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Avoidance games are PSPACE-Complete

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Abstract

Avoidance games are games in which two players claim vertices of a hypergraph and try to avoid some structures. These games are studied since the introduction of the game of SIM in 1968, but only few complexity results are known on them. In 2001, Slany proved some partial results on Avoider-Avoider games complexity, and in 2017 Bonnet *et al.* proved that short Avoider-Enforcer games are Co-W[1]-hard. More recently, in 2022, Miltzow and Stojaković proved that these games are NP-hard. As these games corresponds to the misère version of the well-known Maker-Breaker games, introduced in 1963 and proven PSPACE-complete in 1978, one could expect these games to be PSPACE-complete too, but the question remained open since then. We prove here that both Avoider-Avoider and Avoider-Enforcer conventions are PSPACE-complete, and as a consequence of it that some particular Avoider-Enforcer games also are.

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Keywords and phrases Games, Avoider-Enforcer, Maker-Breaker, Complexity, Avoider-Avoider, PSPACE-complete

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1 Introduction

1.1 Related works

Avoidance games belong to the class of positional games, that were introduced by Hales and Jewett in 1963 [14] and popularised by Erdős and Selfridge in 1973 [11]. In this class of games, the board is a hypergraph and two players alternately select a vertex of the hypergraph that has not been claimed before. Winning conditions depend on the convention and are related to the hyperedges. TIC-TAC-TOE and HEX are two famous examples of positional games. To learn more about positional games, we refer the reader to the recent survey of Hefetz *et al.* [18].

Among positional games, a natural dichotomy exists: on the one hand, there are games in which players seek to build a structure, and on the other hand, there are games in which players want to avoid a structure. The former set contains both Maker-Maker and Maker-Breaker conventions, in which the hyperedges are winning sets, and the player either want to fill a winning set (Maker role), or to play at least once in each of them (Breaker role). The latter contains Avoider-Avoider and Avoider-Enforcer conventions, that can be seen as the misère version of the former. In these games, the hyperedges are losing sets, and the players either want not to fill one losing set (Avoider role), or to force their opponent to fill one of them (Enforcer role).

When positional games were introduced, the focus was on Maker-Breaker games, *i.e.* games in which one player, Maker, aims to fill a hyperedge, and the second one, Breaker, wants to prevent it by claiming at least one vertex in each hyperedge. This convention is the

most popular, and several games were studied according to this convention. In particular, the survey of Beck [5] presents several results obtained for Maker-Breaker games. The field of Maker-Breaker games is still well investigated today, and some Maker-Breaker games were introduced recently [10, 25].

The first Avoider-Avoider game was introduced in 1968 with the game of SIM and is presented in [28], but the first study of the complexity of Avoidance games was done by Schaefer in 1978 [27]. Avoider-Enforcer games were introduced later by Lu in 1991 [22, 23] under the name of Antimaker-Antibreaker games and corresponds to the misère version of Maker-Breaker games. The standard name of this convention, Avoider-Enforcer, was popularised by Hefetz and different co-authors in 2007 [15, 16, 19, 20]. In this game, Enforcer wins if at some point during the game, Avoider has played all the vertices of a hyperedge, otherwise Avoider wins.

Even if most of the studies of positional games are focused on Maker-Breaker games, Avoider-Enforcer games have become more and more relevant: the famous Ramsey game were introduced in Avoider-Enforcer convention by Beck in 2002 [4] as a generalisation of SIM. As it was done in the Maker-Breaker convention, some games on graphs were introduced in Avoider-Enforcer or Avoider-Avoider conventions, where the losing sets correspond to some structure in the graph, see [2, 3, 13, 17].

In terms of complexity, an overview of the field is proposed by Demaine [9]. In positional games, as they are perfect information games, one player always has a winning strategy (or both players can ensure a draw). The natural decision problem related to games is thus: does the first player have a winning strategy ? This problem was quickly proven to be PSPACE-complete for Maker-Breaker games by Schaefer in 1978 [27] even restricted to 11-uniform hypergraphs (i.e. hypergraphs in which all hyperedges have size 11). This bound was recently improved by Rahman and Watson in 2021 [26], proving that the problem is still PSPACE-complete if the hypergraph is 6-uniform. These two proofs are very technical and a simpler proof of the PSPACE-completeness was provided by Byskov in 2004 [8], proving in the same time that Maker-Maker games are also PSPACE-complete. The complexity of Maker-Breaker games is still studied today, as Galliot *et al.* [12] have proven that the winner of a 3-uniform Maker-Breaker game can be computed in polynomial time, but the gap between the complexity of 6-uniform hypergraphs and 3-uniform hypergraphs remains to be closed.

Despite the fact that Avoidance games were introduced at the same time as Maker-Breaker games, only partial results on complexity are known: determining the winner in Avoider-Avoider games, was proven to be PSPACE-complete by Slany in 2002 [29] for endgames, i.e. games in which some vertices are already attributed to the players, but there is no result yet in the general case. Concerning Avoider-Enforcer, Bonnet *et al.* in 2017 [6] mentioned that the complexity of this problem is still open, when they proved that short games, i.e. games in which a player has only few moves to make, are co-W[1]-hard, with the number of moves taken as a parameter. The best known result today is due to Miltzow and Stojaković in 2022 [24] that states the NP-hardness of this decision problem and conjectures its PSPACE-completeness.

1.2 Presentation of the results

The Avoider-Enforcer game is played as follows: given a hypergraph H , two players, called *Avoider* and *Enforcer*, alternately claim an unclaimed vertex of H with Avoider starting. The game ends when all the vertices have been claimed. If Avoider has claimed all the vertices of a hyperedge, Enforcer wins. Otherwise, Avoider wins. The related decision problem is the

following one.

► **Problem 1.** AVOIDER-ENFORCER

Input: A hypergraph H .

Output: True if and only if AVOIDER has a winning strategy in the AVOIDER-ENFORCER game on H .

This paper will focus on the proof of the following result:

► **Theorem 2.** *The AVOIDER-ENFORCER problem is PSPACE-complete, even when the entry is restricted to hypergraphs with hyperedges of size at most 6.*

Our proof of Theorem 2 follows a similar idea to the proof of Rahman and Watson [26] and the proof of Schaefer [27], by constructing some hyperedges forcing the order of the moves. Contrary to Maker-Breaker games, in AVOIDER-ENFORCER convention, there is no vertex in which the players are urged to play, as in general, players do not want to move in avoidance games. The key idea of this reduction is to create some structures in which playing first is a losing move. In the provided construction, at any moment of the game, only few moves are not losing moves. Thus, we can control the vertices played by the two players.

The proof provided for PSPACE-completeness of AVOIDER-ENFORCER games, enables us to state the following corollary for AVOIDER-AVOIDER games that will also be proven later:

► **Problem 3.** AVOIDER-AVOIDER

Input: A hypergraph H .

Output: True if and only if the second player has a winning strategy in the AVOIDER-AVOIDER game on H .

► **Corollary 4.** *The AVOIDER-AVOIDER problem is PSPACE-complete, even when the entry is restricted to 7-uniform hypergraphs.*

This paper is organised as follows. In section 2, we introduce two lemmas that will be used in the main proof of the results. In particular, we show that pairing strategies that are often used in Maker-Breaker conventions can also be applied to AVOIDER-ENFORCER games. Section 3 describes the reduction used to prove the PSPACE-completeness and define an order on the move that we call the *legitimate order*. We also show in this section that the proof holds if both players follow the legitimate order. In section 4, we show that if a player does not follow the legitimate order then it cannot be a disadvantage to the other player, completing the proof of the Theorem 2. Finally, in section 5, we use Theorem 2 to prove Corollary 4 and to show that the AVOIDER-ENFORCER versions of the Domination game and of the H -game are PSPACE-complete.

