

# Reaching Individually Stable Coalition Structures in Hedonic Games

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## Abstract

The formal study of coalition formation in multiagent systems is typically realized using so-called hedonic games, which originate from economic theory. The main focus of this branch of research has been on the existence and the computational complexity of deciding the existence of coalition structures that satisfy various stability criteria. The actual process of forming coalitions based on individual behavior has received very little attention. In this paper, we study the convergence of simple dynamics leading to stable partitions in a variety of classes of hedonic games, including anonymous, dichotomous, fractional, and hedonic diversity games. The dynamics we consider is based on individual stability: an agent will join another coalition if she is better off and no member of the welcoming coalition is worse off. We identify conditions for convergence, provide elaborate counterexamples of existence of individually stable partitions, and study the computational complexity of problems related to the coalition formation dynamics. In particular, we settle open problems suggested by Bogomolnaia and Jackson (2002), Brandl, Brandt, and Strobel (2015), and Boehmer and Elkind (2020).

## 1 Introduction

Coalitions and coalition formation are central concerns in the study of multiagent systems as well as cooperative game theory. Typical real-world examples include individuals joining clubs or societies such as orchestras, choirs, or sport teams, countries organizing themselves in international bodies like the European Union (EU) or the North Atlantic Treaty Organization (NATO), students living together in shared flats, or employees forming unions. The formal study of coalition formation is often realized using so-called hedonic games, which originate from economic theory and focus on coalition structures (henceforth partitions) that satisfy various stability criteria based on the agents' preferences over coalitions. A partition is defined to be stable if single agents or groups of agents cannot gain by deviating from the current partition by means of leaving their current coalition and joining another coalition or forming a new one. Which kinds of deviations are permitted depends on the underlying notion of stability. Two important and well-studied questions in this context concern the existence of stable partitions in restricted classes of hedonic games and the computational complexity of finding a stable partition. However, stability is only concerned with the end-state of the coalition

formation process and ignores how these desirable partitions can actually be reached. Essentially, an underlying assumption in most of the existing work is that there is a central authority that receives the preferences of all agents, computes a stable partition, and has the means to enforce this partition on the agents. By contrast, our work focuses on simple dynamics, where starting with some partition (e.g., the partition of singletons), agents deliberately decide to join and leave coalitions based on their individual preferences. We study the convergence of such a process and the stable partitions that can arise from it. For example, in some cases the only partition satisfying a certain stability criterion is the grand coalition consisting of all agents, while the dynamics based on the agents' individual decisions can never reach this partition and is doomed to cycle.

The dynamics we consider is based on *individual stability*, a natural notion of stability going back to Drèze and Greenberg (1980): an agent will join another coalition if she is better off and no member of the welcoming coalition is worse off. Individual stability is suitable to model the situations mentioned above. For instance, by Article 49 of the Treaty on European Union, admitting new members to the EU requires the unanimous approval of the current members. Similarly, by Article 10 of their founding treaty, unanimous agreement of all parties is necessary to become a member of the NATO. Also, for joining a choir or orchestra it is often necessary to audition successfully, and joining a shared flat requires the consent of all current residents. This distinguishes individual stability from Nash stability, which ignores the consent of members of the welcoming coalition.

The analysis of coalition formation processes provides more insight in the natural behavior of agents and the conditions that are required to guarantee that desirable social outcomes can be reached without a central authority. Similar dynamic processes have been studied in the special domain of matching, which only allows coalitions of size 2 (e.g., Roth and Vande Vate 1990; Abeledo and Rothblum 1995; Brandt and Wilczynski 2019). More recently, the dynamics of coalition formation have also come under scrutiny in the context of hedonic games (Bilò et al. 2018; Hoefer, Vaz, and Wagner 2018; Carosi, Monaco, and Moscardelli 2019). While coalition formation dynamics are an object of study worthy for itself, they can also be used as a means to design algorithms that compute stable outcomes, and have been im-

explicitly used for this purpose before. For example, the algorithm by Boehmer and Elkind (2020) for finding an individually stable partition in hedonic diversity games predefines a promising partition and then reaches an individually stable partition by running the dynamics from there. Similarly, the algorithm by Bogomolnaia and Jackson (2002) for finding an individually stable partition on games with ordered characteristics, a generalization of anonymous hedonic games, runs the dynamics using a specific sequence of deviations starting from the singleton partition.

In many cases, the convergence of the dynamics of deviations follows from the existence of potential functions, whose local optima form individually stable states. Generalizing a result by Bogomolnaia and Jackson (2002), Suksompong (2015) has shown via a potential function argument that an individually stable—and even a Nash stable—partition always exists in subset-neutral hedonic games, a generalization of symmetric additively-separable hedonic games. Using the same potential function, it can straightforwardly be shown that the dynamics converge.<sup>1</sup> Another example are hedonic games with the common ranking property, a class of hedonic games where preferences are induced by a common global order (Farrell and Scotchmer 1988). The dynamics associated with core-stable deviations is known to converge to a core-stable partition that is also Pareto-optimal, thanks to a potential function argument (Caskurlu and Kizilkaya 2019). The same potential function implies convergence of the dynamics based on individual stability.

In this paper, we study the coalition formation dynamics based on individual stability for a variety of classes of hedonic games, including anonymous hedonic games (AHGs), hedonic diversity games (HDGs), fractional hedonic games (FHGs), and dichotomous hedonic games (DHGs). Whether we obtain positive or negative results often depends on the initial partition and on restrictions imposed on the agents’ preferences. Computational questions related to the dynamics are investigated in two ways: the existence of a *path to stability*, that is the existence of a sequence of deviations that leads to a stable state, and the *guarantee of convergence* where every sequence of deviations should lead to a stable state. The former gives an optimistic view on the behavior of the dynamics and may be used to motivate the choice of reachable stable partitions (we can exclude “artificial” stable partitions that may never naturally form). If such a sequence can be computed efficiently, it enables a central authority to coordinate the deviations towards a stable partition. However, since this approach does not give any guarantee on the outcome of the dynamics, we also study the latter, more pessimistic, problem. Our main results are as follows.

- In AHGs, the dynamics converges for (naturally) single-peaked strict preferences. We provide a 15-agent example showing the non-existence of individually stable par-

<sup>1</sup>By inclusion, convergence also holds for symmetric additively-separable hedonic games. Symmetry is essential for this result to hold since an individually stable partition may not exist in additively-separable hedonic games, even under additional restrictions (Bogomolnaia and Jackson 2002).

titions in general AHGs. The previous known counterexample by Bogomolnaia and Jackson (2002) requires 63 agents and the existence of smaller examples was an acknowledged open problem (see Ballester 2004; Boehmer and Elkind 2020).

- In HDGs, the dynamics converges for strict and naturally single-peaked preferences when starting from the singleton partition. In contrast to empirical evidence reported by Boehmer and Elkind (2020), we show that these preference restrictions are not sufficient to guarantee convergence from an arbitrary initial partition.
- In FHGs, the dynamics converges for simple symmetric preferences when starting from the singleton partition or when preferences form an acyclic digraph. We show that individually stable partitions need not exist in general symmetric FHGs, which was left as an open problem by Brandl, Brandt, and Strobel (2015).
- For each of these four classes, including DHGs, we show that deciding whether there is a sequence of deviations leading to an individually stable partition is NP-hard while deciding whether all sequences of deviations lead to an individually stable partition is co-NP-hard. Some of these results hold under preference restrictions and even when starting from the singleton partition.

## 2 Preliminaries

Let  $N = [n] = \{1, \dots, n\}$  be a set of  $n$  agents. The goal of a coalition formation problem is to partition the agents into different disjoint coalitions according to their preferences. A solution is then a partition  $\pi : N \rightarrow 2^N$  such that  $i \in \pi(i)$  for every agent  $i \in N$  and either  $\pi(i) = \pi(j)$  or  $\pi(i) \cap \pi(j) = \emptyset$  holds for every agents  $i$  and  $j$ , where  $\pi(i)$  denotes the coalition to which agent  $i$  belongs. Two prominent partitions are the *singleton partition*  $\pi$  given by  $\pi(i) = \{i\}$  for every agent  $i \in N$ , and the *grand coalition*  $\pi$  given by  $\pi = \{N\}$ .

Since we focus on dynamics of deviations, we assume that there exists an initial partition  $\pi_0$ , which could be a natural initial state (such as the singleton partition) or the outcome of a previous coalition formation process.

### 2.1 Classes of Hedonic Games

In a hedonic game, the agents only express preferences over the coalitions to which they belong, i.e., there are no externalities. Let  $\mathcal{N}_i$  denote all possible coalitions containing agent  $i$ , i.e.,  $\mathcal{N}_i = \{C \subseteq N : i \in C\}$ . A hedonic game is defined by a tuple  $(N, (\succsim_i)_{i \in N})$  where  $\succsim_i$  is a weak order over  $\mathcal{N}_i$  which represents the preferences of agent  $i$ . Since  $|\mathcal{N}_i| = 2^{n-1}$ , the preferences are rarely given explicitly, but rather in some concise representation. These representations give rise to several classes of hedonic games:

- *Anonymous hedonic games (AHGs)* (Bogomolnaia and Jackson 2002): The agents only care about the size of the coalition they belong to, i.e., for each agent  $i \in N$ , there exists a weak order  $\succsim_i$  over integers in  $[n]$  such that  $\pi(i) \succsim_i \pi'(i)$  iff  $|\pi(i)| \succsim_i |\pi'(i)|$ .
- *Hedonic diversity games (HDGs)* (Bredereck, Elkind, and Igarashi 2019): The agents are divided into two different

types, red and blue agents, represented by the subsets  $R$  and  $B$ , respectively, such that  $N = R \cup B$  and  $R \cap B = \emptyset$ . Each agent only cares about the proportion of red agents present in her own coalition, i.e., for each agent  $i \in N$ , there exists a weak order  $\succsim_i$  over  $\{\frac{p}{q} : p \in [|R|] \cup \{0\}, q \in [n]\}$  such that  $\pi(i) \succsim_i \pi'(i)$  iff  $\frac{|R \cap \pi(i)|}{|\pi(i)|} \succsim_i \frac{|R \cap \pi'(i)|}{|\pi'(i)|}$ .

- **Fractional Hedonic Games (FHGs)** (Aziz et al. 2019): The agents evaluate a coalition according to how much they like each of its members on average, i.e., for each agent  $i$ , there exists a utility function  $v_i : N \rightarrow \mathbb{R}$  where  $v_i(i) = 0$  such that  $\pi(i) \succsim_i \pi'(i)$  iff  $\frac{\sum_{j \in \pi(i)} v_i(j)}{|\pi(i)|} \geq \frac{\sum_{j \in \pi'(i)} v_i(j)}{|\pi'(i)|}$ . An FHG can be represented by a weighted complete directed graph  $G = (N, E)$  where the weight of arc  $(i, j)$  is equal to  $v_i(j)$ . An FHG is *symmetric* if  $v_i(j) = v_j(i)$  for every pair of agents  $i$  and  $j$ , i.e., it can be represented by a weighted complete undirected graph with weights  $v(i, j)$  on each edge  $\{i, j\}$ . An FHG is *simple* if  $v_i : N \rightarrow \{0, 1\}$  for every agent  $i$ , i.e., it can be represented by an unweighted directed graph where  $(i, j) \in E$  iff  $v_i(j) = 1$ . We say that a simple FHG is *asymmetric* if, for every pair of agents  $i$  and  $j$ ,  $v_i(j) = 1$  implies  $v_j(i) = 0$ , i.e., it can be represented by an asymmetric directed graph.
- **Dichotomous hedonic games (DHGs)**: The agents only approve or disapprove coalitions, i.e., for each agent  $i$  there exists a utility function  $v_i : \mathcal{N}_i \rightarrow \{0, 1\}$  such that  $\pi(i) \succsim_i \pi'(i)$  iff  $v_i(\pi(i)) \geq v_i(\pi'(i))$ . When the preferences are represented by a propositional formula, such games are called *Boolean hedonic games* (Aziz et al. 2016).

An anonymous game (resp., hedonic diversity game) is *generally single-peaked* if there exists a linear order  $>$  over integers in  $[n]$  (resp., over ratios in  $\{\frac{p}{q} : p \in [|R|] \cup \{0\}, q \in [n]\}$ ) such that for each agent  $i \in N$  and each triple of integers  $x, y, z \in [n]$  (resp.,  $x, y, z \in \{\frac{p}{q} : p \in [|R|] \cup \{0\}, q \in [n]\}$ ) with  $x > y > z$  or  $z > y > x$ ,  $x \succsim_i y$  implies  $y \succsim_i z$ . The obvious linear order  $>$  that comes to mind is, of course, the natural order over integers (resp., over rational numbers). We refer to such games as *naturally single-peaked*. Clearly, a naturally single-peaked preference profile is generally single-peaked but the converse is not true.

## 2.2 Dynamics of Individually Stable Deviations

Starting from the initial partition, agents can leave and join coalitions in order to improve their well-being. We focus on unilateral deviations, which occur when a single agent decides to move from one coalition to another. A *unilateral deviation* performed by agent  $i$  transforms a partition  $\pi$  into a partition  $\pi'$  where  $\pi(i) \neq \pi'(i)$  and, for all agents  $j \neq i$ ,

$$\pi'(j) = \begin{cases} \pi(j) \setminus \{i\} & \text{if } j \in \pi(i) \\ \pi(j) \cup \{i\} & \text{if } j \in \pi'(i) \\ \pi(j) & \text{otherwise} \end{cases}$$

Since agents are assumed to be rational, agents only engage in a unilateral deviation if it makes them better off, i.e.,

$\pi'(i) \succ_i \pi(i)$ . Any partition in which no such deviation is possible is called *Nash stable (NS)*.

This type of deviation can be refined by additionally requiring that no agent in the welcoming coalition is worse off when agent  $i$  joins. A partition in which no such deviation is possible is called *individually stable (IS)*. Formally, a unilateral deviation performed by agent  $i$  who moves from coalition  $\pi(i)$  to  $\pi'(i)$  is an IS-deviation if  $\pi'(i) \succ_i \pi(i)$  and  $\pi'(i) \succsim_j \pi(j)$  for all agents  $j \in \pi'(i)$ . Clearly, an NS partition is also IS.<sup>2</sup> In this article, we focus on dynamics based on IS-deviations. By definition, all terminal states of the dynamics have to be IS partitions.

We are mainly concerned with whether sequences of IS-deviations can reach or always reach an IS partition. If there exists a sequence of IS-deviations leading to an IS partition, i.e., a path to stability, then agents can coordinate (or can be coordinated) to reach a stable partition. The corresponding decision problem is described as follows.

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### $\exists$ -IS-SEQUENCE-[HG]

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Input:	Instance of a particular class of hedonic games [HG], initial partition $\pi_0$
Question:	Does there exist a sequence of IS-deviations starting from $\pi_0$ leading to an IS partition?

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In order to provide some guarantee, we also examine whether *all* sequences of IS-deviations terminate. Whenever this is the case, we say that the dynamics *converges*. The corresponding decision problem is described below.

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### $\forall$ -IS-SEQUENCE-[HG]

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Input:	Instance of a particular class of hedonic games [HG], initial partition $\pi_0$
Question:	Does every sequence of IS-deviations starting from $\pi_0$ reach an IS partition?

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We mainly investigate this problem via the study of its complement: given a hedonic game and an initial partition, does there exist a sequence of IS-deviations that cycles?

A common idea behind hardness reductions concerning these two problems is to exploit prohibitive subconfigurations that evolve from instances without an IS partition or instances which allow for cycling starting from a certain partition.

## 3 Anonymous Hedonic Games (AHGs)

Bogomolnaia and Jackson (2002) showed that IS partitions always exist in AHGs under naturally single-peaked preferences, and proved that this does not hold under general preferences, by means of a 63-agent counterexample. Here, we provide a counterexample that only requires 15 agents and additionally satisfies general single-peakedness. Full proofs for all statements can be found in the appendix.

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<sup>2</sup>It is possible to weaken the notion of individual stability even further by also requiring that no member of the *former* coalition of agent  $i$  is worse off. The resulting stability notion is called *contractual individual stability* and guarantees convergence of our dynamics.

**Proposition 3.1.** *There may not exist an IS partition in AHGs even when  $n = 15$  and the agents have strict and generally single-peaked preferences.*

*Sketch of proof.* Let us consider an AHG with 15 agents with the following (incompletely specified) preferences.

$$\begin{array}{l} 1: 2 \succ 3 \succ 13 \succ 12 \succ 1 \succ [\dots] \\ 2: 13 \succ 3 \succ 2 \succ 1 \succ 12 \succ [\dots] \\ 3, 4: 3 \succ 2 \succ 1 \succ [\dots] \\ 5, \dots, 15: 13 \succ 12 \succ 15 \succ 14 \succ 11 \succ [\dots] \succ 1 \end{array}$$

They can be completed to be generally single-peaked w.r.t. axis  $1 < 2 < 3 < 13 < 12 < 15 < 14 < 11 < \dots < 4$ .

One can prove that in an IS partition,

- (i) agents 3 and 4 are in a coalition of size at most 3;
- (ii) agents 5 to 15 are in the same coalition;
- (iii) agents 3 and 4 are in the same coalition;
- (iv) agents 1 and 2 cannot be both alone.

Therefore, agents 3 and 4 must be together, as well as agents 5 to 15, but not in the same coalition. It remains to identify the coalitions of agents 1 and 2. By (i), they cannot be both with agents 3 and 4. If one agent among them is alone and the other one with agents 5 to 15, then the alone agent can deviate to join them, a contradiction. The remaining possible partitions are present in the cycle of IS-deviations below (the deviating agent is written on top of the arrows).

$$\begin{array}{c} \{\{1\}, \{2, 3, 4\}, \{5, \dots, 15\}\} \xrightarrow{1} \{\{2, 3, 4\}, \{1, 5, \dots, 15\}\} \xrightarrow{2} \{\{3, 4\}, \{1, 2, 5, \dots, 15\}\} \\ \uparrow 2 \\ \{\{1, 2\}, \{3, 4\}, \{5, \dots, 15\}\} \xrightarrow{1} \{\{2\}, \{1, 3, 4\}, \{5, \dots, 15\}\} \xrightarrow{2} \{\{1, 3, 4\}, \{2, 5, \dots, 15\}\} \\ \downarrow 1 \end{array}$$

Hence, there is no IS partition in this instance.  $\square$

However, even in smaller examples where IS partitions do exist, there may still be cycles in the dynamics.

**Proposition 3.2.** *The dynamics of IS-deviations may cycle in AHGs even when starting from the singleton partition or grand coalition, for strict generally single-peaked preferences, and for  $n < 15$ .*

*Proof.* Let us consider an AHG with 7 agents with the following (incompletely specified) preferences.

$$\begin{array}{l} 1: 2 \succ 3 \succ 5 \succ 4 \succ 1 \succ [\dots] \\ 2: 5 \succ 3 \succ 2 \succ 1 \succ 4 \succ [\dots] \\ 3, 4: 3 \succ 2 \succ 1 \succ [\dots] \\ 5, 6, 7: 5 \succ 4 \succ 3 \succ 2 \succ 1 \succ [\dots] \end{array}$$

They can be completed to be generally single-peaked w.r.t. axis  $1 < 2 < 3 < 5 < 4 < 6 < 7$ . Note that  $\{\{1\}, \{3, 5, 6\}, \{2, 4, 7\}\}$  is an IS partition. We represent below a cycle in IS-deviations that can be reached from the singleton partition or the grand coalition.

$$\begin{array}{c} \{\{1, 2\}, \{3, 4\}, \{5, 6, 7\}\} \xrightarrow{2} \{\{1\}, \{2, 3, 4\}, \{5, 6, 7\}\} \xrightarrow{1} \{\{2, 3, 4\}, \{1, 5, 6, 7\}\} \\ \uparrow 1 \\ \{\{2\}, \{1, 3, 4\}, \{5, 6, 7\}\} \xrightarrow{2} \{\{1, 3, 4\}, \{2, 5, 6, 7\}\} \xrightarrow{1} \{\{3, 4\}, \{1, 2, 5, 6, 7\}\} \\ \downarrow 2 \end{array}$$

We know that it is NP-complete to recognize instances for which an IS partition exists in AHGs, even for strict preferences (Ballester 2004). We prove that both checking the existence of a sequence of IS-deviations ending in an IS partition and checking convergence are hard.

**Theorem 3.3.**  $\exists$ -IS-SEQUENCE-AHG is NP-hard and  $\forall$ -IS-SEQUENCE-AHG is co-NP-hard, even for strict preferences.

However, this hardness result does not hold under strict naturally single-peaked preferences, since we show in the next proposition that every sequence of IS-deviations is finite under such a restriction.

**Proposition 3.4.** *The dynamics of IS-deviations always converges to an IS partition in AHGs for strict naturally single-peaked preferences.*

*Proof.* Assume for contradiction that there exists a cycle of IS-deviations. The key idea is to construct an infinite sequence of agents  $(a_k)_{k \geq 1}$  that perform deviations from coalitions  $(C_k)_{k \geq 1}$ , which are strictly increasing in size. Let  $a_1$  be an agent that deviates within this cycle towards a larger coalition by an IS-deviation. This transforms, say, partition  $\pi_1$  into partition  $\pi_1^1$ . Set  $C_1 = \pi_1(a_1)$  and  $\hat{C}_1 = \pi_1^1(a_1)$ . One can for instance take an agent that performs a deviation from a coalition of minimum size amongst all coalitions from which any deviation is performed. We will now observe how the coalition  $\hat{C}_1$  evolves during the cycle. After possibly some agents outside  $\hat{C}_1$  joined it or some left it, some agent  $b$  originally in  $\hat{C}_1$  must deviate from the coalition evolved from  $\hat{C}_1$ . Otherwise, we cannot reach partition  $\pi_1$  again in the cycle. If  $b \neq a_1$ , we assume that the deviation transforms partition  $\pi_2$  into partition  $\pi_2^1$  and we set  $a_2 = b$ ,  $C_2 = \pi_2(b)$ , and  $\hat{C}_2 = \pi_2^1(b)$ . Note that  $|\hat{C}_2| > |C_2| \geq |\hat{C}_1|$ , by single-peakedness and the fact that  $|\hat{C}_2| \succ_b |C_2| \succ_b |C_2| - 1 \succ_b \dots \succ_b |\hat{C}_1| \succ_b |\hat{C}_1| - 1$  (where all preferences but the first follow from the assumption of strictness when some other agent joined the coalition of  $b$ ). In particular,  $|C_2| > |C_1|$ .

If  $b = a_1$ , assume that the deviation transforms partition  $\pi_1^2$  into  $\pi_1^3$ , where possibly  $\pi_1^2 = \pi_1^1$ . We update  $\hat{C}_1 = \pi_1^3(a_1)$ . Note that still  $|\hat{C}_1| > |C_1|$  by single-peakedness, because the original deviation of  $a_1$  performed in partition  $\pi_1$  was towards a larger coalition and  $|\pi_1^2(a_1)| \succeq_{a_1} |\pi_1^1(a_1)|$  (equality if the partitions are the same). We consider again the next deviation from  $\hat{C}_1$  until it is from an agent  $b \neq a_1$ , in which case we proceed as in the first case. This must eventually happen, because every time the deviation is again performed by agent  $a_1$  she gets closer to her peak. We proceed in the same manner. In step  $k$ , we are given a coalition  $\hat{C}_k$  with  $|\hat{C}_k| > |C_k|$  which was just joined by an agent. When the next agent originally in  $\hat{C}_k$  deviates from the coalition evolved from  $\hat{C}_k$ , it is either an agent different from  $a_k$  and we call it  $a_{k+1}$ , and find coalitions  $C_{k+1}$  and  $\hat{C}_{k+1}$  with  $|\hat{C}_{k+1}| > |C_{k+1}| \geq |\hat{C}_k|$ ; or this agent is  $a_k$ , she moves towards an updated coalition  $\hat{C}_k$  which maintains  $|\hat{C}_k| > |C_k|$ .

