega$. This space is an example of an almost countable space which is not countable.

Theorem 6.4.11. *The following are equivalent for points- G_δ X :*

- $S \uparrow \text{Roth}_{C,S}(X)$
- $P \uparrow \text{Roth}_{P,O}(X)$
- $S \xrightarrow{\text{mark}} \text{Roth}_{C,S}(X)$
- $P \xrightarrow{\text{pre}} \text{Roth}_{P,O}(X)$
- X is Rothberger
- X is almost countable
- X is countable

◇

Proof. TODO

□

Corollary 6.4.12. *The following are equivalent for compact points- G_δ X :*

- $S \uparrow \text{Roth}_{C,S}(X)$
- $P \uparrow \text{Roth}_{P,O}(X)$
- $S \xrightarrow{\text{mark}} \text{Roth}_{C,S}(X)$
- $P \xrightarrow{\text{pre}} \text{Roth}_{P,O}(X)$
- $C \not\uparrow \text{Roth}_{C,S}(X)$
- $O \not\uparrow \text{Roth}_{P,O}(X)$
- X is scattered
- X is Rothberger
- X is almost countable

- X is countable

◊

Bibliography

- [1] Matthew H. Baker. Uncountable sets and an infinite real number game. *Mathematics Magazine*, 80(5):377–380, December 2007.
- [2] Jocelyn R. Bell. An infinite game with topological consequences. *Topology Appl.*, 175:1–14, 2014.
- [3] Steven Clontz and Gary Gruenhage. Proximal compact spaces are Corson compact. *Topology Appl.*, 173:1–8, 2014.
- [4] Gabriel Debs. Stratégies gagnantes dans certains jeux topologiques. *Fund. Math.*, 126(1):93–105, 1985.
- [5] David Gale and F. M. Stewart. Infinite games with perfect information. In *Contributions to the theory of games, vol. 2*, Annals of Mathematics Studies, no. 28, pages 245–266. Princeton University Press, Princeton, N. J., 1953.
- [6] Fred Galvin and Ratislav Telgársky. Stationary strategies in topological games. *Topology Appl.*, 22(1):51–69, 1986.
- [7] Gary Gruenhage. Infinite games and generalizations of first-countable spaces. *General Topology and Appl.*, 6(3):339–352, 1976.
- [8] Gary Gruenhage. Covering properties on $X^2 \setminus \Delta$, W -sets, and compact subsets of Σ -products. *Topology Appl.*, 17(3):287–304, 1984.
- [9] Gary Gruenhage. Games, covering properties and Eberlein compacts. *Topology Appl.*, 23(3):291–297, 1986.
- [10] R. C. Haworth and R. A. McCoy. Baire spaces. *Dissertationes Math. (Rozprawy Mat.)*, 141:73, 1977.
- [11] Witold Hurewicz. Über eine Verallgemeinerung des Borelschen Theorems. *Math. Z.*, 24(1):401–421, 1926.
- [12] Kenneth Kunen. *Set theory*, volume 102 of *Studies in Logic and the Foundations of Mathematics*. North-Holland Publishing Co., Amsterdam-New York, 1980. An introduction to independence proofs.
- [13] H. P. A. Künzi, S. Romaguera, and M. A. Sánchez-Granero. On uniformly locally compact quasi-uniform hyperspaces. *Czechoslovak Math. J.*, 54(129)(1):215–228, 2004.

- [14] Donald A. Martin. Borel determinacy. *Ann. of Math. (2)*, 102(2):363–371, 1975.
- [15] Karl Menger. Einige überdeckungssätze der punktmengenlehre. *Sitzungsberichte der Wiener Akademie*, 133:421–444, 1924.
- [16] Jan Mycielski and H. Steinhaus. A mathematical axiom contradicting the axiom of choice. *Bull. Acad. Polon. Sci. Sér. Sci. Math. Astronom. Phys.*, 10:1–3, 1962.
- [17] Peter J. Nyikos. Classes of compact sequential spaces. In *Set theory and its applications (Toronto, ON, 1987)*, volume 1401 of *Lecture Notes in Math.*, pages 135–159. Springer, Berlin, 1989.
- [18] Peter J. Nyikos. Proximal and semi-proximal spaces (preprint). 2013.
- [19] Janusz Pawlikowski. Undetermined sets of point-open games. *Fund. Math.*, 144(3):279–285, 1994.
- [20] Mary Ellen Rudin. The shrinking property. *Canad. Math. Bull.*, 26(4):385–388, 1983.
- [21] Marion Scheepers. Concerning n -tactics in the countable-finite game. *J. Symbolic Logic*, 56(3):786–794, 1991.
- [22] Marion Scheepers. Meager-nowhere dense games. I. n -tactics. *Rocky Mountain J. Math.*, 22(3):1011–1055, 1992.
- [23] Marion Scheepers. A direct proof of a theorem of Telgársky. *Proc. Amer. Math. Soc.*, 123(11):3483–3485, 1995.
- [24] Rastislav Telgársky. On games of Topsøe. *Math. Scand.*, 54(1):170–176, 1984.
- [25] Rastislav Telgársky. Topological games: on the 50th anniversary of the Banach-Mazur game. *Rocky Mountain J. Math.*, 17(2):227–276, 1987.
- [26] Stephen Willard. *General topology*. Dover Publications, Inc., Mineola, NY, 2004. Reprint of the 1970 original [Addison-Wesley, Reading, MA; MR0264581].