2 Preliminaries

In Maker-Breaker games, some moves appear to be better than others. For instance, if a vertex is in all the hyperedges, it is always an optimal move to play it for both players. We present here a similar result to prove that some moves are better than others.

► **Lemma 5.** *Let H be a hypergraph, and u, v two vertices of H such that, for every hyperedge e containing u , e also contains v . If a player has a winning strategy, then this player has a winning strategy in which he never plays v while u is unclaimed.*

Proof. Let H be a hypergraphs and let u, v be two vertices such that, for every hyperedge e containing u , e also contains v . Let \mathcal{S}_1 be a winning strategy for Avoider (Enforcer resp.). We define the strategy \mathcal{S}_2 as follows:

- If \mathcal{S}_1 claims a vertex w in $V \setminus \{v\}$, \mathcal{S}_2 claims w .
- If \mathcal{S}_1 claims v while u is unclaimed, claim u and consider the strategy obtained if v was claimed in \mathcal{S}_1 . If at some point the other player plays v continue as if he played u in \mathcal{S}_1 , and, if the strategy of \mathcal{S}_1 requires that you play u , play on v and continue following \mathcal{S}_1 .

Consider a sequence of moves played against \mathcal{S}_2 . Consider the same sequence played against \mathcal{S}_1 by exchanging the roles of u and v . Note V_1 the vertices claimed by Avoider (Enforcer resp.) in \mathcal{S}_1 , and V_2 the vertices claimed by Avoider (Enforcer resp.) in \mathcal{S}_2 according to this sequence. Note that if $V_1 \neq V_2$, then $V_1 \setminus V_2 = \{v\}$ and $V_2 \setminus V_1 = \{u\}$.

As for every hyperedge e such that $u \in e$, we have $v \in e$, in particular, we have for any hyperedge e , $|e \cap V_1| \geq |e \cap V_2|$. Thus, in this sequence, as \mathcal{S}_1 was a strategy for Avoider (Enforcer resp.) that do not claim all the vertices of a hyperedge (that do not claim a vertex in each hyperedge resp.), \mathcal{S}_2 neither. As this result holds for any sequence of moves, \mathcal{S}_2 is a winning strategy. ◀

The second tool we introduce here is *pairing strategies* in Avoider-Enforcer games. In Maker-Breaker convention, these strategies are often described by using the fact that a player can claim at least one vertex in each pair of vertices. Here in Avoider-Enforcer convention, the main idea of pairing strategies is that it is always possible to force the opponent to play at least once in each pair.

In this section, we will refer to the players by Alice and Bob, as the strategy can be applied both by Avoider and by Enforcer.

► **Lemma 6.** *Let $H = (V, E)$ be a hypergraph. Suppose that Alice plays last in H , i.e. if the game is played until all the vertices have been claimed, Alice will claim the last one. Let $(a_1, b_1), \dots, (a_n, b_n)$ be pairwise disjoint pairs of vertices, and let $v \notin \bigcup_{i=1}^n \{a_i, b_i\}$.*

Alice has a strategy which forces Bob to play at least one vertex in each pair (a_i, b_i) . Bob has a strategy which forces Alice to play v and at least one vertex in each pair (a_i, b_i) .

A strategy satisfying the hypothesis of Lemma 6 will be called a *pairing strategy*.

Proof. We prove by induction that if Alice plays last on H she can force Bob to play at least once in each pair of unplayed vertices (a_i, b_i) :

- If $|V| \in \{0, 1\}$, then there can be no pair of distinct vertices (a_i, b_i) and the strategy is trivially achieved.
- If $|V| = 2p + 1$ with $p \geq 0$, then, since Alice plays last on H , it is Alice's turn to play and there is at least one vertex x in V that is in no pair and Alice can play it. Then, by induction hypothesis, Bob will play one vertex in each pair (a_i, b_i) in $V \setminus \{x\}$.
- If $|V| = 2p$, with $p \geq 1$, then it is Bob's turn to play. If Bob plays a vertex x that is in no pair (a_i, b_i) , then, by induction hypothesis, Alice can force Bob to play once in each pair (a_i, b_i) in $V \setminus \{x\}$. If Bob plays on a vertex a_i or b_i , then Alice can play in the other vertex of the pair. Bob played in the pair (a_i, b_i) and by induction hypothesis Alice can force Bob to play once in each pair $(a_j, b_j)_{j \neq i}$ in $V \setminus \{a_i, b_i\}$.

We prove by induction that if Alice plays last on H , Bob can force Alice to play at least once in each pair of unplayed vertices (a_i, b_i) , and to play on the vertex v :

- If $|V| = 0$, the situation cannot exist as there can be no vertex v .

- If $|V| = 1$, it must be that $V = \{v\}$ and that there is no pair of vertices (a_i, b_i) and since it is the last move, it is Alice's turn, and she has to play in v . Thus, she played on v and in each pair.
- If $|V| = 2p$ with $p \geq 1$, then, since Alice plays last on H , it is Bob's turn to play and there is at least one vertex x in $V \setminus \{v\}$ that is in no pair and Bob can play it. Then, by induction hypothesis, Alice will play on v and on one vertex in each pair (a_i, b_i) in $V \setminus \{x\}$.
- If $|V| = 2p + 1$, with $p \geq 1$, then it is Alice's turn to play. If Alice plays a vertex x that is neither v neither in a pair (a_i, b_i) , then by induction hypothesis Bob can force Alice to play one v and at least once in each pair (a_i, b_i) in $V \setminus \{x\}$. If Alice plays on a vertex a_i or b_i then Bob can play in the other vertex of the pair. Alice played in the pair (a_i, b_i) and by induction hypothesis Bob can force Alice to play on v and once in each pair $(a_j, b_j)_{j \neq i}$ in $V \setminus \{a_i, b_i\}$. If Alice plays on v then either there is no pair (a_i, b_i) and then Alice played on v and in each pair, or there is at least one pair (a_i, b_i) . Bob can then play on a_i , by induction hypothesis Bob can force Alice to play on b_i and in each pair $(a_j, b_j)_{j \neq i}$. Since Alice played on v , and will be forced to play on b_i and in each pair $(a_j, b_j)_{j \neq i}$ the result holds. ◀

3 Proof of the main theorem

In this section, we begin the proof of Theorem 2 by describing the reduction from 3-QBF, introducing an order on the move of Avoider and Enforcer called the *legitimate order* and giving a sketch of the general proof.

► **Theorem 2.** *The AVOIDER-ENFORCER problem is PSPACE-complete, even when the entry is restricted to hypergraphs with hyperedges of size at most 6.*

The first step of the proof is to prove that this game is in PSPACE.

► **Lemma 7.** *The AVOIDER-ENFORCER problem is in PSPACE.*

Proof. Let $H = (V, E)$ be a hypergraph. As the players are not allowed to play an already claimed vertex, any game ends after at most $|V|$ moves. Therefore, according to Lemma 2.2 of Schaefer [27], as the game has a polynomial length and a polynomial number of moves, its winner can be computed with polynomial space. ◀

3.1 Construction of the hypergraph

We reduce the problem 3-QBF to an AVOIDER-ENFORCER game. This problem has been proven PSPACE-complete by Stockmeyer and Meyer [30], and we use the gaming version of this problem as it was formulated by Rahman and Watson [26]. The game is played on a quantified formula φ of the form $\forall X_1 \exists X_2 \dots \forall X_{2n-1} \exists X_{2n} \psi$, with ψ a 3-SAT formula. Alternately, two players, namely Falsifier and Satisfier, chose valuation for the variables, Falsifier for the odd variables (quantified with a \forall) and Satisfier for the even ones (quantified with a \exists). When all the variables have a valuation Satisfier wins if ψ is satisfied, otherwise, Falsifier win.

► **Problem 8.** *3-QBF*

Input: A 3-SAT quantified formula φ of the form $\forall X_1 \exists X_2 \dots \forall X_{2n-1} \exists X_{2n} \psi$.