We have thus constructed an infinite sequence of coalitions  $(C_k)_{k \geq 1}$  occurring in the cycle with  $|C_{k+1}| > |C_k|$  for all  $k \geq 1$ , a contradiction.  $\square$

An interesting open question is whether this convergence result still holds under naturally single-peaked preferences with indifference. However, convergence is also guaranteed under other constrained anonymous games, called *neutral anonymous games*, which are subset-neutral, as defined

by Suksompong (2015), thanks to the use of the same potential function argument.

## 4 Hedonic Diversity Games (HDGs)

Hedonic diversity games take into account more information about the identity of the agents, changing the focus from coalition sizes to proportions of given types of agents. We obtain more positive results regarding the existence of IS partitions. Indeed, there always exists an IS partition in a hedonic diversity game, even with preferences that are not single-peaked (Boehmer and Elkind 2020). However, we prove that there may exist cycles in IS-deviations, even under some strong restrictions. This stands in contrast with empirical evidence for convergence based on extensive computer simulations by Boehmer and Elkind (2020).

**Proposition 4.1.** *The dynamics of IS-deviations may cycle in HDGs even*

1. when preferences are strict and naturally single-peaked,
2. when preferences are strict and the initial partition is the singleton partition or the grand coalition, or
3. when preferences are naturally single-peaked and the initial partition is the singleton partition.

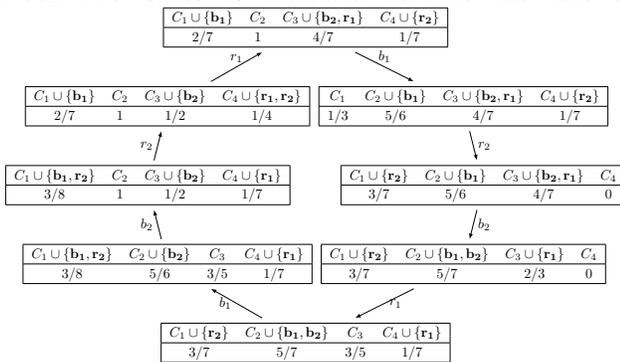
*Sketch of proof.* We only provide the counterexample for an HDG with strict and naturally single-peaked preferences (restriction 1). Let us consider an HDG with 26 agents: 12 red agents and 14 blue agents. There are four deviating agents: red agents  $r_1$  and  $r_2$  and blue agents  $b_1$  and  $b_2$ , and four fixed coalitions  $C_1, C_2, C_3$  and  $C_4$  such that:

- $C_1$  contains 2 red agents and 4 blue agents;
- $C_2$  contains 5 red agents;
- $C_3$  contains 3 red agents and 2 blue agents;
- $C_4$  contains 6 blue agents.

The relevant part of the preferences is given below.

$b_1$ :	$\frac{3}{8}$	$\frac{5}{7}$	$\frac{5}{7}$	$\frac{5}{6}$	$\frac{2}{7}$	$C_1$ :	$\frac{3}{8}$	$\frac{5}{7}$	$\frac{5}{7}$	$\frac{1}{3}$
$b_2$ :	$\frac{5}{7}$	$\frac{4}{7}$	$\frac{1}{2}$	$\frac{5}{6}$	$\frac{5}{7}$	$C_2$ :	$\frac{5}{7}$	$\frac{5}{6}$	$\frac{5}{7}$	$1$
$r_1$ :	$\frac{4}{7}$	$\frac{1}{4}$	$\frac{1}{2}$	$\frac{2}{3}$	$\frac{3}{5}$	$C_3$ :	$\frac{4}{7}$	$\frac{1}{2}$	$\frac{3}{5}$	$\frac{3}{5}$
$r_2$ :	$\frac{1}{4}$	$\frac{3}{8}$	$\frac{3}{7}$	$\frac{1}{7}$	$\frac{1}{7}$	$C_4$ :	$\frac{1}{4}$	$\frac{1}{7}$	$\frac{1}{7}$	$0$

Consider the following sequence of IS-deviations that describe a cycle in the dynamics. The four deviating agents of the cycle  $b_1, b_2, r_1$  and  $r_2$  are marked in bold and the specific deviating agent between two states is indicated next to the arrows.



□

This example does not show the impossibility to reach an IS partition since the IS partition  $\{C_1 \cup \{b_1, r_2\}, C_2, C_3 \cup \{r_1, b_2\}, C_4\}$  can be reached via IS-deviations from some partitions in the cycle. Thus, starting in these partitions, a path to stability may still exist. Nevertheless, it may be possible that every sequence of IS-deviations cycles, even for strict or naturally single-peaked preferences (with indifference), as the next proposition shows. An interesting open question is whether strict and single-peaked preferences allow for the existence of a path to stability.

**Proposition 4.2.** *The dynamics of IS-deviations may never reach an IS partition in HDGs, whatever the chosen path of deviations, even for (1) strict preferences or (2) naturally single-peaked preferences with indifference.*

However, convergence is guaranteed by combining all previous restrictions, as stated in the next proposition.

**Proposition 4.3.** *The dynamics of IS-deviations starting from the singleton partition always converges to an IS partition in HDGs for strict naturally single-peaked preferences.*

*Sketch of proof.* One can easily prove that at any step of the dynamics, a coalition is necessarily of the form  $\{r_1, b_1, \dots, b_k\}$  or  $\{b_1, r_1, \dots, r_{k'}\}$  or  $\{b_1\}$  or  $\{r_1\}$  where  $r_i \in R$  and  $b_j \in B$  for every  $i \in [k'], j \in [k]$  and  $k \leq |B|$  and  $k' \leq |R|$ . Therefore, the ratio of a coalition can only be equal to  $\frac{1}{k+1}, \frac{k'}{k'+1}, 0$  or  $1$ . Let us define as  $\rho(C)$  the modified ratio of a valid coalition  $C$  formed by the dynamics where  $\rho(C) = \begin{cases} \frac{|R \cap C|}{|C|} & \text{if } C = \{b_1, r_1, \dots, r_{k'}\} \text{ for } k' \geq 1 \\ 1 - \frac{|R \cap C|}{|C|} & \text{if } C = \{r_1, b_1, \dots, b_k\} \text{ for } k \geq 2 \\ 0 & \text{otherwise, i.e., } C = \{r_1\} \text{ or } C = \{b_1\} \end{cases}$ . For each partition in a sequence of IS-deviations, we consider the vector composed of the modified ratios  $\rho(C)$  for all coalitions  $C$  in the partition. One can prove that for each sequence of IS-deviations, either this vector strictly increases lexicographically at each deviation or there is an equivalent sequence of IS-deviations where it does. □

Under strict preferences, checking the existence of a path to stability and convergence are hard.

**Theorem 4.4.**  $\exists$ -IS-SEQUENCE-HDG is NP-hard and  $\forall$ -IS-SEQUENCE-HDG is co-NP-hard, even for strict preferences.

## 5 Fractional Hedonic Games (FHGs)

Next, we study fractional hedonic games, which are closely related to hedonic diversity games, but instead of agent types, utilities rely on a cardinal valuation function of the other agents. The first part of the section deals with symmetric games, the second part with simple games.

An open problem for symmetric FHGs was whether they always admit an IS partition (Brandl, Brandt, and Strobel 2015). Here, we provide a counterexample using 15 agents.

**Theorem 5.1.** *There exists a symmetric FHG without an IS partition.*

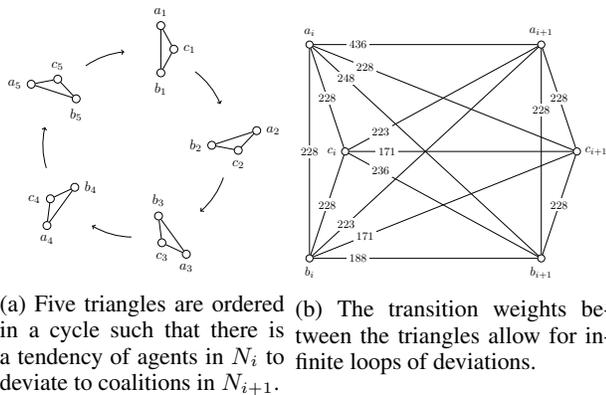


Figure 1: Description of the graph associated with the constructed symmetric FHG without an IS partition.

*Sketch of proof.* Define the sets of agents  $N_i = \{a_i, b_i, c_i\}$  for  $i \in \{1, \dots, 5\}$  and consider the FHG on the agent set  $N = \bigcup_{i=1}^5 N_i$  where symmetric weights are given as in Figure 1b. All weights not specified in this figure are set to  $-2251$ . The FHG consists of five triangles that form a cycle. Its structure is illustrated in Figure 1a.

There is an infinite cycle of deviations starting with the partition  $\{N_5 \cup N_1, N_2, N_3, N_4\}$ . First,  $a_1$  deviates by joining  $N_2$ . Then,  $b_1$  joins this new coalition, then  $c_1$ . After this step, we are in an isomorphic state as in the initial partition. It can be shown that there exists no IS partition in this instance.  $\square$

Employing this counterexample, the methods of Brandl, Brandt, and Strobel (2015), which originate from hardness constructions of Sung and Dimitrov (2010), can be used to show that it is NP-hard to decide about the existence of IS partitions in symmetric FHGs.

**Corollary 5.2.** *Deciding whether there exists an individually stable partition in symmetric FHGs is NP-hard.*

If we consider symmetric, non-negative utilities, the grand coalition forms an NS, and therefore IS, partition of the agents. However, deciding about the convergence of the IS dynamics starting with the singleton partition is NP-hard. The reduction is similar to the one in the previous statement and avoids negative weights by the fact that, due to symmetry of the weights, in a dynamics starting with the singleton partition, all coalitions that can be obtained in the process must have strictly positive mutual utility for all pairs of agents in the coalition.

**Theorem 5.3.**  *$\exists$ -IS-SEQUENCE-FHG is NP-hard and  $\forall$ -IS-SEQUENCE-FHG is co-NP-hard, even in symmetric FHGs with non-negative weights. The former is even true if the initial partition is the singleton partition.*

From now on, we consider simple FHGs. We start with the additional assumption of symmetry.

**Proposition 5.4.** *The dynamics of IS-deviations starting from the singleton partition always converges to an IS partition in simple symmetric FHGs in at most  $\mathcal{O}(n^2)$  steps. The dynamics may take  $\Omega(n\sqrt{n})$  steps.*

*Sketch of proof.* We only prove the upper bound. Note that all coalitions formed through the deviation dynamics are cliques. Hence, every deviation step will increase the total number of edges in all coalitions. More precisely, the dynamics will increase the potential  $\Lambda(\pi) = \sum_{C \in \pi} |C|(|C| - 1)/2$  in every step by at least 1. Since the total number of edges is quadratic, this proves the upper bound.  $\square$

Note that there is a simple way to converge in a linear number of steps starting with the singleton partition by forming largest cliques and removing them from consideration.

If we allow for asymmetries, the dynamics is not guaranteed to converge anymore. For instance, the IS dynamics on an FHG induced by a directed triangle will not converge for any initial partition except for the grand coalition. We can, however, characterize convergence on asymmetric FHGs. Tractability highly depends on the initial partition. First, we assume that we start from the singleton partition.

The key insight is that throughout the dynamic process on an asymmetric FHG starting from the singleton partition, the subgraphs induced by coalitions are always transitive and complete. Convergence is then shown by a potential function argument.

**Proposition 5.5.** *The dynamics of IS-deviations starting from the singleton partition converges in asymmetric FHGs if and only if the underlying graph is acyclic. Moreover, under acyclicity, it converges in  $\mathcal{O}(n^4)$  steps.*

The previous statement shows convergence of the dynamics for asymmetric, acyclic FHGs. In addition, it is easy to see that there is always a sequence converging after  $n$  steps, starting with the singleton partition. One can use a topological order of the agents and allow agents to deviate in decreasing topological order towards a best possible coalition.

There are two interesting further directions. One can weaken either the restriction on the initial partition or on asymmetry. If we allow for general initial partitions, we immediately obtain hardness results that apply in particular to the broader class of simple FHGs.

**Theorem 5.6.**  *$\exists$ -IS-SEQUENCE-FHG is NP-hard and  $\forall$ -IS-SEQUENCE-FHG is co-NP-hard, even in asymmetric FHGs.*

On the other hand, if we transition to simple FHGs while maintaining the initial partition, the problem of deciding whether a path to stability exists becomes hard.

**Theorem 5.7.**  *$\exists$ -IS-SEQUENCE-FHG is NP-hard even in simple FHGs when starting from the singleton partition.*

## 6 Dichotomous Hedonic Games (DHGs)

By taking into account the identity of other agents in the preferences of agents over coalitions, it can be more complicated to get positive results regarding individual stability (see, e.g., Theorem 5.1). However, by restricting the evaluation of coalitions to dichotomous preferences, the existence of an IS partition is guaranteed (Peters 2016), as well as convergence of the dynamics of IS-deviations, when starting from the grand coalition (Boehmer and Elkind 2020).

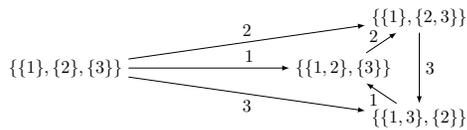
Nevertheless, the convergence of the dynamics is not guaranteed for an arbitrary initial partition and no sequence of IS-deviations may ever reach an IS partition.

**Proposition 6.1.** *The dynamics of IS-deviations may never reach an IS partition in DHGs, whatever the chosen path of deviations, even when starting from the singleton partition.*

*Proof.* Let us consider an instance of a DHG with three agents. Their preferences are described in the table below.

Agent	1	2	3
Approvals	{1, 2}	{2, 3}	{1, 3}
Disapprovals	{1}, {1, 3}, {1, 2, 3}	{2}, {1, 2}, {1, 2, 3}	{3}, {2, 3}, {1, 2, 3}

There is a unique IS partition which consists of the grand coalition  $\{1, 2, 3\}$ . We represent below all possible IS-deviations between all the other possible partitions. An IS-deviation between two partitions is indicated by an arrow mentioning the name of the deviating agent.



One can check that the described deviations are IS-deviations. A cycle is necessarily reached when starting from a partition different from the unique IS partition, which can be reached only if it is the initial partition.  $\square$

Moreover, it is hard to decide on the existence of a sequence of IS-deviations ending in an IS partition, even when starting from the singleton partition, as well as checking convergence.

**Theorem 6.2.**  $\exists$ -IS-SEQUENCE-DHG is NP-hard even when starting from the singleton partition, and  $\forall$ -IS-SEQUENCE-DHG is co-NP-hard.

Note that the counterexample provided in the proof of Proposition 6.1 exhibits a global cycle in the preferences of the agents:  $\{1, 2\} \triangleright \{1, 3\} \triangleright \{2, 3\} \triangleright \{1, 2\}$ . However, by considering dichotomous preferences with *common ranking property*, that is, each agent has a threshold for acceptance in a given global order, we obtain convergence thanks to the same potential function argument used by Caskurlu and Kizilkaya (2019), for proving the existence of a core-stable partition in hedonic games with common ranking property.

Note that when assuming that if a coalition is approved by one agent, then it must be approved by all the members of the coalition (so-called *symmetric dichotomous preferences*), we obtain a special case of preferences with common ranking property where all the approved coalitions are at the top of the global order. Therefore, convergence is also guaranteed under symmetric dichotomous preferences.

## 7 Conclusion

We have investigated dynamics of deviations based on individual stability in hedonic games. The two main questions we considered were whether there exists *some* sequence of deviations terminating in an IS partition, and whether *all* sequences of deviations terminate in an IS partition, i.e., the dynamics converges. Our results are mostly negative with

examples of cycles in dynamics or even non-existence of IS partitions under rather strong preference restrictions. In particular, we have answered a number of open problems proposed in the literature. On the other hand, we have identified natural conditions for convergence that are mostly based on preferences relying on a common scale for the agents, like the common ranking property, single-peakedness or symmetry. An overview of our results can be found in Table 1.

Class	Convergence	Hardness
AHGs	<ul style="list-style-type: none"> <li>✓ strict &amp; nat. SP (single-peaked) (Prop. 3.4)</li> <li>✓ neutral (derived from Suksompong (2015))</li> <li>○ strict &amp; gen. SP; singletons / grand coalition (Prop. 3.2)</li> </ul>	<ul style="list-style-type: none"> <li><math>\exists</math> strict (Th. 3.3)</li> <li><math>\forall</math> strict (Th. 3.3)</li> </ul>
HDGs	<ul style="list-style-type: none"> <li>✓ strict &amp; nat. SP; singletons (Prop. 4.3)</li> <li>○ strict &amp; nat. SP (Prop. 4.1)</li> <li>○ strict; singletons / grand coalition (Prop. 4.1)</li> <li>○ nat. SP; singletons (Prop. 4.1)</li> </ul>	<ul style="list-style-type: none"> <li><math>\exists</math> strict (Th. 4.4)</li> <li><math>\forall</math> strict (Th. 4.4)</li> </ul>
FHGs	<ul style="list-style-type: none"> <li>✓ simple &amp; sym.; singletons (Prop. 5.4)</li> <li>✓ acyclic digraph (Th. 5.5)</li> <li>○ sym. (Th. 5.1)</li> </ul>	<ul style="list-style-type: none"> <li><math>\exists</math> sym. (Th. 5.3)</li> <li><math>\exists</math> simple; singletons (Th. 5.7)</li> <li><math>\exists</math> asym. (Th. 5.6)</li> <li><math>\forall</math> sym. (Th. 5.3)</li> <li><math>\forall</math> asym. (Th. 5.6)</li> </ul>
DHGs	<ul style="list-style-type: none"> <li>✓ grand coalition (Boehmer and Elkind)</li> <li>✓ common ranking property or symmetric (derived from Caskurlu and Kizilkaya (2019))</li> <li>○ singletons (Prop. 6.1)</li> </ul>	<ul style="list-style-type: none"> <li><math>\exists</math> singletons (Th. 6.2)</li> <li><math>\forall</math> general (Th. 6.2)</li> </ul>

Table 1: Convergence and hardness results for the dynamics of IS-deviations in various classes of hedonic games. Symbol  $\checkmark$  marks convergence under the given preference restrictions and initial partition (if applicable) while  $\circ$  marks non-convergence, i.e., cycling dynamics. Symbol  $\exists$  (resp.,  $\forall$ ) denotes that problem  $\exists$ -IS-SEQUENCE-HG (resp.,  $\forall$ -IS-SEQUENCE-HG) is NP-hard (resp., co-NP-hard).

For all hedonic games under study, it turned out that the existence of cycles for IS-deviations is sufficient to prove the hardness of recognizing instances for which there exists a finite sequence of deviations or whether all sequences of deviations are finite, i.e., the dynamics converges. While our results cover a broad range of hedonic games considered in the literature, there are still promising directions for further research. First, even though our hardness results hold under strong restrictions, the complexity of these questions remains open for other interesting preference restrictions, some of which do not guarantee convergence. Following our work, the most intriguing cases are AHGs under single-peaked weak preferences, simple symmetric FHGs with arbitrary initial partitions, and HDGs under single-peaked preferences. Secondly, one could investigate more specific rules of IS-deviations that quickly terminate in IS partitions, even in classes of hedonic games that allow for cyclic IS-deviations. For instance, for simple symmetric FHGs, there is the possibility of convergence such that each agent deviates at most once, but the selection of the deviating agents in this approach requires to solve a maximum clique problem (cf. the discussion after Proposition 5.4). Finally, the dynamics we consider only guarantee individual stability. One could also aim at reaching outcomes that satisfy Pareto optimality or other desirable properties on top of individual stability.

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## References

- Abeledo, H.; and Rothblum, U. G. 1995. Paths to marriage stability. *Discrete Applied Mathematics* 63(1): 1–12.
- Aziz, H.; Brandl, F.; Brandt, F.; Harrenstein, P.; Olsen, M.; and Peters, D. 2019. Fractional Hedonic Games. *ACM Transactions on Economics and Computation* 7(2): 1–29.
- Aziz, H.; Harrenstein, P.; Lang, J.; and Wooldridge, M. 2016. Boolean Hedonic Games. In *Proceedings of the 15th International Conference on Principles of Knowledge Representation and Reasoning (KR)*, 166–175.
- Ballester, C. 2004. NP-completeness in hedonic games. *Games and Economic Behavior* 49(1): 1–30.
- Berman, P.; Karpinski, M.; and Scott, A. 2003. Approximation hardness of short symmetric instances of MAX-3SAT. Technical Report TR03-049, Electronic Colloquium on Computational Complexity (ECCC).
- Bilò, V.; Fanelli, A.; Flammini, M.; Monaco, G.; and Moscardelli, L. 2018. Nash Stable Outcomes in Fractional Hedonic Games: Existence, Efficiency and Computation. *Journal of Artificial Intelligence Research* 62: 315–371.
- Boehmer, N.; and Elkind, E. 2020. Individual-Based Stability in Hedonic Diversity Games. In *Proceedings of the 34th AAAI Conference on Artificial Intelligence (AAAI)*, 1822–1829.
- Bogomolnaia, A.; and Jackson, M. O. 2002. The Stability of Hedonic Coalition Structures. *Games and Economic Behavior* 38(2): 201–230.
- Brandl, F.; Brandt, F.; and Strobel, M. 2015. Fractional Hedonic Games: Individual and Group Stability. In *Proceedings of the 14th International Conference on Autonomous Agents and Multiagent Systems (AAMAS)*, 1219–1227.
- Brandt, F.; and Wilczynski, A. 2019. On the Convergence of Swap Dynamics to Pareto-Optimal Matchings. In *Proceedings of the 15th International Conference on Web and Internet Economics (WINE)*, 100–113.
- Bredereck, R.; Elkind, E.; and Igarashi, A. 2019. Hedonic Diversity Games. In *Proceedings of the 18th International Conference on Autonomous Agents and Multiagent Systems (AAMAS)*, 565–573.
- Carosi, R.; Monaco, G.; and Moscardelli, L. 2019. Local Core Stability in Simple Symmetric Fractional Hedonic Games. In *Proceedings of the 18th International Conference on Autonomous Agents and Multiagent Systems (AAMAS)*, 574–582.
- Caskurlu, B.; and Kizilkaya, F. E. 2019. On Hedonic Games with Common Ranking Property. In *Proceedings of the 11th International Conference on Algorithms and Complexity (CIAC)*, 137–148. Springer International Publishing.
- Drèze, J. H.; and Greenberg, J. 1980. Hedonic Coalitions: Optimality and Stability. *Econometrica* 48(4): 987–1003.
- Farrell, J.; and Scotchmer, S. 1988. Partnerships. *Quarterly Journal of Economics* 103: 279–297.
- Hofer, M.; Vaz, D.; and Wagner, L. 2018. Dynamics in matching and coalition formation games with structural constraints. *Artificial Intelligence* 262: 222–247.
- Karp, R. M. 1972. Reducibility among Combinatorial Problems. In Miller, R. E.; and Thatcher, J. W., eds., *Complexity of Computer Computations*, 85–103. Plenum Press.
- Peters, D. 2016. Complexity of Hedonic Games with Dichotomous Preferences. In *Proceedings of the 30th AAAI Conference on Artificial Intelligence (AAAI)*, 579–585.
- Roth, A. E.; and Vande Vate, J. H. 1990. Random Paths to Stability in Two-Sided Matching. *Econometrica* 58(6): 1475–1480.
- Suksompong, W. 2015. Individual and Group Stability in Neutral Restrictions of Hedonic Games. *Mathematical Social Sciences* 78: 1–5.
- Sung, S. C.; and Dimitrov, D. 2010. Computational Complexity in Additive Hedonic Games. *European Journal of Operational Research* 203(3): 635–639.





Although we have created many agents, the construction remains polynomial by considering reasonable values of  $\alpha$ ,  $\beta_1^+$ ,  $\beta_1^-$ ,  $\beta_2^+$  and  $\beta_2^-$ , as previously described.