Output: True if and only if Satisfier has a winning strategy in the 3-QBF game on ϕ

A round in a 3-QBF formula corresponds to the steps i during which Falsifier gives a valuation to X_{2i-1} and then Satisfier gives a valuation to X_{2i} . In this reduction, any round corresponds to ten vertices and eight hyperedges. Four of the ten vertices are $\{x_{2i-1}, \overline{x_{2i-1}}, x_{2i}, \overline{x_{2i}}\}$, and the six others are $u_{6i-5}, u_{6i-4}, u_{6i-3}, u_{6i-2}, u_{6i-1}, u_{6i}$. The eight hyperedges are constructed as follows:

$$\begin{aligned} A_{2i} &= (x_{2i}, \overline{x_{2i}}, u_{6i+1}, u_{6i+3}) & C_{6i-2}^- &= (u_{6i-2}, u_{6i-1}, u_{6i+1}, \overline{x_{2i}}) \\ C_{6i}^+ &= (u_{6i}, u_{6i+1}, u_{6i+3}, x_{2i}) & B_{2i-1} &= (x_{2i-1}, \overline{x_{2i-1}}, u_{6i-1}) \\ C_{6i}^- &= (u_{6i}, u_{6i+1}, u_{6i+3}, \overline{x_{2i}}) & C_{6i-4}^+ &= (u_{6i-4}, u_{6i-3}, u_{6i-1}, x_{2i-1}) \\ C_{6i-2}^+ &= (u_{6i-2}, u_{6i-1}, u_{6i+1}, x_{2i}) & C_{6i-4}^- &= (u_{6i-4}, u_{6i-3}, u_{6i-1}, \overline{x_{2i-1}}) \end{aligned}$$

Moreover, for each clause $F_j = l_{j_1} \vee l_{j_2} \vee l_{j_3} \in \psi$ where the vertices l_{j_1}, l_{j_2} and l_{j_3} are literals either positive or negative, we add a hyperedge D_j containing six vertices. For $k = 1, 2, 3$, if l_{j_k} is a positive variable X_i , then x_i is in D_j , if l_{j_k} is a negative one $\neg X_i$, then $\overline{x_i}$ is in D_j . If j_k is odd, then u_{6j_k-1} is in D_j , if j_k is even, then u_{6j_k+1} is in D_j .

Finally, the CNF game ϕ is reduced to the hypergraph $H = (V, E)$ with

$$\begin{aligned} V &= \{\{x_i\}_{1 \leq i \leq 2n} \cup \{\overline{x_i}\}_{1 \leq i \leq 2n} \cup \{u_j\}_{1 \leq j \leq 6n}\} \\ E &= \{\{A_{2i}\}_{1 \leq i \leq n} \cup \{C_{2i}^+\}_{1 \leq i \leq 3n} \cup \{C_{2i}^-\}_{1 \leq i \leq 3n} \cup \{B_{2i-1}\}_{1 \leq i \leq n} \cup \{D_j\}_{1 \leq j \leq m}\} \end{aligned}$$

With this construction, we say that Avoider and Enforcer follow a *legitimate order* if during each round i the moves are made in the following way, with each round played in increasing order:

Legitimate order during round i

1. Avoider starts and plays u_{6i-5} .
2. Enforcer plays u_{6i-4} .
3. Avoider plays u_{6i-3} .
4. Enforcer plays one of x_{2i-1} or $\overline{x_{2i-1}}$.
5. Avoider plays the remaining vertex in $(x_{2i-1}, \overline{x_{2i-1}})$.
6. Enforcer plays u_{6i-2} .
7. Avoider plays u_{6i-1} .
8. Enforcer plays u_{6i} .
9. Avoider plays one of x_{2i} or $\overline{x_{2i}}$.
10. Enforcer plays the remaining vertex in $(x_{2i}, \overline{x_{2i}})$.

3.2 Sketch of the proof

To prove that, with our construction, Avoider wins the AVOIDER-ENFORCER game, if and only if Satisfier wins the QBF game, we first prove that this statement is true if the order of the move is legitimate, as the moves will give the valuation obtained in QBF. To force the players to play in the legitimate order, the main idea of the construction is that players want to play some vertices as late as possible. Therefore, we prove that it is always optimal to respect the legitimate order of the moves. We introduce the three following lemmas that will be proved in the next section.

► **Lemma 9.** *When the game is restricted to the legitimate order, Avoider has a winning strategy in the Avoider-Enforcer game on H if and only if Satisfier has a winning strategy for the 3-QBF game on φ .*

► **Lemma 10.** *If Enforcer has a winning strategy in φ when the legitimate order is respected by the two players, then he has a winning strategy in H .*

► **Lemma 11.** *If Avoider has a winning strategy in φ when the legitimate order is respected by the two players, then she has a winning strategy in H .*

We first admit these lemmas and we prove Theorem 2.

Proof. Let φ be a boolean formula. Consider the hypergraph H obtained from φ by following the construction of Section 3.1. This construction has polynomial size, and the hypergraph H has all its hyperedges of size at most 6. According to Lemma 9, when the order is respected, if Satisfier (Falsifier resp.) has a winning strategy in φ , Avoider (Enforcer resp.) has a winning strategy in H . Thus, according to Lemma 11 (Lemma 10 resp.), if Avoider (Enforcer resp.) has a winning strategy on H when the legitimate order is respected, she (he resp.) has one in general in H . Thus, Satisfier wins on φ if and only if, Avoider wins on H . Therefore, the AVOIDER-ENFORCER PROBLEM is PSPACE-complete. ◀

3.3 Game in legitimate order

In this section, we suppose that both players follow a legitimate order of moves.

If the order of moves is legitimate, the only choices available for Avoider and Enforcer are on the vertices x_i and \bar{x}_i . For each $1 \leq i \leq 2n$, Avoider plays one of x_i, \bar{x}_i and Enforcer the other. Therefore, if both Avoider and Enforcer plays one vertex in $\{x_i, \bar{x}_i\}$, we define the *underlying valuation* given to ψ as the following one:

$$X_i = \begin{cases} True & \text{if Avoider has played } \bar{x}_i \text{ and Enforcer has played } x_i \\ False & \text{if Avoider has played } x_i \text{ and Enforcer has played } \bar{x}_i \end{cases}$$

► **Lemma 9.** *When the game is restricted to the legitimate order, Avoider has a winning strategy in the Avoider-Enforcer game on H if and only if Satisfier has a winning strategy for the 3-QBF game on φ .*

Proof. Consider a game played on H for which both Avoider and Enforcer respected the legitimate order through the whole game.

▷ **Claim 12.** Avoider won the game on H if and only if the formula ψ is satisfied by the underlying valuation of the X_i s.

Proof. Since the legitimate order is respected, Enforcer played all the vertices u_{2i} and thus played at least once in all the hyperedges C_{2i}^+ and C_{2i}^- . Moreover, for each pair of variables (x_i, \bar{x}_i) , Enforcer played one of the vertices of the pair and so played at least one vertex in all the hyperedges A_i and B_i . Thus, the only hyperedges that could possibly be fully played by Avoider are the hyperedges D_j .

Since, in the legitimate order, Avoider plays on all the vertices u_{2i+1} , a hyperedge D_j is fully played by Avoider if and only if she played on all the vertices $x(l_k)$ for $l_k \in F_j$. If this is the case, then this means that the formula ψ is not satisfied by the underlying valuation because the clause F_j has all its literals assigned to False. On the contrary, if the formula ψ is satisfied by the underlying valuation, then, for all clause F_j , at least one of its literal is assigned to True and so Enforcer played at least once in each hyperedge D_j .