The preferences of the agents over sizes of coalitions are given below for every  $1 \leq i \leq p$ ,  $1 \leq i' < p$ ,  $1 \leq j \leq m+1$ ,  $\ell \in \{1, 2\}$  (notation  $cl(x_i^\ell)$  (resp.,  $cl(\bar{x}_i^\ell)$ ) stands for the index of the clause to which the  $\ell^{\text{th}}$  occurrence of literal  $x_i$  (resp.,  $\bar{x}_i$ ) belongs, the framed value is the size of the initial coalition in partition  $\pi_0$ , and  $[...]$  denotes an arbitrary order over the rest of the coalition sizes):

$$\begin{array}{l}
y_i^1 : |K_{cl(x_i^1)}| + 2 \succ |K_{cl(x_i^1)+1}| + 2 \succ |K_{cl(x_i^1)+1}| + 1 \succ |K_{cl(x_i^1)}| + 1 \succ \\
\quad |Y_i^1| + 2 \succ |Y_i^2| + 2 \succ |Y_i^2| + 1 \succ |Y_i^1| + 1 \succ [1] \succ [...] \\
y_{i'}^2 : |K_{cl(x_{i'}^2)}| + 2 \succ |K_{cl(x_{i'}^2)+1}| + 2 \succ |K_{cl(x_{i'}^2)+1}| + 1 \succ |K_{cl(x_{i'}^2)}| + 1 \succ \\
\quad |Y_{i'}^2| + 2 \succ |Y_{i'}^1| + 2 \succ |Y_{i'}^1| + 1 \succ |Y_{i'}^2| + 1 \succ [1] \succ [...] \\
y_p^2 : |K_{cl(x_p^2)}| + 2 \succ |K_{cl(x_p^2)+1}| + 2 \succ |K_{cl(x_p^2)+1}| + 1 \succ |K_{cl(x_p^2)}| + 1 \succ \\
\quad |Y_p^2| + 2 \succ |K_1| + 2 \succ |K_1| + 1 \succ |Y_p^2| + 1 \succ [1] \succ [...] \\
\bar{y}_i^1 : |K_{cl(\bar{x}_i^1)}| + 2 \succ |K_{cl(\bar{x}_i^1)+1}| + 2 \succ |K_{cl(\bar{x}_i^1)+1}| + 1 \succ |K_{cl(\bar{x}_i^1)}| + 1 \succ \\
\quad |Y_i^1| + 2 \succ |Y_i^2| + 2 \succ |Y_i^2| + 1 \succ |Y_i^1| + 1 \succ [1] \succ [...] \\
\bar{y}_{i'}^2 : |K_{cl(\bar{x}_{i'}^2)}| + 2 \succ |K_{cl(\bar{x}_{i'}^2)+1}| + 2 \succ |K_{cl(\bar{x}_{i'}^2)+1}| + 1 \succ |K_{cl(\bar{x}_{i'}^2)}| + 1 \succ \\
\quad |Y_{i'}^2| + 2 \succ |Y_{i'}^1| + 2 \succ |Y_{i'}^1| + 1 \succ |Y_{i'}^2| + 1 \succ [1] \succ [...] \\
\bar{y}_p^2 : |K_{cl(\bar{x}_p^2)}| + 2 \succ |K_{cl(\bar{x}_p^2)+1}| + 2 \succ |K_{cl(\bar{x}_p^2)+1}| + 1 \succ |K_{cl(\bar{x}_p^2)}| + 1 \succ \\
\quad |Y_p^2| + 2 \succ |K_1| + 2 \succ |K_1| + 1 \succ |Y_p^2| + 1 \succ [1] \succ [...] \\
t : |K_{m+1}| + 2 \succ |Y_1^1| + 2 \succ |Y_1^1| + 1 \succ |Y_1^1| + 2 \succ \\
\quad |Y_1^1| + 1 \succ |K_{m+1}| + 1 \succ [1] \succ [...] \\
\hline
K_j : |K_j| + 2 \succ |K_j| + 1 \succ [K_j] \succ 1 \succ [...] \\
Y_i^\ell : |Y_i^\ell| + 2 \succ |Y_i^\ell| + 1 \succ [Y_i^\ell] \succ 1 \succ [...] \\
\bar{Y}_i^\ell : |\bar{Y}_i^\ell| + 2 \succ |\bar{Y}_i^\ell| + 1 \succ [\bar{Y}_i^\ell] \succ 1 \succ [...]
\end{array}$$

We claim that there exists a cycle of IS-deviations iff formula  $\varphi$  is satisfiable<sup>3</sup>.

Suppose first that formula  $\varphi$  is satisfiable by a truth assignment of the variables denoted by  $\phi$ . Let us denote by  $\ell_j$  a chosen literal-agent associated with an occurrence of a literal true in  $\phi$  which belongs to clause  $C_j$ . Since all the clauses of  $\varphi$  are satisfied by  $\phi$ , there exists such a literal-agent  $\ell_j$  for each clause  $C_j$ . Now let us denote by  $z_i^1$  and  $z_i^2$  the literal-agents associated with the two occurrences of the literal of variable  $x_i$  which is false in  $\phi$ . In the same vein, let us denote by  $Z_i^1$  and  $Z_i^2$  the coalitions of dummy variable agents associated with  $z_i^1$  and  $z_i^2$ , respectively. Since  $\phi$  is a truth assignment of the variables,  $z_i^1$ ,  $z_i^2$ ,  $Z_i^1$  and  $Z_i^2$  all correspond to the same literal (either  $x_i$  or  $\bar{x}_i$ ) and it holds that  $\bigcup_{1 \leq j \leq m} \ell_j \cap \bigcup_{1 \leq i \leq p} \{z_i^1, z_i^2\} = \emptyset$ . We will construct a cycle in IS-deviations involving, as deviating agents, the literal-agents  $\ell_j$ , for every  $1 \leq j \leq m$ , the literal-agents  $z_i^1$  and  $z_i^2$ , for every  $1 \leq i \leq p$ , and agent  $t$ . Since  $m$  is even in a (3,B2)-SAT (recall that  $m = 4/3p$ ), there is an odd number of deviating agents in total.

First of all, let agent  $z_p^2$  and then agent  $\ell_1$  join coalition  $K_1$ . For each  $1 < i \leq p$ , let agent  $z_{i-1}^2$  and then agent  $z_i^1$  join coalition  $Z_i^1$ . Let agent  $t$  and then agent  $z_1^1$  join coalition  $Z_1^1$ . For each even  $j$  such that  $3 < j \leq m$ , let agent  $\ell_{j-1}$  and then agent  $\ell_j$  join coalition  $K_j$ . Finally, let agent  $\ell_2$  join coalition  $K_3$ . The reached partition is  $\pi := \{K_1 \cup \{\ell_1, z_p^2\}, K_2, K_3 \cup \{\ell_2\}, K_4 \cup$

$\{\ell_3, \ell_4\}, K_5, K_6 \cup \{\ell_5, \ell_6\}, K_7, \dots, K_m \cup \{\ell_{m-1}, \ell_m\}, K_{m+1}, Z_1^1 \cup \{t, z_1^1\}, Z_2^1, Z_2^1 \cup \{z_1^2, z_2^1\}, Z_2^2, \dots, Z_p^1 \cup \{z_{p-1}^2, z_p^1\}, Z_p^2, \bar{Z}_1^1, \bar{Z}_1^2, \dots, \bar{Z}_p^1, \bar{Z}_p^2\}$ , where coalition  $\bar{Z}_i^\ell$  refers to  $\bar{Y}_i^\ell$  if  $Z_i^\ell = Y_i^\ell$  and to  $Y_i^\ell$  if  $Z_i^\ell = \bar{Y}_i^\ell$ . Partition  $\pi$  is the first step of the cycle.

From partition  $\pi$ , let literal-agent  $\ell_3$  deviate from current coalition  $K_4 \cup \{\ell_3, \ell_4\}$  to join coalition  $K_3 \cup \{\ell_2\}$ . This deviation makes literal-agent  $\ell_4$  worse off, who then deviates to join coalition  $K_5$ . Then, the same deviations occur for literal-agents  $\ell_5$  and  $\ell_6$ , and so on. More generally, for every odd  $j$  such that  $3 \leq j \leq m$  by increasing order of indices, literal-agent  $\ell_j$  leaves coalition  $K_{j+1} \cup \{\ell_j, \ell_{j+1}\}$  to join coalition  $K_j \cup \{\ell_{j-1}\}$  and then literal-agent  $\ell_{j+1}$ , who is worse off by this deviation, deviates to join coalition  $K_{j+2}$ . After that, agent  $t$  deviates from coalition  $Z_1^1 \cup \{t, z_1^1\}$  to join coalition  $K_{m+1} \cup \{\ell_m\}$ , which makes literal-agent  $z_1^1$  worse off. Then, for each  $1 \leq i \leq p$  by increasing order of indices, let literal-agent  $z_i^1$  deviate from coalition  $Z_i^1 \cup \{z_i^1\}$  to join coalition  $Z_i^2$  and then literal-agent  $z_i^2$  deviate from coalition  $Z_{i+1}^1 \cup \{z_i^2, z_{i+1}^1\}$  (or  $K_1 \cup \{z_i^2, \ell_1\}$  if  $i = p$ ) to join coalition  $Z_i^2 \cup \{z_i^1\}$ , which makes literal-agent  $z_{i+1}^1$  (or  $\ell_1$  if  $i = p$ ) worse off. We thus reach partition  $\pi_1 := \{K_1 \cup \{\ell_1\}, K_2, K_3 \cup \{\ell_2, \ell_3\}, K_4, K_5 \cup \{\ell_4, \ell_5\}, K_6, K_7 \cup \{\ell_6, \ell_7\}, \dots, K_{m-1} \cup \{\ell_{m-2}, \ell_{m-1}\}, K_m, K_{m+1} \cup \{\ell_m, t\}, Z_1^1, Z_1^2 \cup \{z_1^1, z_1^2\}, Z_2^1, Z_2^2 \cup \{z_2^1, z_2^2\}, \dots, Z_p^1, Z_p^2 \cup \{z_p^1, z_p^2\}, \bar{Z}_1^1, \bar{Z}_1^2, \dots, \bar{Z}_p^1, \bar{Z}_p^2\}$ .

Then, from partition  $\pi_1$ , for every odd  $j$  such that  $1 \leq j < m$  by increasing order of indices, let literal-agent  $\ell_j$  deviate from coalition  $K_j \cup \{\ell_j\}$  to join coalition  $K_{j+1}$  and then literal-agent  $\ell_{j+1}$  deviate from  $K_{j+2} \cup \{\ell_{j+1}, \ell_{j+2}\}$  (or  $K_{m+1} \cup \{\ell_m, t\}$  if  $j = m-1$ ) to join coalition  $K_{j+1} \cup \{\ell_j\}$ , which makes literal-agent  $\ell_{j+2}$  (or agent  $t$  if  $j = m-1$ ) worse off. Let agent  $t$  then deviate from coalition  $K_{m+1} \cup \{t\}$  to join coalition  $Z_1^1$  and literal-agent  $z_1^1$  deviate from coalition  $Z_1^2 \cup \{z_1^1, z_1^2\}$  to join coalition  $Z_1^1 \cup \{t\}$ , which makes literal-agent  $z_1^2$  worse off. Then, for each  $1 \leq i < p$  by increasing order of indices, let literal-agent  $z_i^2$  deviate from coalition  $Z_i^2 \cup \{z_i^2\}$  to join coalition  $Z_{i+1}^1$ , and literal-agent  $z_{i+1}^1$  deviate from coalition  $Z_{i+1}^2 \cup \{z_{i+1}^1, z_{i+1}^2\}$  to join coalition  $Z_{i+1}^1 \cup \{z_i^2\}$ , which makes literal-agent  $z_{i+1}^2$  worse off. And then, let literal-agent  $z_p^2$  deviate from coalition  $Z_p^2 \cup \{z_p^2\}$  to join coalition  $K_1$ , and literal-agent  $\ell_1$  deviate from coalition  $K_2 \cup \{\ell_1, \ell_2\}$  to join coalition  $K_1 \cup \{z_p^2\}$ , which makes literal-agent  $\ell_2$  worse off. Finally, let literal-agent  $\ell_2$  deviate from coalition  $K_2 \cup \{\ell_2\}$  to join coalition  $K_3$ , and we have finally reached partition  $\pi$ , leading to a cycle.

Suppose now that there exists a cycle of IS-deviations. Observe first that no dummy agent can deviate. Indeed, the only coalition sizes that are preferred by a dummy agent to the size of her initial coalition are the size of the current coalition plus one and the size of the current coalition plus two. These sizes cannot be reached by joining other coalitions by condition (1), and the fact that the other coalitions do not want to integrate more than two additional agents in their coalition. Therefore, the only possible deviations are when the dummy agents let at most two agents join their coalition. It follows that no agent can belong to a coalition

<sup>3</sup>Note that the singleton partition is nevertheless always IS.

whose size is ranked after size 1 in her preferences, i.e., we do not have to care about the preferences within [...] in the preference ranking of the agents. Indeed, a literal-agent or agent  $t$  (for the sake of simplicity we also talk about agent  $t$  when referring to literal-agents since the behavior is similar), who starts from a coalition of size one, can join some coalitions of dummy agents and sometimes accepts one additional agent in such coalitions. So the worst thing which can happen to these deviating literal-agents is that the other literal-agent in the coalition leaves the coalition but in such a case, they are still in a coalition whose size is ranked before one in their preferences. Observe that literal-agents can only join coalitions of dummy agents with at most one other literal-agent in this coalition and that no literal-agent can join another literal-agent outside a coalition of dummy agents, because size two is not ranked before size one in the preferences of the agents (recall that a coalition of dummy agents cannot be of size smaller than 2). Moreover, since the literal-agents can never be in a coalition of size less preferred than one, once a literal-agent deviates from her initial coalition where she is alone, she has no incentive to come back to the coalition where she is alone. Hence, the deviations in the cycle must be performed by literal-agents who change of coalition of dummy agents.

Each deviating literal-agent  $i$  in the cycle must be left at some step otherwise, there would be no reason for her to come back to a previous coalition. Since she can be left only by one other literal-agent, it follows that the current coalition of agent  $i$  was of size  $|K| + 2$  for a given coalition  $K$  of dummy agents and becomes of size  $|K| + 1$ . To be able to come back to a previous coalition, agent  $i$  must prefer  $|K| + 2$  over  $|K| + 1$  and there must be intermediate sizes in the preference ranking of agent  $i$  between  $|K| + 2$  and  $|K| + 1$ . Therefore, if agent  $i$  is an agent  $y_i^\ell$  (resp.,  $\bar{y}_i^\ell$ ), then agent  $i$  must be left by another literal-agent from the coalition of dummy agents (a)  $K_{cl(x_i^\ell)}$  (resp.,  $K_{cl(\bar{x}_i^\ell)}$ ), i.e., the coalition associated with the clause to which the occurrence of the literal of the literal-agent belongs, or (b)  $Y_i^\ell$  (resp.,  $\bar{Y}_i^\ell$ ), i.e., the coalition associated with the occurrence of the literal of the literal-agent.

(a) If this is the coalition of dummy agents  $K_{cl(x_i^\ell)}$  (resp.,  $K_{cl(\bar{x}_i^\ell)}$ ), then the other literal-agent who leaves the coalition must not be associated with an occurrence of a literal belonging to this clause otherwise, it would be her most preferred size and she would not have incentive to leave the coalition. Therefore, according to the preferences of the literal-agents, the only possibility is that this other literal-agent who leaves the coalition  $K_j := K_{cl(x_i^\ell)}$  (resp.,  $K_j := K_{cl(\bar{x}_i^\ell)}$ ) is associated with an occurrence of a literal belonging to  $C_{j-1}$  if  $j > 1$  or is agent  $y_p^2$  or  $\bar{y}_p^2$  if  $j = 1$ . Due to the preferences of the literal-agents, if a literal-agent leaves such a coalition, it is necessarily for joining the coalition of dummy agents  $K_{j-1}$  (which has an additional literal-agent) if  $j > 1$  or  $Y_p^2$  or  $\bar{Y}_p^2$  (with an additional literal-agent) if  $j = 1$ . In the latter case ( $j = 1$ ), this is the only possibility even if the associated deviating agent  $y_p^2$  (resp.,  $\bar{y}_p^2$ ) prefers several coalition sizes over  $|K_1| + 2$ , because

the other choices would prevent her to come back to size  $|K_1| + 2$ : the worst thing which can occur after some steps if she chooses other coalitions is that she is in a coalition of size  $|K_{cl(x_p^2)}| + 1$  or  $|K_{cl(x_p^2)+1}| + 1$  (resp.,  $|K_{cl(\bar{x}_p^2)}| + 1$  or  $|K_{cl(\bar{x}_p^2)+1}| + 1$ ) which are both preferred to  $|K_1| + 2$ , contradicting the cycle.

(b1) Otherwise, if this is the coalition of dummy agents  $Y_i^1$  or  $\bar{Y}_i^1$ , then the only possibility is that the other literal-agent who leaves the coalition is literal-agent  $y_{i-1}^2$  or  $\bar{y}_{i-1}^2$  if  $i > 1$ , or agent  $t$  if  $i = 1$ . If  $i > 1$ , as mentioned earlier, literal-agent  $y_{i-1}^2$  (resp.,  $\bar{y}_{i-1}^2$ ) cannot deviate to coalitions of dummy clause agents, otherwise she would never come back to the current coalition size. If we talk about coalition  $Y_i^1$ , then the only possibility is that literal-agent  $y_{i-1}^2$  (resp.,  $\bar{y}_{i-1}^2$ ) deviates for joining coalition  $Y_{i-1}^2$  (resp.,  $\bar{Y}_{i-1}^2$ ) (and an additional literal-agent). Otherwise, i.e., if we talk about  $\bar{Y}_i^1$ , then literal-agent  $y_{i-1}^2$  (resp.,  $\bar{y}_{i-1}^2$ ) deviates to join  $Y_{i-1}^2$  (resp.,  $\bar{Y}_{i-1}^2$ ) (and an additional literal-agent) but she could also deviate for joining coalition of dummy variable agents  $Y_i^1$ . But, in such a case, she would be joined or would join literal-agent  $y_i^1$  who has no reason to deviate (to join dummy variable coalitions), therefore literal-agent  $y_{i-1}^2$  (resp.,  $\bar{y}_{i-1}^2$ ) would still need to deviate to join coalition  $Y_{i-1}^2$  (resp.,  $\bar{Y}_{i-1}^2$ ) (and an additional literal-agent). If  $i = 1$ , the same arguments can be applied and then agent  $t$  deviates to join coalition of clause agents  $K_{m+1}$ .

(b2) If this is the coalition of dummy agents  $Y_i^2$  (resp.,  $\bar{Y}_i^2$ ), then the only possibility is that the other literal-agent who leaves the coalition is literal-agent  $y_i^1$  (resp.,  $\bar{y}_i^1$ ). Since, literal-agent  $y_i^1$  (resp.,  $\bar{y}_i^1$ ) cannot deviate to join a coalition of dummy clause agents, she will necessarily join the coalition of dummy variable agents  $Y_i^1$  (resp.,  $\bar{Y}_i^1$ ) (with an additional literal-agent).

To summarize, if there is a cycle, only the following can occur:

- agent  $t$  in coalition  $K_{m+1}$  can only be left by a literal-agent corresponding to an occurrence of a literal belonging to clause  $C_m$  who deviates to join coalition of dummy clause agents  $K_m$ ;
- a literal-agent  $y_i^\ell$  (resp.,  $\bar{y}_i^\ell$ ) in a coalition of dummy clause agents  $K_j$  (for  $1 < j \leq m$ ), corresponding to the clause  $C_j$  to which the  $\ell^{\text{th}}$  occurrence of  $x_i$  (resp.,  $\bar{x}_i$ ) belongs, can only be left by a literal-agent corresponding to an occurrence of a literal belonging to clause  $C_{j-1}$  who deviates to join coalition of dummy clause agents  $K_{j-1}$ ;
- a literal-agent  $y_i^\ell$  (resp.,  $\bar{y}_i^\ell$ ) in coalition of dummy clause agents  $K_1$ , corresponding to the clause  $C_1$  to which the  $\ell^{\text{th}}$  occurrence of  $x_i$  (resp.,  $\bar{x}_i$ ) belongs, can only be left by literal-agent  $y_p^2$  (or  $\bar{y}_p^2$ ) who joins coalition of dummy variable agents  $Y_p^2$  (or  $\bar{Y}_p^2$ );
- a literal-agent  $y_i^2$  (resp.,  $\bar{y}_i^2$ ), for  $1 \leq i \leq p$ , in a coalition of dummy variable agents  $Y_i^2$  (resp.,  $\bar{Y}_i^2$ ) can only be left by literal-agent  $y_i^1$  (resp.,  $\bar{y}_i^1$ ) who joins coalition of dummy variable agents  $Y_i^1$  (resp.,  $\bar{Y}_i^1$ );
- a literal-agent  $y_i^1$  (resp.,  $\bar{y}_i^1$ ), for  $1 < i \leq p$ , in a coalition



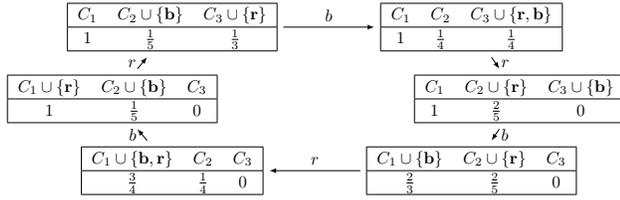
*Proof.* Let us consider an HDG with 10 agents: 4 red agents and 6 blue agents. There are two deviating agents: red agent  $r$  and blue agent  $b$ , and three fixed coalitions  $C_1$ ,  $C_2$  and  $C_3$  such that:

- $C_1$  contains 2 red agents;
- $C_2$  contains 1 red agent and 3 blue agents;
- $C_3$  contains 2 blue agents.

A part of the preferences of the agents is described below, with on the left the preferences for the case of (1) strict preferences and on the right the preferences for the case of (2) naturally single-peaked preferences with indifference.

$$\begin{array}{l}
 (1) \\
 r : \begin{array}{l} \frac{3}{4} \succ \frac{2}{5} \succ \frac{1}{4} \succ \frac{1}{3} \succ 1 \\ \frac{1}{4} \succ \frac{1}{5} \succ \frac{3}{4} \succ \frac{2}{3} \succ 0 \end{array} \\
 b : \begin{array}{l} \frac{3}{4} \succ \frac{2}{5} \succ \frac{1}{4} \succ \frac{1}{3} \succ 1 \\ \frac{1}{4} \succ \frac{1}{5} \succ \frac{3}{4} \succ \frac{2}{3} \succ 0 \end{array} \\
 C_1 : \begin{array}{l} \frac{3}{4} \succ \frac{2}{5} \succ \frac{1}{4} \succ \frac{1}{3} \succ 1 \\ \frac{1}{4} \succ \frac{1}{5} \succ \frac{3}{4} \succ \frac{2}{3} \succ 0 \end{array} \\
 C_2 : \begin{array}{l} \frac{2}{5} \succ \frac{1}{4} \succ \frac{1}{5} \succ \frac{1}{4} \\ \frac{1}{4} \succ \frac{1}{5} \succ \frac{3}{4} \succ \frac{2}{3} \succ 0 \end{array} \\
 C_3 : \begin{array}{l} \frac{1}{4} \succ \frac{1}{3} \succ 0 \\ \frac{1}{4} \succ \frac{1}{5} \succ \frac{3}{4} \succ \frac{2}{3} \succ 0 \end{array} \\
 \\
 (2) \\
 r : \begin{array}{l} \frac{3}{4} \succ \frac{2}{5} \succ \frac{1}{4} \sim \frac{1}{3} \succ 1 \\ \frac{1}{4} \succ \frac{1}{5} \succ \frac{3}{4} \sim \frac{2}{3} \succ 0 \end{array} \\
 b : \begin{array}{l} \frac{3}{4} \succ \frac{2}{5} \succ \frac{1}{4} \sim \frac{1}{3} \succ 1 \\ \frac{1}{4} \succ \frac{1}{5} \succ \frac{3}{4} \sim \frac{2}{3} \succ 0 \end{array} \\
 C_1 : \begin{array}{l} \frac{3}{4} \succ \frac{2}{5} \succ \frac{1}{4} \succ \frac{1}{3} \succ 1 \\ \frac{1}{4} \succ \frac{1}{5} \succ \frac{3}{4} \succ \frac{2}{3} \succ 0 \end{array} \\
 C_2 : \begin{array}{l} \frac{2}{5} \succ \frac{1}{4} \succ \frac{1}{5} \sim \frac{1}{4} \\ \frac{1}{4} \succ \frac{1}{5} \succ \frac{3}{4} \succ \frac{2}{3} \succ 0 \end{array} \\
 C_3 : \begin{array}{l} \frac{1}{4} \succ \frac{1}{3} \succ 0 \\ \frac{1}{4} \succ \frac{1}{5} \succ \frac{3}{4} \succ \frac{2}{3} \succ 0 \end{array}
 \end{array}$$

Consider the following sequence of IS-deviations that describe a cycle in the dynamics. The two deviating agents of the cycle  $r$  and  $b$  are marked in bold and the specific deviating agent between two states is indicated next to the arrows.



Note that at each state, the deviation performed by agent  $r$  or  $b$  is the only possible one that they can do. Moreover, for the other agents, by assuming that in case (1) all the omitted fractions are ranked after the mentioned partial preferences, and in case (2) that they are all indifferent, none of them has incentive to deviate at any state. Therefore, the cycle is the only possible sequence of IS-deviations, and the cycle cannot be avoided in this instance.  $\square$

**Proposition 4.3.** *The dynamics of IS-deviations starting from the singleton partition always converges to an IS partition in HDGs for strict naturally single-peaked preferences.*

*Proof.* First of all, observe that since the dynamics starts from the singleton partition and the preferences are strict and naturally single-peaked, (\*) at any step of the dynamics, a coalition is necessarily of the form  $\{r_1, b_1, \dots, b_k\}$  or  $\{b_1, r_1, \dots, r_{k'}\}$  or  $\{b_1\}$  or  $\{r_1\}$  where  $r_i \in R$  and  $b_j \in B$  for every  $i \in [k']$ ,  $j \in [k]$  and  $k \leq |B|$  and  $k' \leq |R|$ . Therefore, the ratio of a coalition can only be equal to  $\frac{1}{k+1}$ ,  $\frac{k'}{k'+1}$ ,  $0$  or  $1$ . We prove property (\*) by induction on the steps of the dynamics. Initially, in the first steps of the dynamics where a deviating agent joins a singleton coalition from a singleton coalition, the only possibility is that we have a red agent who joins a blue agent (or reversely), leading to a coalition of ratio  $\frac{1}{2}$  from two singleton coalitions of ratio  $0$  and  $1$ . Two agents of the same color cannot form a coalition because otherwise there would not be a strict improvement for the deviating agent. By this fact, our statement is trivially true for the first steps of the dynamics. Let us assume that property

(\*) holds until a certain step in the dynamics and consider the next IS-deviation. We suppose, w.l.o.g., that the deviating agent is red agent  $r$  (the case of a deviating blue agent is symmetric), and assume for the sake of contradiction that the IS-deviation of agent  $r$  breaks property (\*). The only possibilities for that is that (1)  $r$  joins a coalition  $\{r_1, b_1, \dots, b_k\}$  with  $k > 1$ , or (2)  $r$  leaves a coalition  $\{r_1, b_1, \dots, b_k\}$  with  $k > 1$ .

1.  $r$  joins a coalition  $\{r_1, b_1, \dots, b_k\}$  with  $k > 1$ : By induction assumption, all the previous steps satisfy property (\*), therefore red agent  $r_1$  never left the coalition. From the combination of this argument with the arrival of  $r$  in the coalition, it follows that  $\frac{2}{k+2} \succ_{r_1} \frac{1}{k+1} \succ_{r_1} \frac{1}{k} \succ_{r_1} \dots \succ_{r_1} \frac{1}{2} \succ_{r_1} 1$ . For this preference ranking to be naturally single-peaked, it must hold that  $\frac{2}{k+2} < \frac{1}{k}$ . Therefore, we must have  $k < 2$ , a contradiction.
2.  $r$  leaves a coalition  $\{r_1, b_1, \dots, b_k\}$  with  $k > 1$ : By induction assumption, all the previous steps satisfy property (\*), therefore red agent  $r$  never left the coalition. It follows that  $\frac{1}{k+1} \succ_{r_1} \frac{1}{k} \succ_{r_1} \dots \succ_{r_1} \frac{1}{2} \succ_{r_1} 1$ . From (1),  $r$  cannot join a coalition  $\{r_1, b_1, \dots, b_k\}$  with  $k > 1$ , therefore she can only join a coalition  $\{b_1, r_1, \dots, r_{k'}\}$  with  $k' > 0$ ,  $\{b\}$  or  $\{r\}$ . The two latter cases are trivially impossible because it would imply that the ratio of the new coalition  $r$  would be equal to  $\frac{1}{2}$  or  $1$  and then  $r$  would be worse off by her deviation. Thus  $r$  must join a coalition  $\{b_1, r_1, \dots, r_{k'}\}$ . Then, it means that  $\frac{k'+1}{k'+2} \succ_r \frac{1}{k+1} \succ_{r_1} \frac{1}{k} \succ_{r_1} \dots \succ_{r_1} \frac{1}{2} \succ_{r_1} 1$ . For this preference ranking to be naturally single-peaked, it must hold that  $k = 1$ , a contradiction.

Thus, property (\*) always holds.

Let us define as  $\rho(C)$  the modified ratio of a valid (in the sense of property (\*\*)) coalition  $C$  formed by the dynamics where

$$\rho(C) = \begin{cases} \frac{|R \cap C|}{|C|} & \text{if } C = \{b_1, r_1, \dots, r_{k'}\} \text{ for } k' \geq 1 \\ 1 - \frac{|R \cap C|}{|C|} & \text{if } C = \{r_1, b_1, \dots, b_k\} \text{ for } k \geq 2 \\ 0 & \text{otherwise, i.e., } C = \{r\} \text{ or } C = \{b\} \end{cases}$$

For each partition in a sequence of IS-deviations, we consider the vector composed of the modified ratios  $\rho(C)$  for all coalitions  $C$  in the partition. We will prove that for each sequence of IS-deviations, there is an equivalent sequence of IS-deviations where the vector of modified ratios strictly increases lexicographically at each deviation.

Suppose that a blue agent  $b$  (the case of a red agent is symmetric) performs an IS-deviation, at step  $t$  of the dynamics, which makes the vector of modified ratios decrease or being the same lexicographically. By definition of modified ratios and the type of valid coalitions, it must hold that  $b$  deviates from a coalition  $C_1 := \{r_1, b_1, \dots, b_{k_1}\}$  to a new coalition  $C_2 := \{r_1, b_1, \dots, b_{k_2}\}$  where  $k_2 < k_1$ . Therefore, it must hold that  $\frac{1}{k_2+1} \succ_b \frac{1}{k_1+1}$ . It follows that  $b$  is the last arrived agent in  $C_1$ , otherwise there would have been another agent entering in the coalition after her, implying that  $\frac{1}{k_2+1} \succ_b \frac{1}{k_1+1} \succ_b \frac{1}{k_1}$ , which contradicts the single-peakedness of the preferences (if some agents left coalition

$C_1$  after the arrival of agent  $b$ , then they must also be blue agents by property (\*), and then it does not change the fact that the peak of agent  $b$  is on the left in the single-peaked axis). Let us call  $C_0$  the coalition from which  $b$  comes when she deviates to join  $C_1$ . If her deviation from  $C_0$  to  $C_1$  does not trigger further deviations, we can assume that  $b$  directly deviates from  $C_0$  to  $C_2$  at step  $t - 1$  (the deviations are the same in total except that we skip the deviation from  $C_0$  to  $C_1$  performed by  $b$ ) and then we reach the same vector of modified ratios (with one step less) as in the initial case with only strict lexicographic increases of the vector of modified ratios.

Suppose otherwise that the deviation of agent  $b$  from  $C_0$  to  $C_1$  triggers further deviations, that is we cannot obtain the same outcome by just postponing the deviation of  $b$  to directly  $C_2$  (it follows that  $C_0$  cannot be the singleton coalition  $\{b\}$  of ratio 0). By property (\*),  $C_0$  must also be a coalition of type  $\{r_1, b_1, \dots, b_{k_0}\}$ . Moreover, let us assume, w.l.o.g., that the deviation of  $b$  from  $C_1$  to  $C_2$  is the first deviation of  $b$  that makes the vector of modified ratios decrease, i.e., it was not the case for her deviation from  $C_0$  to  $C_1$ . Let us call  $\frac{1}{k_1^0+1}$  and  $\frac{1}{k_1^1+1}$  the ratios of coalition  $C_1$  after the arrival of  $b$  but before and after, respectively, some possible departures of agents from the coalition. Therefore, by using these notations, we have that  $\frac{1}{k_1^0+1} \succ_b \frac{1}{k_0+1}$  and  $\frac{1}{k_2+1} \succ_b \frac{1}{k_1^1+1}$  and thus, by natural single-peakedness and by the previous assumptions, we have that  $k_0 < k_1^0$ ,  $k_1^1 \leq k_1^0$  and  $k_2 < k_1^1$ . The only possible order in order to respect natural single-peakedness is  $k_0 < k_2 < k_1^1 \leq k_1^0$ . Therefore, w.l.o.g., we can merge the two ratios  $k_1^0$  and  $k_1^1$  in one ratio  $k_1$  and assume that no agent left coalition  $C_1$  after the arrival of agent  $b$ . Hence, to summarize, we have  $k_0 < k_2 < k_1$  and  $\frac{1}{k_2+1} \succ_b \frac{1}{k_1+1} \succ_b \frac{1}{k_0+1}$ .

Recall that the deviation of agent  $b$  from  $C_0$  to  $C_1$  triggers further deviations. Thus, one of the following holds.

1. There is an agent  $b_j$  who leaves coalition  $C_0$  to join a coalition  $D := \{r_1, b_1, \dots, b_\ell\}$ . This deviation was not possible before the departure of  $b$  (otherwise it would not be triggered by it) therefore, the preferences of  $b_j$  are such that  $\frac{1}{k_0+1} \succ_{b_j} \frac{1}{\ell+1} \succ_{b_j} \frac{1}{k_0}$ . By natural single-peakedness, it implies that  $\ell > k_0$ . Note also that the deviation of  $b_j$  must trigger the deviation of  $b$  from  $C_1$  to  $C_2$ , otherwise  $b$  would have no reason to pass by coalition  $C_1$  and could have deviated to  $C_2$  directly. Therefore, there must exist a sequence of IS-deviations starting from the deviation of  $b_j$  to  $D$  that results in the deviation of  $b$  from  $C_1$  to  $C_2$ . The next implied deviation in this sequence must be performed by a blue agent  $b_a$ ; it can be (i) a deviation from  $C_0$  to a coalition  $D'$ , (ii) a deviation to  $C_0$  from coalition  $C_{-1}$  or (iii) a deviation to coalition  $D$  (this may be agent  $b$  with  $D = C_2$ ). Case (i) has the same properties as the deviation performed by  $b_j$ , thus there is no need to further explain this case. Case (iii) implies that  $\frac{1}{\ell+2} \succ_{b_j} \frac{1}{\ell+1}$  whereas  $\ell > k_0$  and  $\frac{1}{k_0+1} \succ_{b_j} \frac{1}{\ell+1}$ , contradicting the natural single-peakedness of the preferences. Therefore, the only meaningful next deviation follows case (ii). Note that in such a case,  $b_a$  cannot be agent  $b$  (otherwise she

would be worse off by coming back to  $C_0$ ). Thus, agent  $b_a$  deviates from coalition  $C_{-1}$  with ratio  $\frac{1}{\ell_1+1}$  to coalition  $C_0$  with ratio  $\frac{1}{k_0}$ . Since this deviation was not possible before, it holds that  $\frac{1}{k_0} \succ_{b_a} \frac{1}{\ell_1+1} \succ_{b_a} \frac{1}{k_0+1}$ , and thus  $\ell_1 < k_0$ . Based on the same arguments as after the deviation of  $b_j$ , no agent can enter into  $C_0$  afterwards so the only possible next deviation is from an agent who deviates to  $C_{-1}$  whereas it was not possible before. All in all, we obtain a sequence of IS-deviations where each agent deviates from a coalition  $C_{-i}$  of ratio  $\frac{1}{\ell_i+1}$  to a coalition  $C_{-i+1}$  of ratio  $\frac{1}{\ell_{i-1}+1}$  (or  $\frac{1}{\ell_{i-1}}$  in case  $\ell_{i-1} = k_0$ ) where  $\ell_i < \ell_{i-1}$  and  $\ell_0 = k_0$ . At the end, there is agent  $b$  who deviates from  $C_{-k} = C_1$  to  $C_{-k+1}$  and then we get that  $k_1 = \ell_k < \dots < \ell_2 < \ell_1 < k_0$ , contradicting the fact that  $k_0 < k_1$ .

2. There is an agent  $b_j$  who leaves a coalition  $D$  of ratio  $\frac{1}{\ell+1}$  to join coalition  $C_0$ . This deviation was not possible before the departure of  $b$  therefore,  $\frac{1}{k_0+1} \succ_{b_j} \frac{1}{\ell+1} \succ_{b_j} \frac{1}{k_0+2}$ . By natural single-peakedness, it implies that  $\ell < k_0$ . Then, as in the previous case we have a series of triggered IS-deviations which ends with  $b$  deviating from  $C_1$  to  $C_2$ . The next deviation in this sequence cannot be a deviation to  $C_0$  because agent  $b_j$  would refuse it. Therefore, it must be a deviation from a coalition  $C_{-1}$  with ratio  $\frac{1}{\ell_1+1}$  to coalition  $D$  with  $\ell_1 < \ell$ . By following the same argument as in the previous case, we obtain at the end of this sequence of deviations that  $k_1 = \ell_k < \dots < \ell_2 < \ell_1 < \ell < k_0$ , contradicting the fact that  $k_0 < k_1$ .

Hence, we cannot have that  $b$  is the last entered in  $C_1$  without having the possibility to postpone her deviation directly to  $C_2$  from  $C_0$  under strict and single-peaked preferences.

In conclusion, since for each sequence of IS-deviations, there is an equivalent sequence of IS-deviations where the vector of modified ratios strictly increases lexicographically at each deviation, it holds that the dynamics of IS-deviations converges.  $\square$

**Theorem 4.4.**  $\exists$ -IS-SEQUENCE-HDG is NP-hard and  $\forall$ -IS-SEQUENCE-HDG is co-NP-hard, even for strict preferences.

We prove the two hardness results by providing separate reductions for each problem in the next two lemmas.

**Lemma B.1.**  $\exists$ -IS-SEQUENCE-HDG is NP-hard even for strict preferences.

*Proof.* Let us perform a reduction from (3,B2)-SAT (Berman, Karpinski, and Scott 2003). In an instance of (3,B2)-SAT, we are given a CNF propositional formula  $\varphi$  where every clause  $C_j$ , for  $1 \leq j \leq m$ , contains exactly three literals and every variable  $x_i$ , for  $1 \leq i \leq p$ , appears exactly twice as a positive literal and twice as a negative literal. From such an instance, we construct an instance of a hedonic diversity game with initial partition as follows. The proof works in the same way as the proof of Lemma A.1 except that we have to ensure appropriate ratios of red agents in each coalition.

For each  $\ell^{\text{th}}$  occurrence ( $\ell \in \{1, 2\}$ ) of a positive literal  $x_i$  (resp., negative literal  $\bar{x}_i$ ), we create a red literal-agent  $y_i^\ell$  (resp., a blue literal-agent  $\bar{y}_i^\ell$ ). All literal-agents are singletons in the initial partition  $\pi_0$ . Let us consider three integers  $\alpha$ ,  $\beta$  and  $\gamma$  such that (1)  $\alpha > 2m - 1$ ,  $\beta > \max\{3p - 2; 3p\alpha + 3p - 2\}$ ,  $\gamma > \max\{12p - 2; 6p\beta + 12p - 1\}$ . For instance, we can set the following values:  $\alpha = m^2$ ,  $\beta = m^4$  and  $\gamma = m^7$  (one can verify that condition (1) is satisfied, especially because in a (3,B2)-SAT instance, it holds that  $m \geq 4$  and  $p = 3/4m$ ). For each clause  $C_j$ , we then create  $\alpha$  dummy clause-agents with among them  $2j - 1$  red agents. They are all grouped within the same coalition  $K_j$  in the initial partition  $\pi_0$ . For each literal  $x_i$  (resp.,  $\bar{x}_i$ ), we create a red variable-agent  $z_i$  (resp., a blue variable-agent  $\bar{z}_i$ ) and  $\beta - 1$  (resp.,  $\beta - 1$ ) dummy variable-agents with among them  $3i - 2$  (resp.,  $3i - 2$ ) red agents ( $z_i$  included). They are all grouped within the same coalition  $Z_i$  (resp.,  $\bar{Z}_i$ ) in the initial partition  $\pi_0$ . Finally, for each variable  $x_i$ , we create three coalitions in partition  $\pi_0$  of dummy agents  $G_i^1$ ,  $G_i^2$  and  $G_i^3$  of size  $i\gamma$  with among them,  $6(p - i) + 1$ ,  $6(p - i) + 3$  or  $6(p - i) + 5$  red agents, for each coalition respectively. These dummy agents are used as a gadget for a cycle. Although we have created many agents, the construction remains polynomial by considering reasonable values of  $\alpha$ ,  $\beta$  and  $\gamma$ , as previously described.

The preferences of the agents over ratios of red agents are given below for every  $1 \leq i \leq p$ ,  $1 \leq j \leq m$ ,  $\ell \in \{1, 2\}$  (notation  $cl(x_i^\ell)$  (resp.,  $cl(\bar{x}_i^\ell)$ ) stands for the index of the clause to which the  $\ell^{\text{th}}$  occurrence of literal  $x_i$  (resp.,  $\bar{x}_i$ ) belongs, the framed value corresponds to the ratio of the initial coalition in partition  $\pi_0$ , and  $[...]$  denotes an arbitrary order over the rest of the coalition ratios):

$$\begin{array}{l}
z_i : \frac{3i}{\beta+2} \succ \frac{6(p-i)+2}{i\gamma+2} \succ \frac{6(p-i)+4}{i\gamma+1} \succ \frac{6(p-i)+6}{i\gamma+2} \succ \frac{6(p-i)+6}{i\gamma+1} \succ \\
\quad \frac{6(p-i)+2}{i\gamma+1} \succ \frac{3i-1}{\beta+1} \succ \boxed{\frac{3i-2}{\beta}} \succ [...] \\
\bar{z}_i : \frac{3i-2}{\beta+2} \succ \frac{6(p-i)+6}{i\gamma+2} \succ \frac{6(p-i)+3}{i\gamma+1} \succ \frac{6(p-i)+2}{i\gamma+2} \succ \frac{6(p-i)+1}{i\gamma+1} \succ \\
\quad \frac{6(p-i)+5}{i\gamma+1} \succ \frac{3i-2}{\beta+1} \succ \boxed{\frac{3i-2}{\beta}} \succ [...] \\
y_i^\ell : \frac{2cl(x_i^\ell)}{\alpha+1} \succ \frac{3i}{\beta+2} \succ \frac{3i-1}{\beta+1} \succ \boxed{1} \succ [...] \\
\bar{y}_i^\ell : \frac{2cl(\bar{x}_i^\ell)-1}{\alpha+1} \succ \frac{3i-2}{\beta+2} \succ \frac{3i-2}{\beta+1} \succ \boxed{0} \succ [...] \\
\hline
K_j : \frac{2j}{\alpha+1} \succ \frac{2j-1}{\alpha+1} \succ \boxed{\frac{2j-1}{\alpha}} \succ [...] \\
Z_i \setminus \{z_i\} : \frac{3i}{\beta+2} \succ \frac{3i-1}{\beta+1} \succ \boxed{\frac{3i-2}{\beta}} \succ \frac{3i-3}{\beta-1} \succ [...] \\
\bar{Z}_i \setminus \{\bar{z}_i\} : \frac{3i-2}{\beta+2} \succ \frac{3i-2}{\beta+1} \succ \boxed{\frac{3i-2}{\beta}} \succ \frac{3i-2}{\beta-1} \succ [...] \\
G_i^1 : \frac{6(p-i)+2}{i\gamma+2} \succ \frac{6(p-i)+2}{i\gamma+1} \succ \frac{6(p-i)+1}{i\gamma+1} \succ \boxed{\frac{6(p-i)+1}{i\gamma}} \succ [...] \\
G_i^2 : \frac{6(p-i)+4}{i\gamma+1} \succ \frac{6(p-i)+3}{i\gamma+1} \succ \boxed{\frac{6(p-i)+3}{i\gamma}} \succ [...] \\
G_i^3 : \frac{6(p-i)+6}{i\gamma+2} \succ \frac{6(p-i)+6}{i\gamma+1} \succ \frac{6(p-i)+5}{i\gamma+1} \succ \boxed{\frac{6(p-i)+5}{i\gamma}} \succ [...]
\end{array}$$

We claim that there exists a sequence of IS-deviations which leads to an IS partition iff formula  $\varphi$  is satisfiable.

Suppose first that there exists a truth assignment of the variables  $\phi$  that satisfies all the clauses. Let us denote by

$\ell_j$  a chosen literal-agent associated with an occurrence of a literal true in  $\phi$  which belongs to clause  $C_j$ . Since all the clauses of  $\varphi$  are satisfied by  $\phi$ , there exists such a literal-agent  $\ell_j$  for each clause  $C_j$ . For every clause  $C_j$ , let literal-agent  $\ell_j$  join coalition  $K_j$ . These IS-deviations make the chosen literal-agents reach their most preferred ratio so none of them will deviate afterwards. For the clause-agents, they all reach either their first or second most preferred ratio but have no possibility to improve their satisfaction in the latter case so none of them will deviate afterwards neither. Then, let all remaining literal-agents  $y_i^\ell$  (resp.,  $\bar{y}_i^\ell$ ) deviate by joining coalition  $Z_i$  (resp.,  $\bar{Z}_i$ ). Since  $\phi$  is a truth assignment of the variables, for each variable  $x_i$ , there exists a coalition  $Z_i$  or  $\bar{Z}_i$  that is joined by two literal-agents and thus reaches the most preferred ratio  $\frac{3i}{\beta+2}$  or  $\frac{3i-2}{\beta+2}$ . For each variable, if coalition  $Z_i$  (resp.,  $\bar{Z}_i$ ) is not joined by two literal-agents, then it cannot be true for  $\bar{Z}_i$  (resp.,  $Z_i$ ), and variable-agent  $z_i$  (resp.,  $\bar{z}_i$ ) then deviates for joining coalition  $G_i^2$ , and if one literal-agent previously joined coalition  $Z_i$  (resp.,  $\bar{Z}_i$ ) she deviates to be alone. No agent can then move in a IS-deviation because variable-agents  $z_i$  (resp.,  $\bar{z}_i$ ) in the gadget prefer ratios which differ by one blue agent (resp., red agent) from the ratio of the current coalitions. This also holds for literal-agents and dummy agents. Therefore, the current partition is IS.