Therefore, Avoider won the game on H if and only if ψ is satisfied. ◀

Suppose Satisfier has a winning strategy \mathcal{S} on φ . We define a strategy for Avoider as follows: Whenever Avoider has to play a vertex x_{2k} or \bar{x}_{2k} , Avoider considers the underlying valuation given to the X_i s with $i < 2k$. Then, if Satisfier had put X_{2k} to True, she plays

$\overline{x_{2k}}$. Otherwise, she plays x_{2k} . With this strategy, at the end of the game, the underlying valuation of the variables of H will be equivalent to the valuation given by the game that Satisfier played on φ . Since Satisfier has a winning strategy on φ , the underlying valuation satisfies ψ and so Avoider win the game.

Similarly, if Falsifier has a winning strategy, Enforcer can follow the strategy in such a way that at the end the valuation of variables in the game played by Falsifier correspond to the underlying valuation in H . Since Falsifier has a winning strategy, Enforcer wins the game on H . ◀

4 Proofs of Lemma 10 and Lemma 11

The first part of our constructions showed that, if the legitimate order is respected, Avoider wins if and only if φ is satisfied by the underlying valuation provided by the moves. We now prove that, if a player has a winning strategy, he has one that respects the legitimate order of the moves. We introduce here sets of variables in which players do not want to play. These sets will be the main point of the proofs of Lemma 10 and Lemma 11.

- For $i = 1$ to $4n$, we define the set of vertices S_i as $S_{4n} = \{u_{6n}, x_{2n}, \overline{x_{2n}}\}$ and for $i < 4n$:
- if $i = 4k$, $S_i = \{u_{6k}, x_{2k}, \overline{x_{2k}}, u_{6k+1}\} \cup S_{i+1}$
 - if $i = 4k - 1$, $S_i = \{u_{6k-2}, u_{6k-1}\} \cup S_{i+1}$
 - if $i = 4k - 2$, $S_i = \{x_{2k-1}, \overline{x_{2k-1}}\} \cup S_{i+1}$
 - if $i = 4k - 3$, $S_i = \{u_{6k-4}, u_{6k-3}\} \cup S_{i+1}$

4.1 Proof of Lemma 10

► **Lemma 10.** *If Enforcer has a winning strategy in φ when the legitimate order is respected by the two players, then he has a winning strategy in H .*

Proof. Suppose Falsifier has a winning strategy in φ . Consider a strategy for Enforcer in which he plays according to the legitimate order until Avoider does not. If Avoider respects the order until all the vertices are played, by Lemma 9, Enforcer wins. Otherwise, the proof of the following claim provides a winning strategy to Enforcer.

▷ **Claim 13.** If, during the game, Avoider plays in a set S_i in which Enforcer has not played yet, then, after this move, Enforcer has a strategy to win the game.

Proof. The proof is by induction on i .

First, notice that each S_i has an odd number of vertices and, as the total number of vertices in H is $10n$, there is also an odd number of vertices outside S_i . Therefore, if Avoider plays first in an S_i , Enforcer answers by playing an arbitrary vertex that is not in S_i and considers an arbitrary pairing outside S_i , which exists as there is an even number of vertices outside S_i after his move. This way, Avoider has to be the next player to play in S_i .

Base cases:

- Case $i = 4n$: If Avoider plays first in S_{4n} , by pairing the two other vertices in S_{4n} , by using Lemma 6, Enforcer can force Avoider to play another vertex in S_{4n} . Hence, as (u_{6n}, x_{2n}) , $(u_{6n}, \overline{x_{2n}})$ and $(x_{2n}, \overline{x_{2n}})$ are three hyperedges, Avoider will claim the two vertices of one of them and then lose.
- Case $i = 4n - 1$: As shown previously, Enforcer has a strategy such that Avoider is the next player to play in S_{4n-1} . If Avoider has played at least one of its two first moves in S_{4n} , she has lost by the case $i = 4n$. Otherwise, she has played exactly u_{6n-2} and u_{6n-1} . In this case, Enforcer plays on u_{6n} and pairs x_{2n} and $\overline{x_{2n}}$ and by Lemma 6 he forces Avoider to claim all the vertices of C_{6n-2}^+ or C_{6n-2}^- .

Induction steps: Suppose that the first time Avoider does not respect the order of the move, she plays in a set S_i for $i \leq 4n - 2$. If the second move of Avoider in S_i is in S_{i+1} , Enforcer wins by induction hypothesis. Thus, we can suppose that Avoider has played two vertices in $S_i \setminus S_{i+1}$. Moreover, as Enforcer has arbitrarily paired the vertices outside S_i , we describe here the strategy in S_i , and Enforcer plays according to the pairing outside S_i . This strategy ensure that the moves in S_i alternate between both players.

- Case $i = 4k$: Avoider has played twice in $\{u_{6k}, x_{2k}, \overline{x_{2k}}, u_{6k+1}\}$. At least one of $\{u_{6k}, x_{2k}, \overline{x_{2k}}\}$ is available. Enforcer plays it. Avoider has to play a third vertex in this quadruple, otherwise, she plays first in S_{i+1} and loses by induction, and necessarily one of the three vertices she has played is u_{6k+1} . Enforcer plays u_{6k+2} . Avoider either plays first in S_{i+2} and loses by induction hypothesis, or plays u_{6k+3} . At this moment, Avoider has played on the vertices u_{6k+1} and u_{6k+3} , and two of the vertices of $\{u_{6k}, x_{2k}, \overline{x_{2k}}\}$. So she has completed one of the hyperedge $C_{6k}^+ = (u_{6k}, u_{6k+1}, u_{6k+3}, x_{2k})$, $C_{6k}^- = (u_{6k}, u_{6k+1}, u_{6k+3}, \overline{x_{2k}})$ or $A_{2k} = (x_{2k}, \overline{x_{2k}}, u_{6k+1}, u_{6k+3})$.
- Case $i = 4k - 1$: Avoider has played u_{6k-2} and u_{6k-1} . Enforcer plays u_{6k} . Avoider has to play on vertex in $\{x_{2k}, \overline{x_{2k}}, u_{6k+1}\}$, otherwise she plays first in S_{i+2} and loses by induction. Enforcer plays either x_{2k} or $\overline{x_{2k}}$, as at least one of them is available. If Avoider plays a vertex in S_{i+2} she loses by induction. So she has to play the last vertex available in $S_i \setminus S_{i+1}$. With this strategy, Avoider has necessarily played u_{6k+1} and one of x_{2k} and $\overline{x_{2k}}$. Thus, she has played all the vertices of either $C_{6k-2}^+ = (u_{6k-2}, u_{6k-1}, u_{6k+1}, x_{2k})$ or $C_{6k-2}^- = (u_{6k-2}, u_{6k-1}, u_{6k+1}, \overline{x_{2k}})$.
- Case $i = 4k - 2$: Avoider has played x_{2k-1} and $\overline{x_{2k-1}}$. Enforcer plays u_{6k-2} . Either Avoider plays first in S_{i+2} and loses by induction, or she plays u_{6k-1} , the last available vertex in S_{i+1} and loses by having played all the vertices in $B_{2k-1} = (x_{2k-1}, \overline{x_{2k-1}}, u_{6k-1})$.
- Case $i = 4k - 3$: Avoider has played u_{6k-4} and u_{6k-3} . Enforcer plays x_{2k-1} . Avoider has to play $\overline{x_{2k-1}}$, otherwise she plays first in S_{i+2} and loses by induction. Then Enforcer plays u_{6k-2} . If Avoider plays in S_{i+3} she loses by induction. The last vertex available in $S_i \setminus S_{i+3}$ is u_{6k-1} , and if Avoider plays it, she loses by playing all the vertices $C_{6k-4}^- = (u_{6k-4}, u_{6k-3}, u_{6k-1}, \overline{x_{2k-1}})$.