Suppose now that there exists no truth assignment of the variables that satisfies all the clauses. That means that it is not possible that one literal-agent joins each clause coalition while two literal-agents  $y_i^1$  and  $y_i^2$  join coalition  $Z_i$  or  $\bar{y}_i^1$  and  $\bar{y}_i^2$  join coalition  $\bar{Z}_i$  for each variable  $x_i$ . By construction of the preferences, the only agents who want to join a coalition  $K_j$  are literal-agents associated with a literal belonging to clause  $C_j$  and the only agents who want to join a coalition  $Z_i$  (resp.,  $\bar{Z}_i$ ) are literal-agents  $y_i^1$  and  $y_i^2$  (resp.,  $\bar{y}_i^1$  and  $\bar{y}_i^2$ ). Moreover, since each literal-agent prefers to join clause coalitions than variable coalitions, it means that in a maximal sequence of IS-deviations, all clause-agents in  $K_j$  will reach one of the two most preferred ratios,  $\frac{2j}{\alpha+1}$  in case a red literal-agent joined or  $\frac{2j-1}{\alpha+1}$  in case a blue literal-agent joined. In both cases, they have no incentive to deviate afterwards. However, in such a case, there exists a variable  $x_i$  such that at most one literal-agent joins coalition  $Z_i$  and  $\bar{Z}_i$ . It follows that both variable-agents  $z_i$  and  $\bar{z}_i$  have an incentive to deviate to the gadget associated with variable  $x_i$  (their respective most preferred ratios  $\frac{3i}{\beta+2}$  and  $\frac{3i-2}{\beta+2}$  can never be reached). Within the gadget associated with variable  $x_i$ , variable-agents  $z_i$  and  $\bar{z}_i$  are the only agents who can deviate and we necessarily reach a cycle, which is the same as described in the proof of Lemma A.1. Finally, we must verify that all the fractions described in the preferences with different variables are indeed different. First of all, for gadget coalitions, since  $\gamma > 12p - 2$ , it holds that  $\frac{6(p-i)+6}{i\gamma+1} > \frac{6(p-i)+6}{i\gamma+2} > \frac{6(p-i)+5}{i\gamma} > \frac{6(p-i)+5}{i\gamma+1} > \frac{6(p-i)+4}{i\gamma+1} > \frac{6(p-i)+3}{i\gamma} > \frac{6(p-i)+3}{i\gamma+1} > \frac{6(p-i)+2}{i\gamma+1} > \frac{6(p-i)+2}{i\gamma+2} > \frac{6(p-i)+1}{i\gamma} > \frac{6(p-i)+1}{i\gamma+1}$  for every  $i \in [p]$ . Moreover, it holds that  $\frac{6(p-i)+6}{i\gamma+1} > \frac{6(p-(i+1)+1}{(i+1)\gamma+1}$  for every

$i \in [p - 1]$  so all the values associated with ratios preferred to the initial ones are different for all gadget coalitions. For variable coalitions, since  $\beta > 3p - 2$ , it holds that  $\frac{3i}{\beta+2} > \frac{3i-1}{\beta+1} > \frac{3i-2}{\beta} > \frac{3i-2}{\beta+1} > \frac{3i-2}{\beta+2}$  for every  $i \in [p]$ . Moreover, it holds that  $\frac{3i}{\beta+2} < \frac{3(i+1)-2}{\beta+2}$  for every  $i \in [p-1]$  so all the values associated with ratios preferred to the initial ones are different for all variable coalitions. For clause coalitions, since  $\alpha > 2m - 1$ , it holds that  $\frac{2j-1}{\alpha+1} < \frac{2j-1}{\alpha} < \frac{2j}{\alpha+1}$  for every  $j \in [m]$ . Moreover, it holds that  $\frac{2j}{\alpha+1} < \frac{2(j+1)-1}{\alpha+1}$  for every  $j \in [m-1]$  so all the values associated with ratios preferred to the initial ones are different for all clause coalitions. It remains to check that the ratios associated with clause, variable or gadget coalitions do not interfere with each other. Since  $\gamma > 6p\beta + 12p - 1$ , it holds that the highest reachable ratio associated with a gadget coalition is smaller than the smallest reachable ratio associated with a variable coalition, i.e.,  $\frac{6p}{\gamma+1} < \frac{1}{\beta+2}$ . Since  $\beta > 3p\alpha + 3p - 2$ , it holds that the highest reachable ratio associated with a variable coalition is smaller than the smallest reachable ratio associated with a clause coalition, i.e.,  $\frac{3p}{\beta+2} < \frac{1}{\alpha+1}$ . Therefore, all the reachable ratios are indeed different for clause, variable and gadget coalitions. It follows that the previously described deviations are indeed the only possible ones and hence no sequence of IS-deviations can reach an IS partition.  $\square$

**Lemma B.2.**  $\forall$ -IS-SEQUENCE-HDG is co-NP-hard even for strict preferences.

*Proof.* For this purpose, we prove the NP-hardness of the complement problem, which asks whether there exists a cycle in IS-deviations. Let us perform a reduction from (3,B2)-SAT (Berman, Karpinski, and Scott 2003). In an instance of (3,B2)-SAT, we are given a CNF propositional formula  $\varphi$  where every clause  $C_j$ , for  $1 \leq j \leq m$ , contains exactly three literals and every variable  $x_i$ , for  $1 \leq i \leq p$ , appears exactly twice as a positive literal and twice as a negative literal. From such an instance, we construct an instance of a hedonic diversity game with initial partition as follows. The proof works in the same way as the proof of Lemma A.2 except that we have to ensure appropriate ratios of red agents in each coalition.

For each  $\ell^{\text{th}}$  occurrence ( $\ell \in \{1, 2\}$ ) of a positive literal  $x_i$  (resp., negative literal  $\bar{x}_i$ ), we create a red literal-agent  $y_i^\ell$  (resp., a blue literal-agent  $\bar{y}_i^\ell$ ). We create another red agent  $t$ . All these agents are singletons in the initial partition  $\pi_0$ . Let us consider four integers  $\alpha$ ,  $\beta_1^+$ ,  $\beta_1^-$  and  $\beta_2$  such that (1)  $\alpha > 6m + 2$ ,  $\beta_1^+ > \max\{4p - 2; (2p + 1)\alpha + 4p\}$ ,  $\beta_1^- > \max\{4p - 2; 2p\beta_1^+ + 2p - 2\}$  and  $\beta_2 > \max\{3p - 2; 3p\beta_1^- + 4p\}$ . For instance, we can set the following values:  $\alpha = m^3$ ,  $\beta_1^+ = m^5$ ,  $\beta_1^- = m^7$  and  $\beta_2 = m^9$  (one can verify that condition (1) is satisfied, especially because in a (3,B2)-SAT instance, it holds that  $m \geq 4$  and  $p = 3/4m$ ). For each clause  $C_j$ , we then create  $\alpha$  dummy clause-agents with among them  $3j - 2$  red agents. They are all grouped within the same coalition  $K_j$  in the initial partition  $\pi_0$ . We also create  $\alpha$  dummy agents with among them  $3m + 1$  red

agents, they are all grouped within the same coalition  $K_{m+1}$  in initial partition  $\pi_0$ . For each first occurrence of literal  $x_i$  (resp.  $\bar{x}_i$ ), we create  $\beta_1^+$  (resp.,  $\beta_1^-$ ) dummy variable agents with among them  $2i - 1$  red agents, they are all grouped within the same coalition  $Y_i^1$  (resp.,  $\bar{Y}_i^1$ ) in the initial partition  $\pi_0$ . Finally, for each second occurrence of literal  $x_i$  (resp.  $\bar{x}_i$ ), we create  $\beta_2$  dummy variable agents with among them  $3i - 2$  red agents, they are all grouped within the same coalition  $Y_i^2$  (resp.,  $\bar{Y}_i^2$ ) in the initial partition  $\pi_0$ . Although we have created many agents, the construction remains polynomial by considering reasonable values of  $\alpha$ ,  $\beta_1^+$ ,  $\beta_1^-$  and  $\beta_2$ , as previously described.

The preferences of the agents over sizes of coalitions are given below for every  $1 \leq i \leq p$ ,  $1 \leq i' < p$ ,  $1 \leq j \leq m + 1$ ,  $\ell \in \{1, 2\}$  (notation  $cl(x_i^\ell)$  (resp.,  $cl(\bar{x}_i^\ell)$ ) stands for the index of the clause to which the  $\ell^{\text{th}}$  occurrence of literal  $x_i$  (resp.,  $\bar{x}_i$ ) belongs, the framed value corresponds to the ratio of the initial coalition in partition  $\pi_0$ , and  $[\dots]$  denotes an arbitrary order over the rest of the coalition ratios):

$$\begin{aligned}
 y_i^1 : & \frac{3cl(x_i^1)}{\alpha+2} > \frac{3cl(x_i^1)-1}{\alpha+2} > \frac{3cl(x_i^1)+1}{\alpha+2} > \frac{3cl(x_i^1)+1-1}{\alpha+2} > \frac{3cl(x_i^1)+1-1}{\alpha+1} > \dots \\
 & \frac{3cl(x_i^1)-1}{\alpha+1} > \frac{2i+1}{\beta_1^++2} > \frac{2i}{\beta_1^++2} > \frac{3i}{\beta_2+2} > \frac{3i-1}{\beta_2+1} > \frac{2i}{\beta_1^++1} > \boxed{1} > [\dots] \\
 y_{i'}^2 : & \frac{3cl(x_{i'}^2)}{\alpha+2} > \frac{3cl(x_{i'}^2)-1}{\alpha+2} > \frac{3cl(x_{i'}^2)+1}{\alpha+2} > \frac{3cl(x_{i'}^2)+1-1}{\alpha+2} > \frac{3cl(x_{i'}^2)+1-1}{\alpha+1} > \dots \\
 & \frac{3cl(x_{i'}^2)-1}{\alpha+1} > \frac{3i'}{\beta_2+2} > \frac{2(i'+1)+1}{\beta_1^++2} > \frac{2(i'+1)}{\beta_1^++2} > \frac{2(i'+1)}{\beta_1^++1} > \frac{2(i'+1)-1}{\beta_1^++1} > \boxed{1} > [\dots] \\
 y_p^2 : & \frac{3cl(x_p^2)}{\alpha+2} > \frac{3cl(x_p^2)-1}{\alpha+2} > \frac{3cl(x_p^2)+1}{\alpha+2} > \frac{3cl(x_p^2)+1-1}{\alpha+2} > \frac{3cl(x_p^2)+1-1}{\alpha+1} > \dots \\
 & \frac{3cl(x_p^2)-1}{\alpha+1} > \frac{3p}{\beta_2+2} > \frac{3}{\alpha+2} > \frac{2}{\alpha+2} > \frac{3p-1}{\beta_2+1} > \boxed{1} > [\dots] \\
 \bar{y}_i^1 : & \frac{3cl(\bar{x}_i^1)-1}{\alpha+2} > \frac{3cl(\bar{x}_i^1)-2}{\alpha+2} > \frac{3cl(\bar{x}_i^1)+1}{\alpha+2} > \frac{3cl(\bar{x}_i^1)+1-1}{\alpha+2} > \frac{3cl(\bar{x}_i^1)+1-2}{\alpha+1} > \dots \\
 & \frac{3cl(\bar{x}_i^1)-2}{\alpha+1} > \frac{2i}{\beta_1^-+2} > \frac{2i-1}{\beta_1^-+2} > \frac{3i-2}{\beta_2+2} > \frac{3i-2}{\beta_2+1} > \frac{2i-1}{\beta_1^-+1} > \boxed{0} > [\dots] \\
 \bar{y}_{i'}^2 : & \frac{3cl(\bar{x}_{i'}^2)-1}{\alpha+2} > \frac{3cl(\bar{x}_{i'}^2)-2}{\alpha+2} > \frac{3cl(\bar{x}_{i'}^2)+1}{\alpha+2} > \frac{3cl(\bar{x}_{i'}^2)+1-1}{\alpha+2} > \frac{3cl(\bar{x}_{i'}^2)+1-2}{\alpha+1} > \dots \\
 & \frac{3cl(\bar{x}_{i'}^2)-2}{\alpha+1} > \frac{3i'-2}{\beta_2+2} > \frac{2(i'+1)}{\beta_1^++2} > \frac{2(i'+1)-1}{\beta_1^++2} > \frac{2(i'+1)-1}{\beta_1^++1} > \frac{2(i'+1)}{\beta_1^++1} > \boxed{0} > [\dots] \\
 \bar{y}_p^2 : & \frac{3cl(\bar{x}_p^2)-1}{\alpha+2} > \frac{3cl(\bar{x}_p^2)-2}{\alpha+2} > \frac{3cl(\bar{x}_p^2)+1}{\alpha+2} > \frac{3cl(\bar{x}_p^2)+1-1}{\alpha+2} > \frac{3cl(\bar{x}_p^2)+1-2}{\alpha+1} > \dots \\
 & \frac{3cl(\bar{x}_p^2)-2}{\alpha+1} > \frac{3p-2}{\beta_2+2} > \frac{2}{\alpha+2} > \frac{1}{\alpha+2} > \frac{1}{\alpha+1} > \frac{3p-2}{\beta_2+1} > \boxed{0} > [\dots] \\
 t : & \frac{3m+3}{\alpha+2} > \frac{3m+2}{\alpha+2} > \frac{3}{\beta_1^++2} > \frac{2}{\beta_1^++2} > \frac{2}{\beta_1^++1} > \frac{2}{\beta_1^++1} > \frac{3m+2}{\alpha+1} > \boxed{1} > [\dots] \\
 K_j : & \frac{3j}{\alpha+2} > \frac{3j-1}{\alpha+2} > \frac{3j-2}{\alpha+2} > \frac{3j-1}{\alpha+1} > \frac{3j-2}{\alpha+1} > \frac{3j-2}{\alpha} > [\dots] \\
 Y_i^1 : & \frac{2i+1}{\beta_1^++2} > \frac{2i}{\beta_1^++2} > \frac{2i}{\beta_1^++1} > \frac{2i-1}{\beta_1^++1} > \frac{2i-1}{\beta_1^++1} > \boxed{\frac{2i-1}{\beta_1^++1}} > [\dots] \\
 \bar{Y}_i^1 : & \frac{2i}{\beta_1^-+2} > \frac{2i-1}{\beta_1^-+2} > \frac{2i}{\beta_1^-+1} > \frac{2i-1}{\beta_1^-+1} > \frac{2i-1}{\beta_1^-+1} > \boxed{\frac{2i-1}{\beta_1^-+1}} > [\dots] \\
 Y_i^2 : & \frac{3i}{\beta_2+2} > \frac{3i-1}{\beta_2+1} > \frac{3i-2}{\beta_2} > [\dots] \\
 \bar{Y}_i^2 : & \frac{3i-2}{\beta_2+2} > \frac{3i-2}{\beta_2+1} > \frac{3i-2}{\beta_2} > [\dots]
 \end{aligned}$$

We claim that there exists a cycle of IS-deviations iff formula  $\varphi$  is satisfiable. We omit the formal proof of equivalence which follows exactly the same arguments as the proof of Lemma A.2 with even the same name of agents and fixed coalitions. When given a truth assignment of the variables which satisfies formula  $\varphi$ , it is easy to see that the cycle described in the first part of the proof of Lemma A.2 can also occur in this instance, proving the if part. For the only if part, the same arguments as the ones given in the second part of the proof of Lemma A.2 also hold, except that we need to adapt to the context of evaluations of coalitions based on red agent ratios. The only point that must be additionally

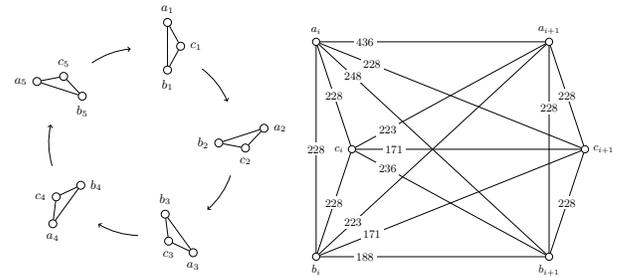
checked is that all the fractions described in the preferences with different variables are indeed different.

First of all, for clause coalitions, since  $\alpha > 6m + 2$ , it holds that  $\frac{3j}{\alpha+2} > \frac{3j-1}{\alpha+1} > \frac{3j-1}{\alpha+2} > \frac{3j-2}{\alpha} > \frac{3j-2}{\alpha+1} > \frac{3j-2}{\alpha+2}$  for every  $j \in [m+1]$ . Moreover, it holds that  $\frac{3j}{\alpha+2} < \frac{3(j+1)-2}{\alpha+2}$  for every  $j \in [m]$  so all the values associated with ratios preferred to the initial ones are different for all clause coalitions. For variable coalitions associated with the first positive occurrence of a variable, since  $\beta_1^+ > 4p - 2$ , it holds that  $\frac{2i+1}{\beta_1^++2} > \frac{2i}{\beta_1^++1} > \frac{2i}{\beta_1^++2} > \frac{2i-1}{\beta_1^+} > \frac{2i-1}{\beta_1^++1}$  for every  $i \in [p]$ . Moreover, it holds that  $\frac{2i+1}{\beta_1^++2} < \frac{2(i+1)-1}{\beta_1^++1}$  for every  $i \in [p-1]$  so all the values associated with ratios preferred to the initial ones are different for all variable coalitions associated with the first positive occurrence of a variable. For variable coalitions associated with the first negative occurrence of a variable, since  $\beta_1^- > 4p - 2$ , it holds that  $\frac{2i}{\beta_1^-+2} > \frac{2i}{\beta_1^-+1} > \frac{2i-1}{\beta_1^-} > \frac{2i-1}{\beta_1^-+1} > \frac{2i-1}{\beta_1^-+2}$  for every  $i \in [p]$ . Moreover, it holds that  $\frac{2i}{\beta_1^-+2} < \frac{2(i+1)-1}{\beta_1^-+2}$  for every  $i \in [p-1]$  so all the values associated with ratios preferred to the initial ones are different for all variable coalitions associated with the first negative occurrence of a variable. For variable coalitions associated with the second occurrence of a literal, since  $\beta_2 > 3p - 2$ , it holds that  $\frac{3i}{\beta_2+2} > \frac{3i-1}{\beta_2+1} > \frac{3i-2}{\beta_2} > \frac{3i-2}{\beta_2+1} > \frac{3i-2}{\beta_2+2}$  for every  $i \in [p]$ . Moreover, it holds that  $\frac{3i}{\beta_2+2} < \frac{3(i+1)-2}{\beta_2+2}$  for every  $i \in [p-1]$  so all the values associated with ratios preferred to the initial ones are different for all variable coalitions associated with the second occurrence of a literal.

It remains to check that the ratios associated with clause or variable coalitions do not interfere with each other. Since  $\beta_2 > 3p\beta_1^- + 4p$ , it holds that the highest reachable ratio associated with a variable coalition related to the second occurrence of a literal is smaller than the smallest reachable ratio associated with a variable coalition related to the first negative occurrence of a variable, i.e.,  $\frac{3p}{\beta_2+2} < \frac{1}{\beta_1^-+2}$ . Since  $\beta_1^- > 2p\beta_1^+ + 2p - 2$ , it holds that the highest reachable ratio associated with a variable coalition related to the first negative occurrence of a variable is smaller than the smallest reachable ratio associated with a variable coalition related to the first positive occurrence of a variable, i.e.,  $\frac{2p}{\beta_1^-+2} < \frac{1}{\beta_1^++1}$ . Since  $\beta_1^+ > (2p+1)\alpha + 4p$ , it holds that the highest reachable ratio associated with a variable coalition related to the first positive occurrence of a variable is smaller than the smallest reachable ratio associated with a clause coalition, i.e.,  $\frac{2p+1}{\beta_1^++2} < \frac{1}{\alpha+2}$ . Therefore, all the reachable ratios are indeed different for all clause and variable coalitions. It follows that the deviations described in the second part of the proof of Lemma A.2 are the only possible ones. Hence the described cycle is actually the only possible one.  $\square$

## C Fractional Hedonic Games (FHGs)

The hardness reductions in this section are from the NP-complete problem exact 3-Cover (Karp 1972). An instance



(a) Five triangles are ordered in a cycle such that there is a tendency of agents in  $N_i$  to deviate to coalitions in  $N_{i+1}$ . (b) The transition weights between the triangles allow for finite loops of deviations.

Figure 1: Description of the graph associated with the constructed symmetric FHG without IS partition.

of exact 3-cover consists of a tuple  $(R, S)$ , where  $R$  is a ground set together with a set  $S$  of 3-element subsets of  $R$ . A ‘yes’-instance is an instance so that there exists a subset  $S' \subseteq S$  that partitions  $R$ .

**Theorem 5.1.** *There exists a symmetric FHG without an IS partition.*

*Proof.* Define the sets of agents  $N_i = \{a_i, b_i, c_i\}$  for  $i \in \{1, \dots, 5\}$  and consider the FHG on the agent set  $N = \bigcup_{i=1}^5 N_i$  where symmetric weights are given by

- $v(a_i, b_i) = v(b_i, c_i) = v(a_i, c_i) = 228, i \in \{1, \dots, 5\}$ ,
- $v(a_i, a_{i+1}) = 436, v(a_i, b_{i+1}) = 228, v(a_i, c_{i+1}) = 248, i \in \{1, \dots, 5\}$ ,
- $v(b_i, a_{i+1}) = 223, v(b_i, b_{i+1}) = 171, v(b_i, c_{i+1}) = 236, i \in \{1, \dots, 5\}$ ,
- $v(c_i, a_{i+1}) = 223, v(c_i, b_{i+1}) = 171, v(c_i, c_{i+1}) = 188, i \in \{1, \dots, 5\}$ , and
- $v(x, y) = -2251$  for all agents  $x, y \in N$  such that the weight is not defined yet.

In the above definition, all indices are to be read modulo 5 (where the modulo function is assumed to map to  $\{1, \dots, 5\}$ ). Note that the large negative weight exceeds the sum of positive weights incident to any agents. Hence, agents linked by a negative weight, can never be in a common coalition in any IS partition. The FHG consists of five triangles that form a cycle. The structure of the game is illustrated in Figure 1. There is an infinite loop of deviations starting with the partition  $(N_5 \cup N_1, N_2, N_3, N_4)$ . First,  $a_1$  deviates by joining  $N_2$ . Then,  $b_1$  join this new coalition, then  $c_1$ . After this step, we are in an isomorphic state as in the initial partition.

Let  $\pi$  be any partition of the agents and assume that  $\pi$  is IS. In particular, no agent receives negative utility. Therefore there exists an  $i \in \{1, \dots, 5\}$  such that  $\pi(a_i) \cap \{a_1, \dots, a_5\} = \{a_i\}$ . We may assume, w.l.o.g., that  $a_1$  is such an agent. In the following, we will exclude all possible coalitions for agent  $a_1$ , deriving a contradiction.

- Goal 1: show that  $c_2 \notin \pi(a_1)$ .

First, assume that  $c_2 \in \pi(a_1)$ . If  $\pi(a_2) \subseteq \{a_2, b_2, b_1, c_1\}$ , then  $v_{a_2}(\pi) \leq 168.5$  while  $v_{a_2}(\{a_2\} \cup \pi(a_1)) \geq 221$

and  $a_2$  has an incentive to deviate (making no agent in  $\pi(a_1)$  worse). Hence,  $\pi(a_2) \subseteq \{a_2, b_2, a_3, b_3, c_3\}$ . In addition, by the same potential deviation,  $a_3 \in \pi(a_2)$  and  $|\pi(a_2)| \geq 3$ .

Next, consider the case that  $b_2 \in \pi(a_2)$ . Then,  $v_{c_2}(\pi) \leq 142.5$ , while  $v_{c_2}(\{c_2\} \cup \pi(a_2)) \geq 169.75$  and  $c_2$  would deviate. Hence,  $b_2 \notin \pi(a_2)$ . If  $b_2 \notin \pi(a_1)$ , then  $v_{b_2}(\pi) \leq \max\{141.34, 119.67\} = 141.34$  (this is if  $b_2$  forms a coalition with  $N_1 \setminus \{a_1\}$  and  $N_3 \setminus \{a_3\}$ , respectively), while  $v_{b_2}(\{b_2\} \cup \pi(a_1)) \geq 158.6$  and it is easily seen that  $b_2$  can only improve agents in  $\pi(a_1)$ . It follows that  $b_2 \in \pi(a_1)$ .

If  $b_3 \notin \pi(a_2)$ , then  $\pi(a_2) = \{a_2, a_3, c_3\}$  and  $b_3$  would deviate by joining  $\pi(a_2)$ . Hence,  $\{a_2, a_3, b_3\} \subseteq \pi(a_2)$ . But then  $v_{c_2}(\pi) \leq 159.6$  while  $v_{c_2}(\{c_2\} \cup \pi(a_2)) \geq 171.6$  and joining with  $c_2$  makes no agent worse. In conclusion, the initial assumption was wrong and  $c_2 \notin \pi(a_1)$ .

- Goal 2:  $b_2 \notin \pi(a_1)$ .