By applying this induction, at any moment of the game, if Avoider plays first in a set S_i , she loses. \triangleleft

Finally, if Enforcer has played according to the legitimate order, at any moment of the game, Avoider has to play in a set S_i in which Avoider has already played. Therefore, she has to respect the order of the moves. The only moment when she can change this order is by playing u_{6k+1} instead of one of the vertices $x_{2k}, \overline{x_{2k}}$. But if she does so, Enforcer can play one of them, for instance x_{2k} , and Avoider will be forced to play $\overline{x_{2k}}$. If this happens, everything happens as if Avoider has played $\overline{x_{2k}}$ first and u_{6k+1} after. The strategy can then continue as if the order has been respected, as this does not change the order in which the valuation of the variables is chosen in φ , and Falsifier had a winning strategy if Satisfier had put X_{2k} to True by hypothesis.

To conclude, if Falsifier has a winning strategy in φ , Enforcer has a winning strategy in H . \blacktriangleleft

4.2 Proof of Lemma 11

In this section, we prove that if Satisfier has a winning strategy in φ , Avoider has one in H , even if Enforcer does not respect the order. The main idea of the strategy is to respect

the order, and if Enforcer does not respect the order, Avoider has a pairing strategy to force enforcer to claim some vertices x_i , or the odd u_j that follows it. By construction, any hyperedge containing a vertex x_i contains also the next odd vertex u_i in the order, and this will prove that when Enforcer do not respect the order, it will benefit Avoider.

► **Lemma 11.** *If Avoider has a winning strategy in φ when the legitimate order is respected by the two players, then she has a winning strategy in H .*

Proof. If Satisfier has a winning strategy \mathcal{S} in φ , and if Enforcer respects the order, Avoider has a winning strategy according to Lemma 9.

While Enforcer respects the legitimate order, Avoider also respects it. Suppose that at any moment of the game, Enforcer does not respect the legitimate order. Denote by y_A the vertex he would have played according to the legitimate order, and by y_E the vertex he has played instead. First, note that, according to Lemma 5, we can suppose that y_E is not a vertex u_j with j odd. Indeed, for each vertex u_{2i+1} , the hyperedges that contain the previous vertex in the legitimate order (if this vertex is a vertex x_j or \bar{x}_j this is true for any of them), also contain u_{2i+1} . If y_A is a vertex x_{2i} or \bar{x}_{2i} , Avoider pairs it with u_{6i+1} and continues as if Enforcer should have played u_{6i+2} . As any hyperedge containing x_{2i} or \bar{x}_{2i} , also contains u_{6i+1} which is the next vertex Avoider should have played according to the legitimate order, it benefits her if Enforcer finally plays u_{6i+1} according to Lemma 5.

Denote by k the smallest integer such that $y_E \notin S_k$, and by k' the largest integer such that $y_A \in S_{k'}$. Note that all the vertices outside $S_{k'}$ have already been played or are paired, and that $S_{k'} \setminus S_k$ is then the set of vertices perturbed by the move of Enforcer. We consider $k = 4n + 1$ if $y_E \in S_{4n}$. As all the set S_i have an odd number of variables, Avoider knows that the number of remaining vertices outside S_k is odd. (as an even number of moves have been done in it). According to \mathcal{S} , Satisfier has a winning strategy starting with the value already given to the variables x_i and \bar{x}_i that are outside $S_{k'}$. Avoider considers than arbitrary moves for Falsifier in \mathcal{S} and the corresponding moves for Satisfier until all the vertices x_i s and \bar{x}_i s in S_k are played in \mathcal{S} . According to these moves, we will denote by x_j^E the vertex among (x_j, \bar{x}_j) played by Enforcer and by x_j^A the vertex played by Avoider, such that their underlying valuation is the one desired by \mathcal{S} .

Avoider will then play a strategy different in S_k and outside S_k :

- In $H \setminus S_k$, Avoider plays y_A , the vertex that Enforcer should have played according to the order, then plays according to a pairing strategy, that is presented in the next paragraph.
- In S_k , Avoider considers the strategy she would have played if all the vertices outside S_k were played according to the legitimate order, with the valuation she considered in \mathcal{S} .

The pairing we define is the following one: (u_{6i-4}, x_{2i-1}^A) , (u_{6i-3}, u_{6i-6}) , (x_{2i-1}^E, u_{6i-1}) , (u_{6i-2}, x_{2i}^A) , (u_{6i+1}, x_{2i}^E) . This pairing starts at the vertex y_A and we consider only pairs containing a vertex outside S_k . Note that, by construction, exactly one vertex of this pairing is already played, and exactly one is in S_k . Therefore, to make the pairing contain only vertices not played and outside S_k , some modifications are done. These modifications are presented in Figure 1. By applying Lemma 6, Avoider can ensure that Enforcer plays at least one in each of these pairs.

▷ **Claim 14.** The pairing strategy ensures that Enforcer plays at least once in each hyperedge A_i , B_i or C_i containing at all their vertices in $S_{k'}$ and at least one outside S_k .

Proof. First, if the hyperedge contain no vertex whose pairing has been modified because of their appurtenance to y_A or y_E , it contains two paired vertices. We show in bold text the paired vertices:

y_A	changes	y_E	changes
u_{6i-4}	$u_{6i-3} \longleftrightarrow x_{2i-1}^A$	u_{6i-4}	no changes
x_{2i-1} or $\overline{x_{2i-1}}$	$x_{2i-1}^* \longleftrightarrow u_{6i-1}$	x_{2i-1} or $\overline{x_{2i-1}}$	$x_{2i-1}^* \longleftrightarrow u_{6i-4}$
u_{6i-2}	$u_{6i-1} \longleftrightarrow x_{2i}^A$	u_{6i-2}	no changes
u_{6i}	$u_{6i+3} \longleftrightarrow x_{2i}^A$	u_{6i}	no changes
		x_{2i} or $\overline{x_{2i}}$	$x_{2i}^* \longleftrightarrow u_{6i+1}, u_{6i-2} \longleftrightarrow u_{6i}$

■ **Figure 1** Changes of the matching. (x_k^* refers to the variable between x_k and $\overline{x_k}$ that has not been played)

$$\begin{aligned}
A_{2i} &= (x_{2i}^A, \mathbf{x}_{2i}^E, \mathbf{u}_{6i+1}, u_{6i+3}) & C_{6i-2}^E &= (u_{6i-2}, u_{6i-1}, \mathbf{u}_{6i+1}, \mathbf{x}_{2i}^E) \\
C_{6i}^A &= (\mathbf{u}_{6i}, u_{6i+1}, \mathbf{u}_{6i+3}, x_{2i}^A) & B_{2i-1} &= (x_{2i-1}^A, \mathbf{x}_{2i-1}^E, \mathbf{u}_{6i-1}) \\
C_{6i}^E &= (u_{6i}, \mathbf{u}_{6i+1}, u_{6i+3}, \mathbf{x}_{2i}^E) & C_{6i-4}^A &= (\mathbf{u}_{6i-4}, u_{6i-3}, u_{6i-1}, \mathbf{x}_{2i-1}^A) \\
C_{6i-2}^A &= (\mathbf{u}_{6i-2}, u_{6i-1}, u_{6i+1}, \mathbf{x}_{2i}^A) & C_{6i-4}^E &= (u_{6i-4}, u_{6i-3}, \mathbf{u}_{6i-1}, \mathbf{x}_{2i-1}^E)
\end{aligned}$$

For the first hyperedges of the matching, there are two paired vertices:

- If $y_A = u_{6i-4}$, only the hyperedges C_{6i-4}^E and C_{6i-4}^A are concerned by the changes. In the former x_{2i-1}^E is paired with u_{6i-1} , in the latter x_{2i-1}^A is paired with u_{6i-3} .
- If $y_A \in \{x_{2i-1}, \overline{x_{2i-1}}\}$, the only hyperedges concerned by the change is B_{2i-1} . In it, the other vertex in $\{x_{2i-1}, \overline{x_{2i-1}}\}$ is paired with u_{6i-1} .
- If $y_A = u_{6i-2}$, only the hyperedges C_{6i-2}^E and C_{6i-2}^A are concerned by the changes. In the former x_{2i}^E is paired with u_{6i+1} , in the latter x_{2i}^A is paired with u_{6i-1} .
- If $y_A = u_{6i}$, only the hyperedges C_{6i}^E and C_{6i}^A are concerned by the changes. In the former x_{2i}^E is paired with u_{6i+1} , in the latter x_{2i}^A is paired with u_{6i+3} .

For the last hyperedges that contains vertices of the matching, the following happens:

- If $y_E = u_{6i-4}$, the pairing stops at u_{6i-3} . The only two hyperedges that contains at least one vertex in S_k and one vertex outside S_k are C_{6i-4}^+ and C_{6i-4}^- , in which Enforcer has played y_E .
- If $y_E = x_{2i-1}$ or $\overline{x_{2i-1}}$, the pairing stops after the second vertex in $\{x_{2i-1}, \overline{x_{2i-1}}\}$. The only one hyperedge containing at least one vertex in S_k and one outside S_k is B_{2i-1} , in which Enforcer has already played y_E .
- If $y_E = u_{6i-2}$, the pairing stops at u_{6i-1} . The only two hyperedges that contains at least one vertex in S_k and one vertex outside S_k are C_{6i-2}^+ and C_{6i-2}^- , in which Enforcer has played y_E .
- If $y_E = u_{6i}$, the pairing stops at u_{6i+1} . The three hyperedges that contains both vertices in S_k and vertices outside S_k are C_{6i}^+ , C_{6i}^- and A_{2i} . In C_{6i}^+ , C_{6i}^- , Enforcer has played y_E , and in A_{2i} , Enforcer will play one of x_{2i}^E or u_{6i+1} as these two vertices are paired together.
- If $y_E = x_{2i}$ or $\overline{x_{2i}}$, the pairing stops at u_{6i+1} . The three hyperedges that contains vertices inside S_k and outside S_k are C_{6i}^+ , C_{6i}^- and A_{2i} . As the second vertex in $\{x_{2i}, \overline{x_{2i}}\}$ is paired with u_{6i+1} , either Enforcer has played both x_{2i} and $\overline{x_{2i}}$, and any of these three hyperedges contain at least one of them; or Enforcer has played u_{6i+1} which is in these three hyperedges.

If the pairing stops because it goes until the end (i.e. $k = 4n + 1$), one vertex is not paired. According to Lemma 6, as Enforcer plays the last move in H , Avoider can force him to play it and still play once in each pair of the pairing.

Finally, in any hyperedge A_i, B_i or C_i containing at least one vertex of the matching, Enforcer has played at least one vertex. \triangleleft

Now, we can prove that the strategy we defined for Avoider is a winning strategy. In all the hyperedges A_i, B_i or C_i , Enforcer played at least once: If Enforcer has respected the order until vertices of this hyperedge are reached, he has to play in it, otherwise by Claim 14, Avoider can force Enforcer to play in it as this hyperedge is considered in a set of hyperedges in which Enforcer has not respected the order, as the only hyperedges in which Enforcer is not the first player to claim a vertex according to the order are the A_{2i} , and in them, the vertex x_{2i}^E is always paired with u_{6i+1} .

In the hyperedges D_j , as the strategy defined by \mathcal{S} is a winning strategy, Satisfier has a strategy to force at least one literal l_i to be True in F_j . By construction, if when the vertex $x(l_i)$ has to be played, the order was respected, Enforcer has played it. If it has not, then Avoider has paired it with the vertex $u(l_i)$. In both cases, Enforcer has played in D_j . \blacktriangleleft

5 Applications

5.1 From 6-hypergraphs to 6-uniform hypergraphs

The construction provided in Section 3.1 provided a hypergraphs in which all hyperedges have size at most six. We prove here that we can suppose that all hyperedges have size six without changing the outcome.

A hypergraph $H = (V, E)$ is a k -hypergraph if each edge $e \in E$ has size at most k . It is said to be k -uniform if each edge $e \in E$ has size exactly k .

► **Lemma 15.** *Let $H = (V, E)$ be a k -hypergraph. Let $m = \min_{e \in E} |e|$. If $m < k$, there exists a k -hypergraph $H' = (V', E')$ where $\min_{e \in E'} |e| = m + 1$, and having $|E'| \leq 2|E|$ and $|V'| \leq |V| + 2$ such that Avoider has a winning strategy in Avoider-Enforcer on H if and only if she has one in H' .*

Proof. Let $H = (V, E)$ be a k -hypergraph. Let $m = \min_{e \in E} |e|$. We define $H' = (V', E')$ as follows. We start from $H' = H$. We add two vertices $\{a_1, a_2\}$ in V' . For each edge $e \in E$, we do the following:

- If $|e| > m$, we keep e in E' .
- If $|e| = m$, we consider $e_1 = e \cup \{a_1\}$ and $e_2 = e \cup \{a_2\}$. We then replace e in E' by e_1 and e_2 .

We have $|V'| = |V| + 2$, $|E'| \leq 2|E|$ and $\min_{e \in E'} |e| = m + 1$.

Now, if Avoider (Enforcer resp.) had a winning strategy \mathcal{S} in E , we can define a strategy \mathcal{S}' in E' as follows:

- If the opponent plays a vertex in V , or if it is the first move of the player, play as in \mathcal{S} .
- If the opponent plays a vertex in $\{a_1, a_2\}$, or if there is no vertex in V available, play an available vertex in $\{a_1, a_2\}$.

Following this strategy, Avoider (Enforcer resp.) has played exactly the same vertices in H' as he (she resp.) would have played in H according to \mathcal{S} with the addition of exactly one of $\{a_1, a_2\}$.

Therefore, if Avoider had a winning strategy in H , then for each $e \in E$, there exists one vertex $v \in e$, that Enforcer has played. This vertex is also in e if $e \in E'$ or in e_1 and e_2 if e_1 and e_2 were added to E' when we considered e . So this strategy ensure Avoider that Enforcer has played one vertex in e , and so it is a winning strategy for Avoider.

If Enforcer had a winning strategy in H , following this strategy, there exists an edge $e \in E$ in which Avoider has coloured all the vertices. If $|e| \geq m + 1$, Avoider has also coloured all the vertices of $e \in E'$, so Enforcer has won. If $|e| = m$, as the strategy \mathcal{S}' forces Avoider to play at least one of $\{a_1, a_2\}$, suppose without loss of generality that she has played a_1 . Then, she has played a_1 and all the vertices of e , so she has filled the edge e_1 . Therefore, this strategy is a winning strategy for Enforcer.

Finally, H' has the same outcome as H and $\min_{e \in E'} |e| = m + 1$. ◀

► **Corollary 16.** *Avoider-Enforcer is PSPACE-complete even on 6-uniform hypergraphs*

Several games have been proven to be PSPACE-complete in the Maker-Breaker convention, thanks to the proofs of Schaefer or of Rahman and Watson. Due to the similarities between the two convention, some reductions may be adapted to prove that these games are PSPACE-complete in the Avoider-Enforcer convention. In particular, we prove in this section that Avoider-Avoider games are PSPACE-complete, and we show that the Domination Game and the H -Game are PSPACE-complete in Avoider-Enforcer convention.

5.2 Avoider-Avoider games

We prove here that Avoider-Avoider games are PSPACE-complete.