Second, assume that  $b_2 \in \pi(a_1)$ . As in the previous case, it is easily seen that  $\pi(a_2) \subseteq \{a_2, b_2\} \cup N_3$ ,  $a_3 \in \pi(a_2)$ , and  $|\pi(a_2)| \geq 3$ . If  $c_2 \notin \pi(a_2)$ , then  $v_{c_2}(\pi) \leq 118$ , while  $v_{c_2}(\{c_2\} \cup \pi(a_2)) \geq 155.5$ . Hence,  $c_2 \in \pi(a_2)$ . But then  $v_{b_2}(\pi) \leq 168$  while  $v_{b_2}(\{b_2\} \cup \pi(a_2)) \geq 169.75$  and  $b_2$  would join  $\pi(a_2)$  making no agent worse. We conclude that  $b_2 \notin \pi(a_1)$  and can therefore assume that  $\pi(a_1) \subseteq N_1 \cup N_5$ .

- Goal 3:  $b_1 \notin \pi(a_1)$ .

Third, assume that  $b_1 \in \pi(a_1)$ . Then,  $v_{a_5}(\pi) \leq \max\{223, 171\} = 223$  (where the first utility in the maximum refers to the coalition  $N_4 \cup N_5$  and the second utility to  $N_5 \cup \{c_1\}$ ). However,  $v_{a_5}(\{a_5\} \cup \pi(a_1)) \geq 228$ . Since joining  $\pi(a_1)$  with  $a_5$  makes no agent worse, this is not possible. Hence,  $b_1 \notin \pi(a_1)$ .

- Goal 4:  $c_1 \notin \pi(a_1)$ .

Forth, assume that  $c_1 \in \pi(a_1)$ . Then,  $v_{b_1}(\{b_1\} \cup \pi(a_1)) \geq 152$  and adding  $b_1$  to  $\pi(a_1)$  leaves no agent worse off. Since,  $v_{b_1}(\{b_1\} \cup N_2) = 145.5$ , it must hold that  $\pi(b_1) \subseteq \{b_1\} \cup N_5$  and even  $\{a_5, c_5\} \subseteq \pi(b_1)$  since otherwise  $v_{b_1}(\pi) \leq 145.4$ . But then  $v_{a_1}(\pi) \leq 150.4$  while  $v_{a_1}(\{a_1\} \cup \pi(b_1)) \geq 221.75$  and  $a_1$  would deviate making no agent worse. It follows that  $c_1 \notin \pi(a_1)$ .

- Goal 5:  $\pi(a_1) \not\subseteq \{a_1, b_5, c_5\}$

It remains the case that  $\pi(a_1) \subseteq \{a_1, b_5, c_5\}$ . If  $|\pi(b_1)| \geq 2$ , then  $a_1$  would deviate by joining  $\pi(b_1)$ , making no agent worse. If, however,  $b_1$  is in a singleton coalition, then  $b_1$  would join  $\pi(a_1)$ , making no agent worse and improving her utility.  $\square$

For the corollary, we only give a brief proof sketch, because the main method will also be applied in the proof of Lemma C.1, which considers convergence of the IS dynamics in the case that the FHGs even have non-negative weights.

**Corollary 5.2.** *Deciding whether there exists an individually stable partition in symmetric FHGs is NP-hard.*

*Sketch of proof.* In the reduction of Brandl, Brandt, and Strobel (2015, Theorem 5), we replace the non-symmetric gadget by a vertex-minimal symmetric FHG that admits no IS

partition. Such an FHG exists according to Theorem 5.1. The weights in the symmetric part of their reduced instances must be large enough to incentivize the agent in the gadget to stay in a coalition outside the gadget.  $\square$

**Theorem 5.3.**  *$\exists$ -IS-SEQUENCE-FHG is NP-hard and  $\forall$ -IS-SEQUENCE-FHG is co-NP-hard, even in symmetric FHGs with non-negative weights. The former is even true if the initial partition is the singleton partition.*

We provide separate reductions for the two hardness results in the next lemmas.

**Lemma C.1.**  *$\exists$ -IS-SEQUENCE-FHG is NP-hard even in symmetric FHGs with non-negative weights where the initial partition is the singleton partition.*

*Proof.* We provide a reduction from exact 3-cover.

Let  $(R, S)$  be an instance of exact 3-cover. We may assume that every  $r \in R$  occurs in at least one set of  $S$ . Let  $m_r := |\{s \in S : r \in s\}| - 1 \geq 0$ , for  $r \in R$ . We define the symmetric FHG on agent set  $N$ , where the underlying graph consists of a 4-clique for every set in  $s$ , and  $m_r$  copies of a non-negative version of the example from Theorem 5.1. Formally,  $N = \bigcup_{s \in S} (\{t_s\} \cup \{s^i : i \in s\}) \cup \bigcup_{r \in R} \bigcup_{v=1}^{m_r} \{a_w^{r,v}, b_w^{r,v}, c_w^{r,v} : w = 1, \dots, 5\}$ , and non-negative, symmetric weights are given by

- For all  $r \in R$ ,  $v \in \{1, \dots, m_r\}$ , and  $w \in \{1, \dots, 5\}$ ,
  - $v(a_w^{r,v}, b_w^{r,v}) = v(b_w^{r,v}, c_w^{r,v}) = v(a_w^{r,v}, c_w^{r,v}) = 228$ ,
  - $v(a_w^{r,v}, a_{w+1}^{r,v}) = 436$ ,  $v(a_w^{r,v}, b_{w+1}^{r,v}) = 228$ ,  
 $v(a_w^{r,v}, c_{w+1}^{r,v}) = 248$ ,
  - $v(b_w^{r,v}, a_{w+1}^{r,v}) = 223$ ,  $v(b_w^{r,v}, b_{w+1}^{r,v}) = 171$ ,  
 $v(b_w^{r,v}, c_{w+1}^{r,v}) = 236$ , and
  - $v(c_w^{r,v}, a_{w+1}^{r,v}) = 223$ ,  $v(c_w^{r,v}, b_{w+1}^{r,v}) = 171$ ,  
 $v(c_w^{r,v}, c_{w+1}^{r,v}) = 188$ .
- $v(t_s, s^i) = 304$ ,  $s \in S$ ,  $i \in s$ ,
- $v(s^j, s^i) = 304$ ,  $s \in S$ ,  $i, j \in s$ ,
- $v(s^i, a_1^{i,v}) = 304$ ,  $s \in S$ ,  $i, j \in s$ ,  $v \in \{1, \dots, m_r\}$ , and
- $v(x, y) = 0$  for all agents  $x, y \in N$  such that the weight is not defined, yet.

In the above definition, all indices are to be read modulo 5 (where the modulo function is assumed to map to  $\{1, \dots, 5\}$ ). For  $s \in S$ , define  $N^s = \{t_s\} \cup \{s^i : i \in s\}$ .

Assume first that  $(R, S)$  is a ‘yes’-instance and let  $S' \subseteq S$  be a partition of  $R$ . For  $r \in R$ , let  $\sigma_r : \{s \in S \setminus S' : r \in s\} \rightarrow \{1, \dots, m_r\}$  be a bijection. Note that the domain and image of  $\sigma_r$  have the same cardinality for every  $r \in R$ , because  $S'$  is a partition of  $R$ . Consider the partition  $\pi = \bigcup_{r \in R} \bigcup_{v=1}^{m_r} \{\{a_2^{r,v}, b_2^{r,v}, c_2^{r,v}, a_3^{r,v}, b_3^{r,v}, c_3^{r,v}\}, \{a_4^{r,v}, b_4^{r,v}, c_4^{r,v}, a_5^{r,v}, b_5^{r,v}, c_5^{r,v}\}, \{b_1^{r,v}, c_1^{r,v}\}\} \cup \bigcup_{s \in S'} \{N^s\} \cup \bigcup_{s \in S \setminus S'} \{\{t_s\}\} \cup \{\{s^i, a_1^{i, \sigma_i(s)}\} : i \in s\}$ . It is quickly checked that  $\pi$  is IS. Moreover,  $\pi$  can be reached by deviations starting from the singleton partition, by forming the coalitions one by one. In particular, coalitions of the type  $\{a_2^{r,v}, b_2^{r,v}, c_2^{r,v}, a_3^{r,v}, b_3^{r,v}, c_3^{r,v}\}$  can be formed by having  $a_3^{r,v}$  join  $b_2^{r,v}$ , forming a coalition that is subsequently joined by  $c_2^{r,v}$ ,  $a_2^{r,v}$ ,  $b_2^{r,v}$ , and finally  $c_2^{r,v}$ . Hence, it is possible to

reach an IS partition with IS-deviations, starting with the singleton partition.

Now, assume that it is possible to reach an IS partition  $\pi$  by starting the dynamics from the singleton partition. Define by  $G = (N, E)$  the graph with edge set  $E = \{\{d, e\} : v(d, e) > 0\}$ , a combinatorial representation of the unweighted version of the FHG under consideration. Note that all coalitions of  $\pi$  are cliques in  $G$ , because all agents that get part of a coalition of size at least 2 have positive utility and would block any further agent that does not award them positive utility. Now, consider a set of agents  $D := \{a_w^{r,v}, b_w^{r,v}, c_w^{r,v} : w = 1, \dots, 5\}$  for some  $r \in R, v \in \{1, \dots, m_r\}$ . Assume for contradiction that for all agents  $d \in D, \pi(d) \subseteq D$ . This yields an IS partition of the game considered in Theorem 5.1, because the agents would also form an IS partition in this game. This is due to the fact that no agents with mutual negative utility would form a coalition, and a deviation with negative weights would still be a deviation if these weights are set to 0. This is a contradiction. Hence, some agent in  $D$  forms a coalition with an agent outside  $D$ . By the fact that all coalitions in  $\pi$  are cliques in  $G$ , the only such agent can be  $a_1^{r,v}$ . By the same fact,  $\pi(a_1^{r,v}) \cap D = \{a_1^{r,v}\}$  and there exists a unique  $s \in S$  with  $r \in s$  such that  $\pi(a_1^{r,v}) = \{a_1^{r,v}, s^r\}$ .

Next, let  $s \in S$ . We claim that  $\{t^s\} \in \pi$  or  $N^s \in \pi$ . Otherwise, consider  $r \in s$  with  $s^r \notin \pi(t^s)$ . Again by the clique property,  $v_{s^r}(\pi) \leq \frac{304}{2}$  and  $\pi(t^s) \subseteq N^s$ . Hence,  $v_{s^r}(\pi(t^s) \cup \{s^r\}) \geq \frac{608}{3}$ , and every agent in  $\pi(t^s)$  would welcome  $s^r$ . This contradicts the individual stability of  $\pi$ .

Consider the set  $T = \{s \in S : \{t^s\} \in \pi\}$ . Then, for every  $s \in T$  and  $r \in s$ , there exists  $v \in \{1, \dots, m_r\}$  with  $\pi(s^r) = \{a_1^{r,v}, s^r\}$ . Otherwise,  $\pi(s^r) \subseteq N^s$  and  $t^s$  can perform a deviation by joining  $\pi(s^r)$ . Hence, the sets in  $T$  cover every element in  $r \in R$  exactly  $m_r$  times (in order to form all the required coalitions of the type  $\{a_1^{r,v}, s^r\}$ ). Since  $S$  covers every  $r \in R$  exactly  $m_r + 1$  times, the set  $S' = S \setminus T$  forms a partition of  $R$ . Hence,  $(R, S)$  is a ‘yes’-instance.  $\square$

**Lemma C.2.**  $\forall$ -IS-SEQUENCE-FHG is co-NP-hard even in symmetric FHGs with non-negative weights.

*Proof.* For this purpose, we prove the NP-hardness of the complement problem, which asks whether there exists a cycle in IS-deviations. We provide a reduction from exact 3-cover.

Let  $(R, S)$  be an instance of exact 3-cover. Let  $l = |S| - |R|/3$ . Choose  $\alpha$  with a polynomial-size representation in the input size satisfying  $\frac{l}{l+1}\alpha < 152 < \frac{l+1}{l+2}\alpha$ . For the reduction to work, any number satisfying these boundaries suffices, and for a polynomial-size representation, one can for example use the midpoint of the boundaries.

Define the symmetric FHG on agent set  $N$  where  $N = R \cup \{r^s : s \in S, r \in s\} \cup \{s_1, s_2 : s \in S\} \cup \{a_w, b_w, c_w : w = 1, \dots, 5\}$ . We define  $C = \{a_w, b_w, c_w : w = 1, \dots, 5\}$ . The utilities are given as follows.

- For all  $w \in \{1, \dots, 5\}$ , reading indices modulo 5 (where the modulo function is assumed to map to  $\{1, \dots, 5\}$ ),
  - $v(a_w, b_w) = v(b_w, c_w) = v(a_w, c_w) = 228$ ,

$$\begin{aligned} - v(a_w, a_{w+1}) &= 436, & v(a_w, b_{w+1}) &= 228, \\ v(a_w, c_{w+1}) &= 248, \\ - v(b_w, a_{w+1}) &= 223, & v(b_w, b_{w+1}) &= 171, \\ v(b_w, c_{w+1}) &= 236, \text{ and} \\ - v(c_w, a_{w+1}) &= 223, & v(c_w, b_{w+1}) &= 171, \\ v(c_w, c_{w+1}) &= 188. \end{aligned}$$

- For all  $s \in S$ ,
  - $v(a_1, s_2) = v(s_1, s_2) = \alpha$ ,
  - $v(s_1, r^s) = \alpha, v(r^s, r) = 2\alpha, r \in S$ , and
- $v(x, y) = 0$  for all agents  $x, y \in N$  such that the weight is not defined, yet.

The reduction is illustrated in Figure 2. Finally, define  $\pi = \{\{r\} : r \in R\} \cup \{\{s_1, i^s, j^s, k^s\} : \{i, j, k\} = s \in S\} \cup \{\{a_1\} \cup \{s_2 : s \in S\}\} \cup \{\{b_1, c_1\}, \{a_2, b_2, c_2, a_3, b_3, c_3\}, \{a_4, b_4, c_4, a_5, b_5, c_5\}\}$ .

We claim that  $(R, S)$  is a ‘yes’-instance if and only if the IS dynamics starting with  $\pi$  can cycle.

First assume that  $(R, S)$  is a ‘yes’-instance and let  $S' \subseteq S$  be a partition of  $R$  by the sets in  $S$ . We consider three stages of deviations. In the first stage, the agents in a coalition with some  $s_1$  for  $s \in S'$  join the agents of type  $r_v$ . This will leave all agents in  $\{s_1 : s \in S'\}$  in singleton coalitions. In the second stage, agents  $s_2$  for  $s \in S'$  join their copies  $s_1$ . This leaves the agent  $a_1$  with a utility of  $\frac{l}{l+1}\alpha < 152 = v_{a_1}(\{a_1, b_1, c_1\})$ . Therefore, we can have  $a_1$  join  $\{b_1, c_1\}$ . From now on, we consider the subgame induced by the agents in  $C$ . We start to let  $a_5, b_5$ , and  $c_5$  join  $\{a_1, b_1, c_1\}$ . Then, we reach essentially the same partition (differing only in an index shift), so we can repeat these deviations.

Conversely, assume that there exists an infinite sequence of deviations starting from  $\pi$ . Agents of the type  $r^s$  can perform at most one deviation joining the agent  $r$  if she is still in a singleton coalition. After this deviation, they land in a coalition that cannot be altered anymore. Therefore, agents of the type  $r$  for  $r \in R$  will never deviate, because they cannot receive positive utility, unless joining an agent of the type  $r^s$ , which will never leave her coalition with  $s_1$  unless joining  $r$ . Agents of the type  $s_1$  will never perform a deviation, because every agent that leaves her coalition can never be joined again, and the agent  $s_2$  can only perform a deviation by joining  $s_1$ . In turn, agents of the type  $s_2$  can only deviate if their copy  $s_1$  is forced into a singleton coalition. At this point, they can deviate exactly once, forming a coalition that can never be changed again.

Agents in  $C \setminus \{a_1\}$  can only perform a deviation after  $a_1$  has performed a deviation. Thus, the only possibility for an infinite length of deviations is if  $a_1$  performs a deviation. Since  $a_1$  cannot join the coalition of agents of the type  $s_2$  again, once they left her coalition, the only possible deviation is by joining the coalition  $\{b_1, c_1\}$ , obtaining a utility of 152. The utility of  $a_1$  for any subset  $C \subseteq \pi(a_1)$  that can arise as her coalition before she deviated for the first time is  $v_{a_1}(C) = \frac{h}{1+h}\alpha$  for  $h = C \cap \{s_2 : s \in S\}$ . It follows that  $a_1$  can only deviate once all except  $l$  agents of the type  $s_2$  have left her coalition. Now let  $\pi'$  be the partition right before the first deviation of  $a_1$  and define  $S' = \{s \in S : s_2 \in \pi'(s_1)\}$ . Then,  $S'$  consists of exactly  $|R|/3$  elements. The only way

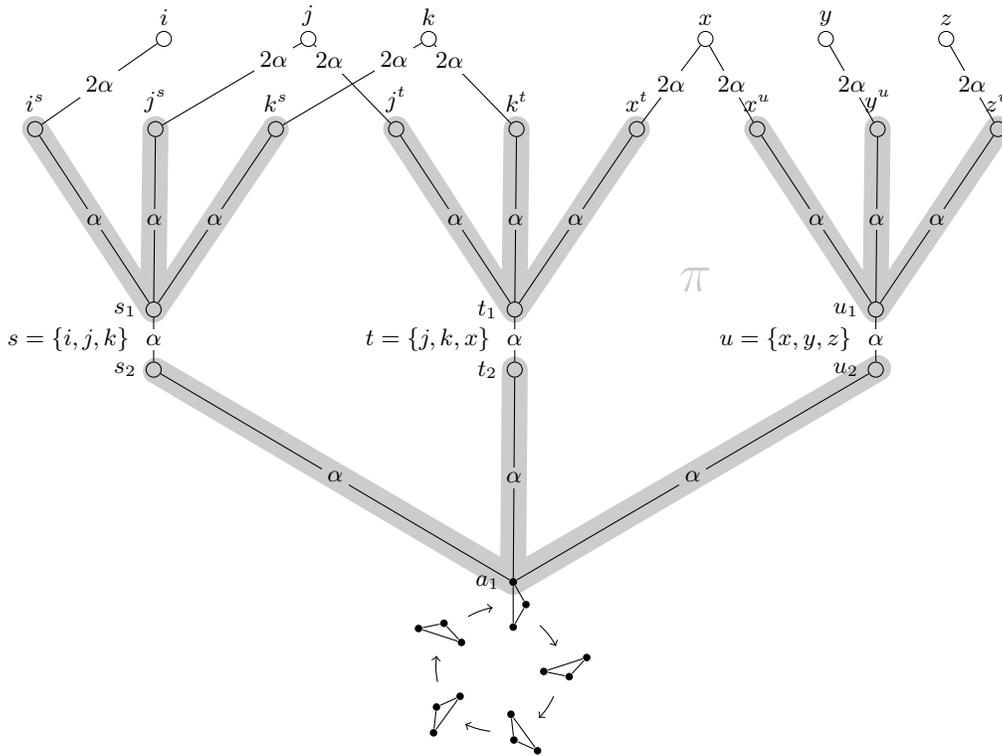


Figure 2: Schematic of the symmetric FHG of the hardness construction. The figure is based on the instance  $(\{i, j, k, x, y, z\}, \{\{i, j, k\}, \{j, k, x\}, \{x, y, z\}\})$ . The non-singleton coalitions above  $a_1$  of the initial partition  $\pi$  are depicted in gray. The only possibility for  $a_1$  to deviate is if two of  $s_2, t_2,$  or  $u_2$  perform a deviation, which in turn can only happen if the coalition partners of their respective partners  $s_1, t_1,$  or  $u_1$  have been deviating before.

that all except  $l$  agents of type  $s_2$  have left  $\pi(a_1)$  is if  $S'$  covers precisely the elements of  $R$ . Hence,  $S'$  forms a partition of  $R$ . Consequently,  $(R, S)$  is a ‘yes’-instance.  $\square$

**Proposition 5.4.** *The dynamics of IS-deviations starting from the singleton partition always converges to an IS partition in simple symmetric FHGs in at most  $\mathcal{O}(n^2)$  steps. The dynamics may take  $\Omega(n\sqrt{n})$  steps.*

*Proof.* We start with the lower bound. Consider the FHG induced by the complete graph on  $n(n+1)/2$  agents. We partition the agents arbitrarily into sets  $C_1, \dots, C_n$  where  $|C_j| = j$ . Now, we perform two phases of IS-deviations. In the first phase, we form the coalitions  $C_j$  by having agents join one by one. In the second phase, there are  $n-1$  steps. In step  $k$ , the agents of coalition  $C_k$  join coalitions  $C_{k+1}, \dots, C_n$  performing  $n-k$  deviations each. The total number of deviations in the second phase is therefore  $\sum_{k=1}^{n-1} k \cdot (n-k) = \frac{1}{6}(n-1)n(n+1)$ . The example shows that there can be  $\Omega(n\sqrt{n})$  IS-deviation steps starting from the singleton partition.

For the upper bound, let an FHG be given. Note that all coalitions formed through the deviation dynamics are cliques. Hence, every deviation step will increase the total number of edges in all coalitions. More precisely, the dynamics will increase the potential  $\Lambda(\pi) = \sum_{C \in \pi} |C|(|C| -$

$1)/2$  in every step by at least 1. Since the total number of edges is bounded by  $n(n-1)/2$ , this proves the upper bound.  $\square$

**Proposition 5.5.** *The dynamics of IS-deviations starting from the singleton partition converges in asymmetric FHGs if and only if the underlying graph is acyclic. Moreover, under acyclicity, it converges in  $\mathcal{O}(n^4)$  steps.*

*Proof.* Let  $G = (V, A)$  be an asymmetric graph on  $n = |V|$  vertices. If the graph contains a cycle, it is easy to find a non-converging series of deviations. There exists a cycle of length at least 3. Let an edge coalition propagate along the cycle.

Assume that the graph is acyclic. Our first observation is that, in every step of the dynamics, the subgraphs induced by coalitions are always transitive and complete, i.e., linear orders (on their vertices). By induction, in a deviation, the coalition that is left still induces a transitive and complete graph and the new coalition induced a transitive and complete graph before the deviation. Hence, every agent except one has at least one outgoing edge and will only accept the new agent if she likes her. Since the deviating agent must have non-negative utility after the deviation, she needs to approve the single agent without outgoing edge. Hence, the newly formed coalition still induces a transitive and complete graph.

We will now define two potentials based on the agents that receive 0 utility in a partition, and based on the coalition sizes. The first potential is monotonically increasing and bounded. The second potential is strictly increasing whenever the first potential is not strictly increasing, and bounded. Hence, we establish convergence of the dynamics.

First, fix a topological order of the agents, i.e., a bijection  $\sigma : V \rightarrow [n]$  such that for all  $(v, w) \in A$ ,  $\pi(v) < \pi(w)$ . For a given partition  $\pi$  of the agents, we define the vector  $v^\sigma(\pi)$  of length  $|\pi|$  that sorts the numbers  $\max_{i \in C} \sigma(i)$  for  $C \in \pi$  in decreasing order, that is it sorts the coalitions in decreasing topological score of the agent with the highest number due to the topological order. This is exactly the unique agent in every coalition receiving 0 utility. In addition, we define the vector  $w(\pi)$  of length  $|\pi|$  that sorts the coalition sizes in increasing order. Note that this vector does not depend on the underlying topological order.

For two vectors  $v = (v_i)_{i=1}^k$  and  $w = (w_i)_{i=1}^l$ , not necessarily of the same length, we say

$$\begin{aligned} v >_{lex} w &\iff \text{there is } i < \max\{k, l\} \text{ with} \\ &v_j = w_j \forall 1 \leq j \leq i \text{ and } v_{i+1} > w_{i+1}, \text{ or} \\ &k > l \text{ and } v_j = w_j \forall 1 \leq j \leq k \end{aligned}$$

In other words,  $v >_{lex} w$  if  $v$  is lexicographically greater than  $w$ .

The key insight is that, for  $\pi'$  formed from  $\pi$  by an IS deviation,  $v^\sigma(\pi') <_{lex} v^\sigma(\pi)$ , or  $v^\sigma(\pi') =_{lex} v^\sigma(\pi)$  and  $w(\pi') >_{lex} w(\pi)$ . For a proof, assume that  $\pi'$  is formed from  $\pi$  by an IS deviation of agent  $i$ . Note that  $\max_{j \in \pi'(i)} \sigma(j) = \max_{j \in \pi(i) \setminus \{i\}} \sigma(j)$ . We distinguish two cases. Either  $i = \arg \max_{j \in \pi(i)} \sigma(j)$  and it follows  $v^\sigma(\pi') <_{lex} v^\sigma(\pi)$ . Otherwise,  $v_i(\pi(i)) \geq \frac{1}{|\pi(i)|}$ , and because  $i$  is improving her utility,  $\frac{1}{|\pi'(i)|} = v_i(\pi') > \frac{1}{|\pi(i)|}$ . It follows that  $|\pi(i)| > |\pi'(i)|$ . Hence,  $|\pi'(i)| - 1 < \min\{|\pi'(i)|, |\pi(i)|\}$ , and therefore  $w(\pi') >_{lex} w(\pi)$ .

We estimate the running time in two steps. First, we bound the number of times that the lexicographic score of  $v^\sigma(\pi)$  can decrease. Then, we estimate the number of deviations that can happen while this score does not change. We call the first kind of deviations *primal* and the second type *secondary*.

The idea to bound the number of primal deviations is to associate with every agent  $v \in V$  a set  $D_v$  that stores a certain amount of deviating agents, so that at every step in the algorithm  $\sum_{v \in V} |D_v|$  is the number of primal deviations so far. We ensure that we can always add the agent  $v$  performing a deviation to a set  $D_w$  such that  $\sigma(v) > \sigma(x)$  for all  $x \in D_w$ . Hence, at the end of the sequence of deviations,  $\sum_{v \in V} |D_v| \leq n^2$ .

Initially, set  $D_v^{\pi_0} = \emptyset$  for all  $v \in V$  and the starting partition  $\pi_0$  of the dynamics. Assume first that agent  $v$  performs a primary deviation that changes partition  $\pi$  into partition  $\pi'$ . If  $v$  was in a singleton coalition, update  $D_v^{\pi'} = \{v\}$  and leave all other sets the same, i.e.,  $D_x^{\pi'} = D_x^\pi$  for all  $x \neq v$ . Otherwise, let  $w = \arg \max_{x \in \pi(v) \setminus \{v\}} \sigma(x)$  be the agent in  $\pi(v)$  different from  $v$  of highest topological score, i.e., the agent in  $\pi(v)$  of second-highest topological score. We up-

date  $D_v^{\pi'} = D_w^\pi \cup \{v\}$ ,  $D_w^{\pi'} = \emptyset$ , and  $D_x^{\pi'} = D_x^\pi$  for all  $x \neq v, w$ . If a secondary deviation is performed from  $\pi$  to  $\pi'$ , leave all sets the same, i.e.,  $D_x^{\pi'} = D_x^\pi$  for all  $x \in V$ .

Given a set of agents  $W \subseteq V$ , let  $m_W = \arg \max_{x \in W} \sigma(x)$  be the agent in  $W$  maximizing the topological score. We have the following invariants for every partition  $\pi$  during the heuristics and for every agent  $v \in V$ :

- If  $v = m_{\pi(v)}$ , then  $D_v^\pi = \emptyset$ .
- If  $v \neq m_{\pi(v)}$ , then  $\sigma(x) < \sigma(m_{\pi(v)})$  for all  $x \in D_v^\pi$ .
- The number of primal deviations of the dynamics until partition  $\pi$  is  $\sum_{v \in V} |D_v^\pi|$ .

The first and third invariants follow directly from the update rules, where we use that the agent newly added to a set has not been in this set due to the second invariant. The second invariant follows by induction, because if  $v$  performs a primal deviation from  $\pi$  to  $\pi'$ , then for all  $x \in D_v^{\pi'}$ ,  $\sigma(x) \leq \sigma(v) < \sigma(m_{\pi'(v)})$ , where the first inequality follows by induction and the second by the fact that the agent in  $\pi'(v)$  which gives positive utility to  $v$  has a higher topological score than  $v$ . Hence, there can be at most  $n^2$  primal deviations, because for the terminal partition  $\pi^*$  of the dynamics,  $\sum_{v \in V} |D_v^{\pi^*}| \leq n^2$ .

While the topological score is the same, there can be at most  $n^2$  secondary deviations, which follows from the same reasoning as in the proof of Proposition 5.4. Hence, together there are at most  $n^4$  deviations.  $\square$

In the previous proposition, it seems that there is still space for improvement of the bound on the running time, in particular due to the interplay of the two nested potentials.

**Theorem 5.6.**  $\exists$ -IS-SEQUENCE-FHG is NP-hard and  $\forall$ -IS-SEQUENCE-FHG is co-NP-hard, even in asymmetric FHGs.

We prove the two hardness results by providing separate reductions for each problem in the next two lemmas.

**Lemma C.3.**  $\exists$ -IS-SEQUENCE-FHG is NP-hard even in asymmetric FHGs.

*Proof.* We provide a reduction from exact 3-cover.

Let  $(R, S)$  be an instance of exact 3-cover. We may assume that every  $r \in R$  occurs in at least one set of  $S$ . Let  $m_r := |\{s \in S : r \in s\}| - 1 \geq 0$ , and  $l = |S| - |R|/3$ . Define the simple, asymmetric FHG based on the directed graph  $G = (V, A)$ , where  $V = \bigcup_{r \in R} \{r_1, \dots, r_{m_r}\} \cup S \cup \bigcup_{s \in S} \{r^s : r \in s\} \cup \bigcup_{v=1}^l \{a_1^v, a_2^v, a_3^v\}$  and  $A = \bigcup_{s \in S} \{(s, r^s), (r^s, r_1), \dots, (r^s, r_{m_r}) : r \in s\} \cup \{(s, a_1^1), \dots, (s, a_1^l)\} \cup \bigcup_{v=1}^l \{(a_1^v, a_2^v), (a_2^v, a_3^v), (a_3^v, a_1^v)\}$ . Finally, define  $\pi = \bigcup_{a \in V \setminus (S \cup \{r^s : s \in S, r \in s\})} \{a\} \cup \{\{s, i_1^s, j_1^s, k_1^s\} : \{i, j, k\} = s \in S\}$ . The reduction is illustrated in Figure 3. It depicts the asymmetric, directed graph corresponding to the instance  $(\{i, j, k, x, y, z\}, \{\{i, j, k\}, \{j, k, x\}, \{x, y, z\})$  together with the initial partition  $\pi$ .

We claim that  $(R, S)$  is a ‘yes’-instance if and only if the IS dynamics starting with  $\pi$  can converge.

Assume first that  $(R, S)$  is a ‘yes’-instance and let  $S' \subseteq S$  be a partition of  $R$  by sets in  $S$ . Consider the following

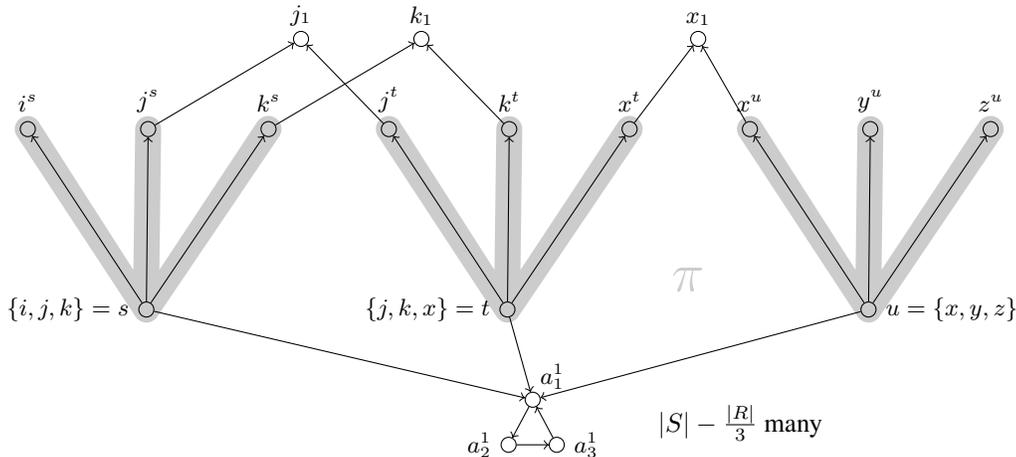


Figure 3: Schematic of the simple, asymmetric FHG of the hardness construction. The figure is based on the instance  $(\{i, j, k, x, y, z\}, \{\{i, j, k\}, \{j, k, x\}, \{x, y, z\}\})$ . The non-singleton coalitions of the initial partition  $\pi$  are depicted in gray.

deviations. First, the agents in the set  $\bigcup_{s \in S \setminus S'} \{r^s : r \in s\}$  join one by one the agents in  $\bigcup_{r \in R} \{r_1, \dots, r_{m_r}\}$  to end up in coalitions of size 2. Since  $S'$  covers every element of  $R$  exactly once, this step can be performed. Next, the agents  $\{s \in S \setminus S'\}$  join the agents  $\{a_1^1, \dots, a_l^1\}$  in an arbitrary bijective way. Finally, agents  $a_2^v$  join agents  $a_3^v$ . It is quickly checked that the resulting partition is IS.

Conversely, assume that there exists a converging sequence of deviations starting with the partition  $\pi_0$  and terminating in partition  $\pi^*$ . Then, one agent of every set  $\{a_1^v, a_2^v, a_3^v\}$  must form a coalition with an agent outside of this set. The only possibility for this is if  $a_1^v$  is joined by an agent corresponding to a set in  $S$ . Every such agent can only perform a deviation if all the other agents in her initial coalition have deviated before. Define  $S' = \{s \in S : \pi_0(s) = \pi^*(s)\}$ . It can only happen that  $3|S| - |R|$  agents corresponding to the sets in  $S \setminus S'$  deviate if  $S'$  forms a partition of  $R$ . Hence,  $(R, S)$  is a ‘yes’-instance.  $\square$

**Lemma C.4.**  $\forall$ -IS-SEQUENCE-FHG is co-NP-hard even in asymmetric FHGs.

*Proof.* For this purpose, we prove the NP-hardness of the complement problem, which asks whether there exists a cycle in IS-deviations. We provide a reduction from exact 3-cover.

Let  $(R, S)$  be an instance of exact 3-cover. We may assume that every  $r \in R$  occurs in at least one set of  $S$ . Let  $m_r := |\{s \in S : r \in s\}| - 1 \geq 0$ , and  $l = |R|/3$ . Define the simple, asymmetric FHG based on the graph  $G = (V, A)$ , where  $V = \{r_1, \dots, r_{m_r} : r \in R\} \cup \{r^s : s \in S, r \in s\} \cup \{s_1, s_2 : s \in S\} \cup \{b_1, b_2, b_3\} \cup \{a_1, \dots, a_l\}$ , and  $A = \bigcup_{s \in S} (\{(r^s, r_1), \dots, (r^s, r_{m_s}), (s_1, r^s) : r \in s\} \cup \{(s_1, s_2), (b_1, s_2)\}) \cup \{(a_v, b_1) : v = 1, \dots, l\} \cup \{(b_2, b_3), (b_3, b_1)\}$ . The reduction is illustrated in Figure 4. Finally, define  $\pi = \{\{r_1\}, \dots, \{r_{m_r}\} : r \in R\} \cup \{\{s_1, j^s, k^s\} : \{i, j, k\} = s \in S\} \cup \{\{b_1\} \cup \{s_2 : s \in S\} \cup \{a_1, \dots, a_l\}\} \cup \{\{b_2\}, \{b_3\}\}$ .

We claim that  $(R, S)$  is a ‘yes’-instance if and only if the IS dynamics starting with  $\pi$  can cycle.

First assume that  $(R, S)$  is a ‘yes’-instance and let  $S' \subseteq S$  be a partition of  $R$  by the sets in  $S$ . We consider three stages of deviations. In the first stage, the agents in a coalition with some  $s_1$  for  $s \notin S'$  join the agents of type  $r_v$ . This will leave all agents in  $\{s_1 : s \notin S'\}$  in singleton coalitions. In the second stage, agents  $s_2$  for  $s \notin S'$  join their copies  $s_1$ . This leaves the agent  $b_1$  with a utility of  $l/(2l+1) < \frac{1}{2}$ . Hence, we start cycling in the final stage by having  $b_1$  join  $b_2$ ,  $b_2$  join  $b_3$ ,  $b_3$  join  $b_1$ , and repeating these deviations.

Now, assume that there exists an infinite sequence of deviations starting from  $\pi$ . Agents of the type  $r_v$  for  $v = 1, \dots, m_r$  will never deviate, because they cannot receive positive utility. Agents of the type  $r^s$  for  $s \in S, r \in s$  can only deviate once to join an agent of the former type. Then, no agent can join their coalition, because the only agents  $r^s$  would allow cannot deviate. In addition,  $r^s$  can never improve her utility again. Hence, this coalition will stay the same for the remainder of the heuristics. Agents of the type  $s_1$  will never deviate, because they are initially in their best coalition, and every agent that leaves can never be joined again. Next, agents of the type  $s_2$  can only deviate if their copy  $s_1$  is forced into a singleton coalition. At this point, they can deviate exactly once, forming a coalition that can never be changed again.

Agents  $a_v$  can never deviate unless  $b$  leaves their coalition. Agents  $b_2$  and  $b_3$  can only be involved in a deviation at most once until  $b_1$  forms a coalition of her own or performs a deviation. Since  $b_1$  can never form a coalition of her own, the only possibility for an infinite length of deviations is if  $b_1$  performs a deviation. Since  $b_1$  cannot join the coalition of agents of the type  $s_2$  again, once they left her coalition, the only possible deviation is by joining the agent  $b_2$  obtaining a utility of  $\frac{1}{2}$ . The utility of  $b_1$  for any subset  $C \subseteq \pi(b_1)$  that can arise before she deviated for the first time is  $v_{b_1}(C) = \frac{h}{l+1+h}$  for  $h = C \cap \{s_2 : s \in S\}$ . It follows that  $b_1$  can only deviate once all except  $l$  agents

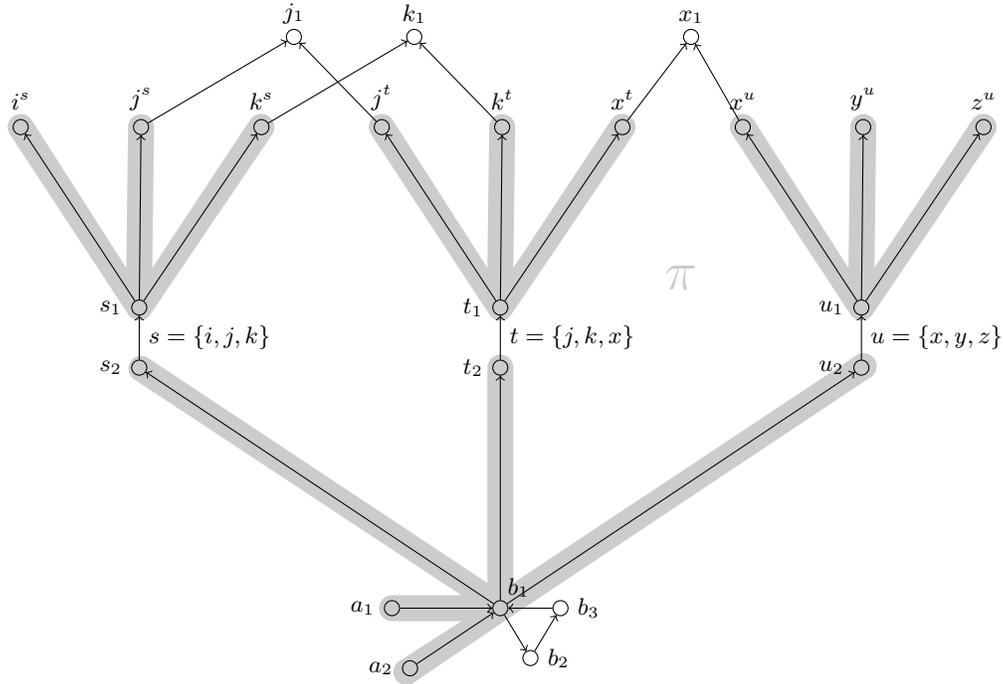


Figure 4: Schematic of the simple, asymmetric FHG of the hardness construction. The figure is based on the instance  $(\{i, j, k, x, y, z\}, \{\{i, j, k\}, \{j, k, x\}, \{x, y, z\}\})$ . The non-singleton coalitions of the initial partition  $\pi$  are depicted in gray. The only possibility for  $b_1$  to deviate is if one of  $s_2$ ,  $t_2$ , or  $u_2$  performs a deviation, which in turn can only happen if the coalition partners of her respective partner  $s_1$ ,  $t_1$ , or  $u_1$  have been deviating before.

of the type  $s_2$  have left her coalition. Now let  $\pi'$  be the partition right before the first deviation of  $b_1$  and define  $S' = \{s \in S : v_{s_1}(\pi') > 0\}$ . Then,  $S'$  consists of exactly  $|R|/3$  elements. The only way that all except  $l$  agents of type  $s_2$  have left  $\pi(b_1)$  is if  $S'$  covers precisely the elements of  $R$ . Hence,  $S'$  forms a partition of  $R$ . Consequently,  $(R, S)$  is a ‘yes’-instance.  $\square$

**Theorem 5.7.**  $\exists$ -IS-SEQUENCE-FHG is NP-hard even in simple FHGs when starting from the singleton partition.

*Proof.* The reduction is from exact 3-cover.

Let an instance  $(R, S)$  of exact 3-cover be given and set  $l = |S| - \frac{|R|}{3}$ . We construct the simple FHG induced by the following directed graph  $G = (V, A)$ . Let  $V = \{r_1, r_2, r_3 : r \in R\} \cup \{s_v^i : v = 1, 2, i \in s \text{ for } s \in S\} \cup \{t_v^w : v = 1, 2, 3, w = 1, \dots, l\}$  and edges given by  $A = \{(r_1, r_2), (r_2, r_3), (r_3, r_1) : r \in R\} \cup \{(r_1, s_1^r), (s_1^r, r_1) : r \in s \text{ for } s \in S\} \cup \{(s_1^i, s_2^i), (s_2^i, s_1^i) : i \in s \text{ for } s \in S\} \cup \{(t_1^w, t_2^w), (t_2^w, t_3^w), (t_3^w, t_1^w) : w = 1, \dots, l\} \cup \{(t_1^w, s_1^i) : w = 1, \dots, l, i \in s \text{ for } s \in S\}$ . The construction is illustrated in Figure 5. We define  $T^w = \{t_1^w, t_2^w, t_3^w\}$  for  $w = 1, \dots, l$ .

Assume first that there exists a 3-cover of  $R$  through sets in  $S$  and let  $S' \subseteq S$  be a set of 3-element sets partitioning  $R$ . Let  $\sigma : \{1, \dots, l\} \rightarrow S \setminus S'$  be a bijection and let  $\tau : R \rightarrow S'$  be the function defined by  $\tau(r) = s$  for the unique  $s \in S'$  with  $r \in s$ , i.e., the function that maps an element

of  $R$  to its partition class. We define the partition of agents  $\pi = \{\{r_2, r_3\}, \{r_1, \tau(r)_1^r\} : r \in R\} \cup \{\{t_1^w\} \cup \{\sigma(w)_1^i : i \in \sigma(w)\} : w = 1, \dots, l\} \cup \{\{s_2^i\} : s \in S\} \cup \{\{t_2^w, t_3^w\} : w = 1, \dots, l\}$ .

Note that  $\pi$  is IS. Agents of the type  $i_2$  or  $t_2^w$  are in their best coalitions. Agents of the type  $i_3, t_3^w$ , or  $s_2^i$  could only obtain positive utility by joining a coalition of which at least one agent would get worse if they joined. Agents of the type  $i_1$  or  $t_1^w$  cannot join another coalition that gives them positive utility because this would be blocked by an agent in that coalition. In particular,  $i_1$  cannot join a coalition  $\{t_1^i, t_1^j, t_1^k, \tau^{-1}(t)\}$  for  $t \in S \setminus S'$  with  $i \in t$ , because  $\tau^{-1}(t)$  blocks this. Similarly,  $t_1^w$  cannot join a coalition  $\{s_1^i, i_1\}$  for  $i \in R$  or a coalition  $\{t_1^x\} \cup \{\sigma(x)_1^i : i \in \sigma(x)\}$  for  $x \neq w$ , because this is blocked by  $i_1$  and  $t_1^x$ , respectively. Finally, agents of the type  $s_1^i$  obtain utility 1/2 and cannot join  $s_2^i$ . Any other deviation to a coalition that gives them positive utility is blocked. Hence,  $\pi$  is an IS partition of agents.

Note that  $\pi$  can be obtained by IS-deviations from the singleton partition by forming each of the coalitions in  $\pi$ . In particular, coalitions of the type  $\{t_1^w\} \cup \{\sigma(w)_1^i : i \in \sigma(w)\}$  are formed by letting  $t_1^w$  join  $\sigma(w)_1^i$  for an arbitrary  $i \in \sigma(w)$  and then the two  $\sigma(w)_1^j$  for  $j \in \sigma(w) \setminus \{i\}$  join one after another. This shows that we find a converging sequence if  $(R, S)$  is a ‘yes’-instance.

Conversely, assume that there exists an IS partition  $\pi$  of the agents that can be reached by IS-deviations starting from the singleton partition. We denote the sequence of partitions

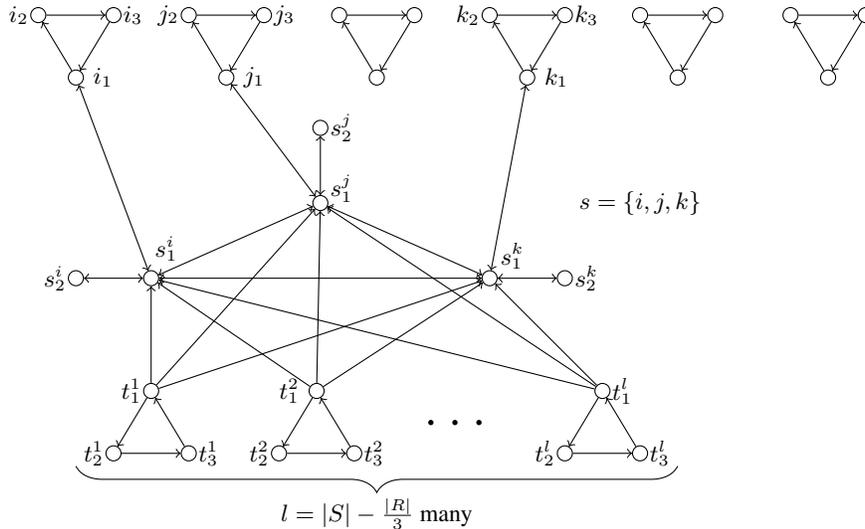


Figure 5: Schematic of the simple FHG of the hardness construction. Bidirected edges indicate a mutual utility of 1.

by  $\pi^0, \dots, \pi^l$  for some integer  $l$ , where  $\pi^0 = \{\{v\} : v \in V\}$  is the singleton partition,  $\pi^l = \pi$ , and partition  $\pi^{p+1}$  can be reached from partition  $\pi^p$  by an IS-deviation of agent  $z^p$  for  $0 \leq p \leq l-1$ .

We start with a technical invariant of the IS heuristics that turns out to be very useful in determining the structure of the coalitions that agents of the type  $r_1$  and  $t_1^w$  eventually will be part of.