► **Corollary 4.** *The AVOIDER-AVOIDER problem is PSPACE-complete, even when the entry is restricted to 7-uniform hypergraphs.*

Proof. Consider the construction provided in the proof of Corollary 16. Consider H' the hypergraph obtained by adding a vertex v_0 in H and adding it in all the hyperedges of H . Note that in H' , all the hyperedges have size seven. By Lemma 5, both player have an optimal strategy in which v_0 will be played last, and as the graph has an odd number of vertices, the first player will play it. Therefore, the second player cannot fill a hyperedge and plays as Enforcer would in the Avoider-Enforcer game. By applying the same strategy as in Avoider-Enforcer, If Avoider wins in Avoider-Enforcer, the game ends by a draw, otherwise the second player wins. ◀

5.3 Particular Avoider-Enforcer games

5.3.1 Avoider-Enforcer Domination game

The Maker-Breaker Domination game was introduced by Duchêne *et al.* in 2020 [10] and follows the study of Domination games on graphs, which were investigated since 2002 [1, 7]. In Maker-Breaker, two players, namely Dominator and Staller alternately claim an unclaimed vertex of the graph, Dominator wins if he manages to take all the vertices from a dominating set. Otherwise, Staller wins. They proved that determining whether Dominator or Staller has a winning strategy is PSPACE-complete using a reduction from Maker-Breaker. The Avoider-Enforcer Domination game can be similarly defined, with Staller winning if Dominator claims a dominating set and Dominator winning otherwise. We prove here that determining the winner of the Avoider-Enforcer Domination Game is PSPACE-complete. Note that the proof is very similar to the reduction from Maker-Breaker games to Maker-Breaker Domination game.

► **Problem 17.** AVOIDER-ENFORCER DOMINATION GAME

Input: A graph G

Output: True if and only if Avoider wins the Avoider-Enforcer Domination Game on G .

► **Theorem 18.** *Avoider-Enforcer Domination game is PSPACE-complete*

Proof. The proof of PSPACE-completeness in Avoider-Enforcer is roughly the same as in Maker-Breaker.

First, Avoider-Enforcer Domination game is in PSPACE, as the number of moves in a game is the number of vertices, and as determining if a set is a dominating set or not, the game is in PSPACE.

Let $H = (V_H, E_H)$ be a hypergraph. Without loss of a generality, we can suppose that each vertex is in at least one hyperedge. We construct the following graph $G = (V, E)$ as follows:

- For each vertex u_i in V_H , we add a vertex v_i in V .
- For each hyperedge C in E_H , we add two vertices v_C^1 and v_C^2 in V .
- If a vertex u_i of V_H belongs to a hyperedge C of E_H , we add the edges $v_i v_C^1$ and $v_i v_C^2$ to E .

Note that the graph created here is bipartite

Suppose Avoider (Enforcer resp.) has a winning strategy \mathcal{S} in H . We define a strategy \mathcal{S}' for Bob (Alice resp.) in G as follows.

- If Avoider (Enforcer resp.) plays the first move in H , play first a vertex v_i such that u_i is the first vertex played in \mathcal{S} .
Then:
- If the opponent plays a vertex v_i , play a vertex v_j such that u_j is the answer to the vertex u_i in \mathcal{S} .
- If a player plays a vertex v_C^k for $k \in \{1, 2\}$, plays the vertex $v_C^{k'}$ for $k' \neq k \in \{1, 2\}$.

Now if Avoider had a winning strategy in H , by applying the strategy \mathcal{S}' , for any vertex v_C^i , Bob has not played all the v_j s adjacent to it. Therefore, Alice has played one of them and all the v_C^i s are dominated. Moreover, all the vertex u_j s are in at least one edge C of H . So v_j is dominated by Alice has played one of (v_C^1, v_C^2) . So Bob has won.

If Enforcer had a winning strategy in H , by applying the strategy \mathcal{S}' , Bob knows that there exists a pair of vertices (v_C^1, v_C^2) , such that Alice has played all the v_j s adjacent to them. As Bob has played exactly one of them, he has not played the second one. Therefore, he does not dominate it and has won. ◀

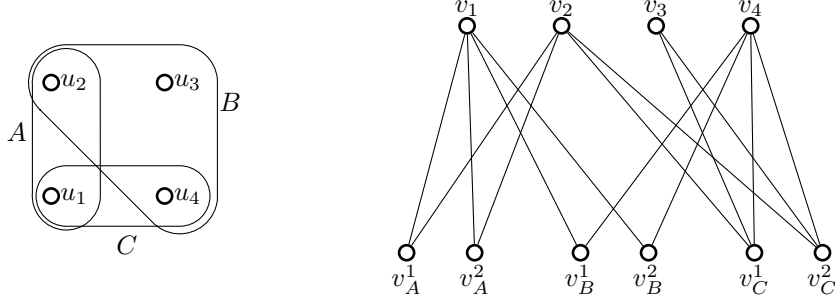
In Figure 2 we provide an example of reduction. Note that by connecting all the vertices v_i , they will form a clique, and this gives the proof Avoider-Enforcer Domination game on split graphs. So the Avoider-Enforcer game is PSPACE-complete on bipartite and split graphs, as the Maker-Breaker Domination game for roughly the same construction.

5.3.2 Vertex H-game

The vertex H -Game has been introduced by Kronenberg, Mond and Naor in [21] on random graphs. It is presented in several conventions, but we will focus here on the Avoider-Enforcer one. The game is played as follows:

Let H be a graph. Avoider and Enforcer play on the vertex set of another graph G . Alternately, Avoider and Enforcer claim an unclaimed vertex of G . Avoider wins if the set of vertices she has claimed do not contain H as a subgraph (not necessarily induced). Otherwise, Enforcer wins.

We prove here that determining the winner of the Avoider-Enforcer H -Game is a PSPACE-complete problem for several graphs H .



■ **Figure 2** Reduction from AVOIDER-ENFORCER.

► **Problem 19.** AVOIDER-ENFORCER H -GAME

Input: A graph G

Output: True if and only if Avoider wins the Avoider-Enforcer H -Game played on G .

We prove that the vertex H -game is PSPACE-complete for several graphs H . To define these graphs, we first need to define some graphs and operations:

- We will denote by I_k the graph being an independent set of size k , i.e. containing k vertices and no edge.
- If G and H are two graphs, we denote by $G \bowtie H$ their join, i.e. if $G = (V_G, E_G)$ and $H = (V_H, E_H)$, we have $G \bowtie H = (V, E)$ with $V = V_G \cup V_H$ and $E = E_G \cup E_H \cup \{(v_G, v_H) | v_G \in V_G, v_H \in V_H\}$.
- If G and H are two graphs, we denote by $G \boxtimes H$ their strong product, i.e. if $G = (V_G, E_G)$ and $H = (V_H, E_H)$, we have $G \boxtimes H = (V, E)$ with $V = \{x_{u,v} | u \in V_G, v \in V_H\}$ and $E = \{(x_{u_1, v_1}, x_{u_2, v_2}) | (u_1 = u_2 \text{ or } (u_1, u_2) \in E_G) \text{ and } (v_1 = v_2 \text{ or } (v_1, v_2) \in E_H)\}$.

Remark that for any graph G , $G \boxtimes P_2$ (where P_2 design the path of length 2) is obtained by taking two copies of G and connecting each vertex to its copy and its copy's neighbours.

We prove here that determining the winner of the Avoider-Enforcer H -Game is a PSPACE-complete problem for several graphs H .

► **Theorem 20.** *Let H_0 be a graph containing at least one edge or at least 6 vertices, and let $k \geq 6$. Consider $H = I_k \bowtie H_0$. The AVOIDER-ENFORCER H -GAME problem is PSPACE-complete.*

Note that complete bipartite graphs $K_{n,m}$, with $n, m \geq 6$, are of this type. Indeed, $K_{n,m} = I_k \bowtie H_0$ for $H_0 = I_m$ and $k = n$.

Proof. First, the H -game is in PSPACE. Indeed, as it is a positional game, if $G = (V, E)$ is a graph, the game ends after at most $|V|$ moves. After that, determining whether a graph H is a subgraph of a graph G can be done in polynomial space.