To formulate the claim, denote  $S_1 = \{s_1^i : i \in s \text{ for } s \in S\}$  and denote  $\mathcal{N} = \{r_1 : r \in R\} \cup \{t_1^w : w = 1, \dots, l\} \cup \{s_2^i : i \in s \text{ for } s \in S\}$ . The set  $\mathcal{N}$  contains precisely the agents that have a directed edge to or from an agent in  $S_1$ , i.e. the outgoing and incoming neighbors of agents in  $S_1$ . We simultaneously pose the following claims for  $0 \leq p \leq l$ :

- $\pi^p(r_3) \subseteq V^r$  for  $r \in R$ ,
- $\pi^p(r_2) \subseteq V^r$  or  $\pi^p(r_2) \subseteq \{r_1, r_2\} \cup \{s_1^i : s \in S, r \in s\}$  for  $r \in R$ ,
- $\pi^p(t_1^w) \subseteq T^w$  for  $v = 1, 2, w = 1, \dots, l$ ,
- $V^r, T^w \not\subseteq \pi^l$  for  $r \in R$  and  $w = 1, \dots, l$ ,
- $\pi^p(s_2^i) \subseteq \{s_1^i, s_2^i\}$  for  $s \in S, i \in s$ ,
- $\pi^p(a) \cap \mathcal{N} = \{a\}$ , for  $a \in \mathcal{N}$ , and
- $\pi^p(a) \cap S_1 \neq \emptyset$  implies  $v_a(\pi^p) > 0$ , for  $a \in \mathcal{N}$ .

The claim is initially true for the singleton partition  $\pi^0$ . Assume that it holds after iteration  $p$  for  $0 \leq p \leq l-1$ . Consider the agent  $z^p$  that performs the IS-deviation to reach  $\pi^{p+1}$ . If  $z^p \notin S_1 \cup \mathcal{N}$ , the claim holds for  $p+1$ , because these agents can only join the coalition with agents in their 3-cycle and if they want to join the coalition of an agent in  $\mathcal{N}$ , this agent will block it if she already forms a coalition with an agent in  $S_1$ . If  $z^p \in \mathcal{N}$ , she will only deviate if she receives positive utility afterwards. The claim is true by induction if this positive utility comes from an agent outside  $S_1$ . Otherwise, she joins the coalition of  $x \in S_1$ . Then,  $\pi^l(x) \cap \mathcal{N} = \emptyset$ , because every agent  $y \in \pi^l(y) \cap \mathcal{N}$  would block the inclusion of agent  $z^p$  (by the final claim). In addition, since  $y^s$  is the deviating agent, she will receive positive utility after

this deviation. Hence, all claims hold. Finally, if  $z^p \in S_1$ , she joins an agent in  $\mathcal{N}$  (otherwise she would not receive positive utility in  $\pi^{p+1}$ ). If she joins an agent of type  $s_2^i$ , the claim follows, because by induction  $\{s_2^i\} \in \pi^p$ . If she joins an agent of type  $i_1$  where  $i \in s$ , then  $i_3 \notin \pi^l(i^1)$  (this agent would block the change). Hence, the claim for the agent  $i_2$  follows by induction. In addition, the claim for the agent  $i_1$  follows because no agent from  $\mathcal{N}$  joins and she receives positive utility through  $s_1^i$  afterwards. Other IS-deviations for the agents in  $S_1$  are not possible. Together, the claims are established. In particular, they all hold for the IS partition  $\pi$ .

We apply the claims to show that for every  $w \in \{1, \dots, l\}$ , there exists a  $s \in S$  and  $i \in s$  with  $s_1^i \in \pi(t_1^w)$ . Otherwise,  $\pi(t_1^w) \subseteq T^w$  for  $v = 1, 2, 3$  and  $T^w \notin \pi$ . Hence,  $\pi$  is not IS.

Now, fix  $w \in \{1, \dots, l\}$  and let  $s \in S$  and  $i \in s$  with  $s_1^i \in \pi(t_1^w)$ . We claim that  $\pi(t_1^w) = \{t_1^w\} \cup \{s_1^j : j \in s\}$ . By the claims,  $\pi(t_1^w) \subseteq \{t_1^w\} \cup S_1$ . Under this condition,  $v_{s_1^i}(\pi) \leq \frac{1}{2}$  and  $v_{s_1^i}(\pi) = \frac{1}{2}$  only if  $\pi(t_1^w) = \{t_1^w\} \cup \{s_1^j : j \in s\}$ . Note that  $\{s_2^i\} \in \pi$ . Hence,  $v_{s_1^i}(\pi) \geq \frac{1}{2}$  since otherwise  $\pi$  is not IS. Hence the claim follows.

Define  $S' = S \setminus \{s \in S : t_1^w \in \pi(s_1^i) \text{ for } i \in s\}$ . The coalitions of type  $\{t_1^w\} \cup \{s_1^j : j \in s\}$  imply that  $|S'| = |S| - (|S| - |R|/3) = |R|/3$ .

By the above claims, for every  $r \in R$ , there exists  $s \in S$  with  $r \in s$  and  $s_1^r \in \pi(r_1)$ . In particular,  $s \in S'$ . Hence,  $\bigcup_{s \in S'} s = R$  and since  $|S'| = |R|/3$  and  $|s| = 3$  for all  $s \in S'$ , the sets in  $S'$  must be disjoint. Hence,  $(R, S)$  is a 'yes'-instance.  $\square$

## D Dichotomous Hedonic Games (DHG)

**Theorem 6.2.**  $\exists$ -IS-SEQUENCE-DHG is NP-hard even when starting from the singleton partition, and  $\forall$ -IS-SEQUENCE-DHG is co-NP-hard.

We prove the two hardness results by providing separate

reductions for each problem in the next two lemmas.

**Lemma D.1.**  $\exists$ -IS-SEQUENCE-DHG is NP-hard even when starting from the singleton partition.

*Proof.* Let us perform a reduction from (3,B2)-SAT (Berman, Karpinski, and Scott 2003). In an instance of (3,B2)-SAT, we are given a CNF propositional formula  $\varphi$  where every clause  $C_j$ , for  $1 \leq j \leq m$ , contains exactly three literals and every variable  $x_i$ , for  $1 \leq i \leq p$ , appears exactly twice as a positive literal and twice as a negative literal. From such an instance, we construct an instance of a dichotomous hedonic game with initial partition as follows.

For each clause  $C_j$ , for  $1 \leq j \leq m$ , we create a clause-agent  $k_j$  and agents  $k_j^2$  and  $k_j^3$ . For each variable  $x_i$ , for  $1 \leq i \leq p$ , we create a variable-agent  $v_i$  and agents  $v_i^2$  and  $v_i^3$ . The agents  $k_j^2$  and  $k_j^3$  (resp.,  $v_i^2$  and  $v_i^3$ ) are used to form a gadget involving clause-agent  $k_j$  (resp., variable-agent  $v_i$ ) to reproduce the counterexample provided in the proof of Proposition 6.1. For each  $\ell^{\text{th}}$  occurrence ( $\ell \in \{1, 2\}$ ) of a positive literal  $x_i$  (resp., negative literal  $\bar{x}_i$ ), we create a literal-agent  $y_i^\ell$  (resp.,  $\bar{y}_i^\ell$ ). The initial partition  $\pi_0$  is the singleton partition, i.e., every agent is initially alone. The approved coalitions of the agents are described in the table below for every  $1 \leq j \leq m$ ,  $1 \leq i \leq p$  and  $\ell \in \{1, 2\}$ , where  $lit_j^r$  denotes the literal-agent associated with the  $r^{\text{th}}$  literal of clause  $C_j$  ( $1 \leq r \leq 3$ ) and  $cl(x_i^\ell)$  (resp.,  $cl(\bar{x}_i^\ell)$ ) denotes the index of the clause to which literal  $x_i^\ell$  (resp.,  $\bar{x}_i^\ell$ ) belongs. All the coalitions that are not mentioned are disapproved by the agents.

Agents	Approved coalitions
$k_j$	$\{k_j, lit_j^1\}, \{k_j, lit_j^2\}, \{k_j, lit_j^3\}, \{k_j, k_j^2\}$
$v_i$	$\{v_i, y_i^1, y_i^2\}, \{v_i, \bar{y}_i^1, \bar{y}_i^2\}, \{v_i, v_i^2\}$
$y_i^\ell$	$\{y_i^\ell, y_i^{3-\ell}\}, \{y_i^\ell, y_i^{3-\ell}, v_i\}, \{y_i^\ell, k_{cl(x_i^\ell)}\}$
$\bar{y}_i^\ell$	$\{\bar{y}_i^\ell, \bar{y}_i^{3-\ell}\}, \{\bar{y}_i^\ell, \bar{y}_i^{3-\ell}, v_i\}, \{\bar{y}_i^\ell, k_{cl(\bar{x}_i^\ell)}\}$
$k_j^2$	$\{k_j^2, k_j^3\}$
$k_j^3$	$\{k_j^2, k_j^3\}$
$v_i^2$	$\{v_i^2, v_i^3\}$
$v_i^3$	$\{v_i^2, v_i^3\}$

We claim that there exists a sequence of IS-deviations ending in an IS partition iff formula  $\varphi$  is satisfiable.

Suppose first that there exists a truth assignment of the variables  $\phi$  such that formula  $\varphi$  is satisfiable. Let us denote by  $\ell_j$  a chosen literal-agent associated with an occurrence of a literal true in  $\phi$  which belongs to clause  $C_j$ . Since all the clauses of  $\varphi$  are satisfied by  $\phi$ , there exists such a literal-agent  $\ell_j$  for each clause  $C_j$ . Now let us denote by  $z_i^1$  and  $z_i^2$  the literal-agents associated with the two occurrences of the literal of variable  $x_i$  which is false in  $\phi$ . Since  $\phi$  is a truth assignment of the variables that satisfies all the clauses of formula  $\varphi$ , it holds that  $\bigcup_{1 \leq j \leq m} \{\ell_j\} \cap \bigcup_{1 \leq i \leq p} \{z_i^1, z_i^2\} = \emptyset$ . Let us consider the following sequence of IS-deviations starting from the singleton partition where every agent has utility 0:

- For every  $1 \leq j \leq m$ , literal-agent  $\ell_j$  joins clause-agent  $C_j$ , which makes both agents happier since they now belong to an approved coalition;
- For every  $1 \leq i \leq p$ , literal-agent  $z_i^1$  joins literal-agent  $z_i^2$ , which makes both agents happier since they now belong to an approved coalition (they correspond to two occurrences of the same literal), and then variable-agent  $v_i$  joins them, which makes  $v_i$  happier without deteriorating the satisfaction of agents  $z_i^1$  and  $z_i^2$ ;
- For every two agents  $y_i^1$  and  $y_i^2$  (resp.,  $\bar{y}_i^1$  and  $\bar{y}_i^2$ ) who were not involved in the previous deviations (i.e., literal  $x_i$  (resp.,  $\bar{x}_i$ ) is true in  $\phi$  but the two occurrences of this literal have not been used for satisfiability of formula  $\varphi$ ), literal-agent  $y_i^1$  joins literal-agent  $y_i^2$ , which makes both agents happier since they now belong to an approved coalition;
- For every  $1 \leq j \leq m$ , agent  $k_j^2$  joins agent  $k_j^3$ , which makes agent  $k_j^2$  happier and does not deteriorate the satisfaction of agent  $k_j^3$  who still belongs to a disapproved coalition;
- For every  $1 \leq i \leq p$ , agent  $v_i^2$  joins agent  $v_i^3$ , which makes agent  $v_i^2$  happier and does not deteriorate the satisfaction of agent  $v_i^3$  who still belongs to a disapproved coalition.

We claim that the resulting partition is IS. Observe that the only dissatisfied agents (who are the only ones who would have an incentive to still perform an IS-deviation) are the literal-agents who remained alone, agents  $k_j^3$  for every  $1 \leq j \leq m$  and agents  $v_i^3$  for every  $1 \leq i \leq p$ . The only better coalition for agent  $k_j^3$  is the one she would form with only clause-agent  $k_j$ . However, there is no clause-agent  $k_j$  still alone since all the clauses are satisfied by truth assignment  $\phi$ . The only better coalition for agent  $v_i^3$  is the one she would form with only variable-agent  $v_i$ . However, there is no variable-agent  $v_i$  still alone since  $\phi$  is a truth assignment of all variables. For remaining literal-agents, they must correspond to a true literal in  $\phi$  for which the literal-agent associated with the other occurrence of the literal already forms a pair with a clause-agent. Therefore, they cannot join this other literal-agent. Moreover, they cannot join their associated clause-agent because she is not alone anymore. Hence, there is no IS-deviation from this partition, which is then IS.

Suppose now that there does not exist a truth assignment of the variables that satisfies all the clauses of formula  $\varphi$ . Observe that if a clause-agent  $k_j$  does not form a coalition with one of the literal-agents associated with the literals of her clause, then there will be a cycle among the agents  $k_j$ ,  $k_j^2$  and  $k_j^3$ , as described in the proof of Proposition 6.1. Additionally, if a variable-agent  $v_i$  does not form a coalition with either  $y_i^1$  and  $y_i^2$  or  $\bar{y}_i^1$  and  $\bar{y}_i^2$ , then there will be a cycle among the agents  $v_i$ ,  $v_i^2$  and  $v_i^3$ , as described in the proof of Proposition 6.1. Therefore, since there is no possibility to find a truth assignment of the variables which satisfies all the clauses, we necessarily get a cycle in a sequence of IS-deviations starting from the singleton partition.  $\square$

**Lemma D.2.**  $\forall$ -IS-SEQUENCE-DHG is co-NP-hard.

*Proof.* For this purpose, we prove the NP-hardness of the

complement problem, which asks whether there exists a cycle in IS-deviations. Let us perform a reduction from the SATISFIABILITY problem which asks the satisfiability of a CNF propositional formula  $\varphi$  given by a set of clauses  $C_1, \dots, C_m$  over variables  $x_1, \dots, x_p$ . We construct an instance of a dichotomous hedonic game with initial partition as follows.

For each clause  $C_j$ , for  $1 \leq j \leq m$ , we create two clause-agents  $k_j$  and  $k'_j$ . Let us denote by  $p_i^+$  (resp.,  $p_i^-$ ) the number of positive (resp., negative) literals of variable  $x_i$  in formula  $\varphi$ . For each  $k^{\text{th}}$  occurrence of literal  $x_i$  (resp.,  $\bar{x}_i$ ) of variable  $x_i$ , we create a literal-agent  $y_i^k$  (resp.,  $\bar{y}_i^k$ ). The initial partition is given by  $\pi^0 := \{\{x_i^1, \dots, x_i^{p_i^+}, \bar{x}_i^1, \dots, \bar{x}_i^{p_i^-}\}_{1 \leq i \leq p}, \{k_j, k'_j\}_{1 \leq j \leq m}\}$ . The dichotomous preferences of the agents over the coalitions to which they belong are summarized below.

- Each literal-agent  $y_i^k$  (resp.,  $\bar{y}_i^k$ ), for  $1 \leq i \leq p$  and  $1 \leq k \leq p_i^+$  (resp.,  $1 \leq k \leq p_i^-$ ), gives utility 1 to the coalitions where agent  $k'_j$  belongs, where  $k'_j$  refers to the clause  $C_j$  to which the  $k^{\text{th}}$  occurrence of literal  $x_i$  (resp.,  $\bar{x}_i$ ) belongs, and to all coalitions only composed of literal-agents associated with variable  $x_i$  where some literal-agents associated with  $\bar{x}_i$  (resp.,  $x_i$ ) are missing. All the other coalitions are valued 0.
- Each clause-agent  $k_j$ , for  $1 \leq j \leq m$ , only gives utility 1 to the coalitions which contain clause-agent  $k'_{j+1}$  and one literal-agent associated with a literal belonging to clause  $C_{j+1}$  (where  $m+1$  refers to 1). All the other coalitions are valued 0.
- Each clause-agent  $k'_j$ , for  $1 \leq j \leq m$ , only gives utility 1 to the coalitions which contain agent  $k_j$ . All the other coalitions are valued 0.

We claim that there exists a cycle of IS-deviations iff formula  $\varphi$  is satisfiable.

Suppose first that formula  $\varphi$  is satisfiable by a truth assignment of the variables denoted by  $\phi$ . For each clause  $C_j$ , for  $1 \leq j \leq m$ , we choose a literal-agent  $y_i^k$  (resp.,  $\bar{y}_i^k$ ) such that the  $k^{\text{th}}$  occurrence of literal  $x_i$  (resp.,  $\bar{x}_i$ ) belongs to clause  $C_j$  and literal  $x_i$  (resp.,  $\bar{x}_i$ ) is true in  $\phi$ . By satisfiability of formula  $\varphi$ , there always exists such a literal-agent. Then, literal-agent  $y_i^k$  (resp.,  $\bar{y}_i^k$ ) deviates from her coalition of literal-agents associated with variable  $x_i$  to coalition  $\{k_j, k'_j\}$ . This deviation is beneficial for the literal-agent because she values her new coalition with utility 1 since  $k'_j$  belongs to it and her old coalition with utility 0 since no literal-agent associated with her opposite literal has left the coalition of literal-agents associated with variable  $x_i$  (we have chosen only literal-agents associated with literals true in  $\phi$ ). Moreover, this deviation does not decrease the utility of the agents of the joined coalition: agent  $k'_j$  still values the coalition with utility 1 since agent  $k_j$  belongs to it and agent  $k_j$  still values the coalition with utility 0. Therefore, this deviation is an IS-deviation. After all these deviations, we reach a partition  $\pi$  which contains the coalitions  $\{k_j, k'_j, \ell_j\}$  for every  $1 \leq j \leq m$ , where  $\ell_j$  denotes a literal-agent associated with a literal true in  $\phi$  which belongs to clause  $C_j$ . Then, for each  $1 \leq j \leq m$ , by increas-

ing order of the indices, clause-agent  $k_j$  deviates to coalition  $\{k_{j+1}, k'_{j+1}, \ell_{j+1}\}$  (where  $m+1$  refers to 1). This deviation is beneficial for clause-agent  $k_j$  since she deviates to a coalition containing  $k'_{j+1}$  and a literal-agent associated with a literal belonging to clause  $C_{j+1}$ . Moreover, this deviation does not hurt the joined coalition: literal-agent  $\ell_{j+1}$  still values the coalition with utility 1 since agent  $k'_{j+1}$  belongs to it, clause-agent  $k'_{j+1}$  still values the coalition with utility 1 since agent  $k_{j+1}$  belongs to it and clause-agent  $k_{j+1}$  still values the coalition with utility 0. Therefore, this deviation is an IS-deviation. However, when clause-agent  $k_j$  has left her old coalition, this old coalition becomes either  $\{k'_j, \ell_j\}$  if  $j = 1$  or  $\{k'_j, \ell_j, k_{j-1}\}$  otherwise. Therefore, this deviation hurts clause-agent  $k'_j$  from the old coalition. After all these deviations, we reach a partition which contains the coalitions  $\{k_j, k'_{j+1}, \ell_{j+1}\}$  for every  $1 \leq j \leq m$  (where  $m+1$  refers to 1). At this point, for each  $1 \leq j \leq m$ , by increasing order of the indices, clause-agent  $k'_j$  deviates to coalition  $\{k_j, k'_{j+1}, \ell_{j+1}\}$  (where  $m+1$  refers to 1), in order to recover utility 1 by belonging to the same coalition as clause-agent  $k_j$ . This deviation does not hurt the joined coalition because literal-agent  $\ell_{j+1}$  still values the coalition with utility 1 since agent  $k'_{j+1}$  belongs to it, clause-agent  $k'_{j+1}$  still values the coalition with utility 0 since clause-agent  $k_{j+1}$  has previously left the coalition (in the previous “round” of deviations) and clause-agent  $k_j$  still values the coalition with utility 1 since agents  $k'_{j+1}$  and  $\ell_{j+1}$  belong to it. Therefore, this deviation is an IS-deviation. However, when clause-agent  $k'_j$  has left her old coalition, this old coalition becomes either  $\{k_{j-1}, \ell_j\}$  if  $j = 1$  or  $\{k_{j-1}, k'_{j-1}, \ell_j\}$  otherwise. Therefore, this deviation hurts clause-agent  $\ell_j$  from the old coalition. After all these deviations, we reach a partition which contains the coalitions  $\{k_j, k'_j, \ell_{j+1}\}$  for every  $1 \leq j \leq m$  (where  $m+1$  refers to 1). At this point, for each  $1 \leq j \leq m$ , by increasing order of the indices, literal-agent  $\ell_j$  deviates to coalition  $\{k_j, k'_j, \ell_{j+1}\}$ , in order to recover utility 1 by belonging to the same coalition as clause-agent  $k'_j$ . This deviation does not hurt the joined coalition because literal-agent  $\ell_{j+1}$  still values the coalition with utility 0 since agent  $k'_{j+1}$  does not belong to it, clause-agent  $k_j$  still values the coalition with utility 0 since agent  $k'_{j+1}$  does not belong to it, and clause-agent  $k'_j$  still values the coalition with utility 1 since agent  $k_j$  belongs to it. Therefore, this deviation is an IS-deviation. After all these deviations, we reach again partition  $\pi$  and thus there is a cycle in the sequence of IS-deviations.

Suppose now that there exists a cycle of IS-deviations. From  $\pi^0$ , no clause-agent has incentive to deviate: each clause-agent  $k'_j$  already values her current coalition with utility 1 since agent  $k_j$  belongs to it, and each clause-agent  $k_j$  values her current coalition with utility 0 but there is no coalition containing both agent  $k'_{j+1}$  and a literal-agent associated with a literal belonging to clause  $C_{j+1}$ . Therefore, some literal-agents must deviate and leave their initial coalition, that they value with utility 0 since no literal-agent has left it yet. Observe that once a literal-agent associated with variable  $x_i$  has left her initial coalition, no literal-agent associated with the opposite literal can leave the coalition

because she values it with utility 1. If a literal-agent deviates, this is for joining coalition  $\{k_j, k'_j\}$  where clause  $C_j$  refers to the clause where her associated literal occurrence appears. After such a deviation which is an IS-deviation because it does not decrease the utility of the members of the joined coalition, the only agents with incentive to deviate are clause-agents  $k_j$  if a literal-agent  $\ell_{j+1}$  has joined coalition  $\{k_{j+1}, k'_{j+1}\}$ . Suppose that there exists a clause coalition  $\{k_j, k'_j\}$  such that no literal-agent has joined it. Then, consider a clause index  $j$  such that no literal-agent has joined coalition  $\{k_{j+1}, k'_{j+1}\}$  and a clause index  $j'$  such that for all clause coalitions  $\{k_r, k'_r\}$ , with  $j' \leq r \leq j$ , a literal-agent  $\ell_r$  has joined the coalition but this is not the case for coalition  $\{k_{j'-1}, k'_{j'-1}\}$  ( $m+1$  refers to 1, and 0 to  $m$ ). Then, by progressive IS-deviations, all agents belonging to clause coalitions from  $j'$  to  $j$  will deviate for joining coalition  $\{k_j, k'_j\}$ . Indeed, clause-agent  $k_{j'}$  will deviate to coalition  $\{k_{j'+1}, k'_{j'+1}, \ell_{j'+1}\}$ , and then clause-agent  $k'_{j'}$  will follow her in this coalition, and then literal-agent  $\ell_{j'}$  will also follow  $k'_{j'}$  in this coalition. But agent  $k_{j'+1}$  has incentive to do the same for coalition  $\{k_{j'+2}, k'_{j'+2}, \ell_{j'+2}\}$ , which leads agents  $k'_{j'+2}$  and  $\ell_{j'+2}$  to follow her, as well as agents  $k_{j'}$ ,  $k'_{j'}$  and  $\ell_{j'}$ . This process of IS-deviations then continues in the same way until all these agents group in coalition  $\{k_j, k'_j, \ell_j\}$ . However, since clause-agent  $k_j$  can never leave this coalition (there is no coalition containing both agent  $k'_{j+1}$  and a literal-agent associated with a literal belonging to clause  $C_{j+1}$ ), no other agent will leave this coalition neither. We will therefore reach a stable state, a contradiction. It follows that each clause coalition  $\{k_j, k'_j\}$ , for  $1 \leq j \leq m$ , must be joined by a literal-agent  $\ell_j$  associated with a literal belonging to clause  $C_j$ . Therefore, by setting to true the literals associated with literal-agents who have joined clause coalitions (we have previously said that no two literal-agents associated with opposite literals can both leave their initial coalition), we get a truth assignment of the variables which satisfies all the clauses of formula  $\varphi$ .  $\square$