We do our reduction from AVOIDER-ENFORCER on 6-uniform hypergraphs which is PSPACE-complete by Corollary 16. Let H_0 be a graph containing at least one edge or at least 6 vertices, and let $k \geq 6$. Let $H = I_k \bowtie H_0$. To avoid confusion while describing the strategies in the two games, we will call the players of the H -Game Alice and Bob, with Alice avoiding creating a subgraph H and Bob forcing her to create one.

Let $H' = (V', E')$ be a 6-uniform hypergraph. Let H'_0 be the strong product $H_0 \boxtimes P_2$. We build $G = (V, E)$ an instance of H -Game as follows:

- **Step 1:** For any vertex $v'_i \in V'$, we add a vertex $v_i \in V$.
- **Step 2:** For any edge $C \in E'$, we add $2(k-6)$ vertices $v_1^C, \dots, v_{2(k-6)}^C$ (note that if $k=6$ these vertices do not exist).
- **Step 3:** For any edge $C \in E'$, we add a copy H_0^C of the graph H_0 in G , and we connect any vertex of H_0^C to all the vertices v_i such that $v'_i \in C$ and to all the vertices v_j^C for $1 \leq j \leq 2k-6$.

▷ **Claim 21.** If Avoider has a winning strategy in H' , Alice has a winning strategy in G .

Proof. Suppose Avoider has a winning strategy \mathcal{S}' in H' . We define Alice's strategy \mathcal{S} in G as follows:

- She starts by playing the vertex v_i , corresponding to the vertex v'_i that Avoider would have played in H' according to \mathcal{S}' .
- If Bob plays a vertex v_i , she answers with the vertex v_j corresponding to the vertex v'_j that Avoider would have played by \mathcal{S}' in H' if Enforcer has played v'_i .
- In H_0^C , as it is a strong product $H_0 \boxtimes P_2$, Alice considers the pairing between any vertex and its copy in the strong product. If Bob plays one of them, she plays the second one.
- For any edge C in H' , Alice considers the set of vertices v_j^C for $1 \leq j \leq 2k-6$. As there is an even number of them, if Bob plays one of them, she can also play one of them.

At the end of the game, by the matching strategy, for each clause C in H' , Alice will have played exactly a copy of H_0 in each H_0^C , exactly $k-6$ vertices among the v_j^C with $1 \leq j \leq 2(k-6)$, and the vertices v_i corresponding to the v'_i that Avoider would have played according to \mathcal{S}' in H' .

Now, consider any copy H_1 of H in G . Suppose that Alice has played all the vertices of H_1 .

Suppose H_0 has at least one edge. We first prove that H_1 cannot contain two vertices v_C and $v_{C'}$ for $C \neq C'$ that have been created by the Steps 2 or Step 3 of our construction. Suppose it does. Consider a decomposition of $H_1 = I_k \bowtie H_0^1$. By construction, the v_C s and the $v_{C'}$ s are not adjacent. Therefore, as these two components are fully connected one to the other, they must either be both in I_k or both in H_0^1 .

Case 1: H_0 has at least one edge.

H_1 also has one edge $e = (u_1, u_2)$. As I_k is a stable set, we have $u_1, u_2 \in H_0^1$. Now, as u_1 can only be adjacent to vertices v_i s created by the vertices of H' (Step 1), v_C and $v_{C'}$ cannot be both adjacent to u_1 . Therefore, as we supposed $C \neq C'$, and as only vertices created during Step 1 can be adjacent to both v_C and $v_{C'}$, any vertex in I_k must be a vertex v_i . Which is not possible otherwise, Alice would have play $k \geq 6$ vertices v_i adjacent to a same v_C , which means that, according to \mathcal{S}' she would have played $k \geq 6$ vertices in the same hyperedge in H' , which contradicts the fact that \mathcal{S}' was a winning strategy for Avoider in H' .

Now, as all the vertices of H_1 are either v_i s or were created by considering the same hyperedge C , and $|H_1| = |H_0| + k$, by the pairing, we know that exactly 6 of them are v_i s. As there are no edges between the v_i s, they must all be on the same side of the join, and therefore, they are all connected to a same vertex. By construction, this is only the case if these six vertices were in a same hyperedge of H' which contradicts that \mathcal{S}' was a winning strategy for Avoider in H' .

Case 2: H_0 has no edges and has $k' \geq 6$ vertices.

This means that H can be written $I_k \bowtie I_{k'}$ for $k, k' \geq 6$ (note that H is a complete bipartite graph). Once again, consider two vertices v_C and $v_{C'}$ for $C \neq C'$ in H_1 . As they cannot be adjacent, they must be both in I_k or both in $I_{k'}$. Thus, v_C and $v_{C'}$ have

$\min(k, k') \geq 6$ common neighbours. This implies that, if $C \neq C'$, at least one of their common neighbour is not a vertex v_i created during Step 1, otherwise Alice would have played six vertices in the same hyperedge of H' . This is not possible by construction. So once again, H_1 cannot contain v_C and $v_{C'}$ created from different hyperedges from H' . Now, if Alice has played all the vertices of H_1 , by construction as $|H_1| = k + k'$, and as her pairing strategy ensure her to play $k - 6$ vertices created during step 2 and k' created during step 3, necessarily, she has played six vertices v_i creating during step 1. As there are no edges between these six vertices, they must all be in the same independent set I_k or $I_{k'}$. Thus, they have a common neighbour. This common neighbour must then be a vertex v_C creating during step 3 as only them are connected to the v_i s. Finally, these six vertices corresponds to six vertices v'_j s that are in the same hyperedge C of H' . Once again, this contradicts the fact that \mathcal{S}' was a winning strategy for Avoider in H' .

◁

▷ **Claim 22.** If Enforcer has a winning strategy \mathcal{S}' in H' , Bob has a winning strategy in G .

Proof. Let \mathcal{S}' be a winning strategy for Enforcer in H' . We consider a strategy \mathcal{S} for Bob in G as follows:

- If Alice plays a vertex v_i , he answers with the vertex v_j that corresponds to the vertex v'_j that Enforcer would have played in response to v'_i in \mathcal{S}' .
- In H_0^C , as it is a strong product $H_0 \boxtimes P_2$, Bob considers the pairing between any vertex and its copy in the strong product. If Alice plays one of them, he plays the second one.
- For any edge $C \in H'$, Bob pairs the vertices v_j^C for $1 \leq j \leq 2k - 6$. If Alice plays one of them, he plays one of them too.
- If at a certain moment of the game, it is Bob's turn and the remaining vertices are all in some H_0^C or vertices v_j^C s, he applies the pairing strategy, so that Alice plays once in any pair of the matching by Lemma 6.

Consider the graph at the end of the game. As \mathcal{S} was a winning strategy for Enforcer in H' , there exists a hyperedge $C \in H'$ in which Avoider has played the six vertices. Up to a renaming of the vertices, denote by v'_1, \dots, v'_6 be these six vertices. Alice has then played v_1, \dots, v_6 in G . According to the pairing strategy, Bob knows that Alice will play exactly $k - 6$ vertices from the v_j^C , denote them v_7, \dots, v_k , and exactly one copy H_1 of H_0 from the vertices of H_0^C . Now, by construction, the vertices v_1, \dots, v_k are a stable set and all the edges exist between any v_i ($1 \leq i \leq k$) and any vertex v of H_1 . Thus, the subgraph formed by these vertices, which were all played by Alice, is isomorphic to $I_k \bowtie H_0 = H$. Thus, Bob has won.

◁

Finally, the H -Game played on G is won by Alice if and only if the Avoider-Enforcer game played on H' is won by Avoider, and determining the winner of the H -Game is PSPACE-complete. ◀

Theses two games are two examples of games in which the proof of PSPACE-completeness in Avoider-Enforcer convention is similar to the one in Maker-Breaker convention, in several other games the Maker-Breaker complexity proof can be adapted to an Avoider-Enforcer one.

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