Partitioning Friends Fairly

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Abstract

We consider the problem of partitioning n agents in an undirected social network into k almost equal in size (differing by at most one) groups, where the utility of an agent for a group is the number of her neighbors in the group. The core and envy-freeness are two compelling axiomatic fairness guarantees in such settings. The former demands that there be no coalition of agents such that each agent in the coalition has more utility for that coalition than for her own group, while the latter demands that no agent envy another agent for the group they are in. We provide (often tight) approximations to both fairness guarantees, and many of our positive results are obtained via efficient algorithms.

1 Introduction

The computer science department at University X is organizing a visit day for its newly admitted students. One of the most anticipated activity is the campus tour, during which the admitted students get to see the department they might one day join. Due to COVID-19 related capacity restrictions, the admitted students are divided into k separate tours. But more tours means the need for more volunteers. Luckily, n current graduate students have volunteered to help lead the tours. We want to partition them almost equally between the k tours so that all the admitted students have equal opportunity to socialize with the current students. However, the current students have developed friendships during their time at the university. We would like to ensure that each volunteer is assigned to a tour with as many of their friends as possible, so they have a good experience and will want to volunteer again next year.

In this paper, we introduce and study a model that captures such real-life applications. Specifically, we consider the problem of partitioning n agents into k almost equal-sized groups (each with size either $\lfloor n/k \rfloor$ or $\lceil n/k \rceil$), when the agents are connected via an undirected social network indicating *friendships*. An agent's utility for being part of a group is the number of her friends who are in that group.

Formally, this model sits within the *hedonic games* formalism in cooperative game theory with nontransferable utilities (Aziz and Savani 2016). Two compelling axiomatic guarantees that have received significant attention in this literature are *the core* (Gillies 1953), which informally requires that there be no *deviating coalition* of agents such that each agent in the coalition has strictly more utility for the coalition than for her group in the given partition, and *envy-freeness* (George and Marvin 1958), which informally requires that no agent receive strictly more utility when swapping places with another agent in the given partition. However, this literature typically does not impose any restriction on the partition (including on the number of groups it has). This would make our problem trivial because the grand coalition — a single group containing all agents — would trivially satisfy both the core and envy-freeness requirements. To study the core and envy-freeness meaningfully, this literature allows agents to have negative utility for other agents. We are interested in the case where the utilities are non-negative, but we require there to be exactly k groups and the groups to be of approximately equal sizes.[1]

This problem can be viewed as a multi-dimensional generalization of the *stable roommates problem* (Irving 1985), in which the goal is to partition $2n$ agents between n rooms of capacity 2 each, and agents have preferences over who they wish to have as a roommate. The core becomes a notion of stability: if a pair of agents prefer each other to their assigned roommates, they may actually deviate and rent a room by themselves. But the core has also been studied in contexts where groups cannot really deviate, such as allocation of public resources (Aziz et al. 2017; Fain, Munagala, and Shah 2018; Conitzer et al. 2019) and clustering (Chen et al. 2019; Micha and Shah 2020). In such cases, it serves as a notion of *group fairness*, generalizing *proportionality* (Steinhaus 1948), because it posits that each set of $\lfloor n/k \rfloor$ or $\lceil n/k \rceil$ agents is entitled to be a group on its own and demands that the agents in the set be treated no worse than if they were their own group. Envy-freeness, on the other hand, serves as a notion of *individual fairness* and requires that no agent envy another agent for the group they belong to.

Our Results

For the core, we study bicriteria approximations of the form (α, β)-core, where a deviating coalition must improve the utility of each of its members by more than a multiplicative

[1]In Section 5, we briefly consider imposing only the former restriction, allowing k arbitrarily-sized non-empty groups.

factor of α and an additive factor of β.[2]

We begin with the most well-studied case of $k = 2$. We show that the $(2, 0)$-core is non-empty, and a 2-partition in the $(3, 0)$-core can be found in polynomial time. For larger k, we note that a k-partition in the $(1, k)$-core always exists when $n < k^2 + k$ and provide a lower bound proving that this guarantee is asymptotically the best possible with respect to an additive approximation. We show that a finite multiplicative approximation of the core is possible in general, but when $n \geqslant k^2 + k$, a min k-cut (a k-partition minimizing the so-called "cut size") is in the $(2k - 1, 0)$-core. While finding a min k-cut is known to be NP-hard, we present a polynomial-time algorithm that finds a (different) partition with the same approximation guarantee. We also show that min k-cuts cannot provide an asymptotically better approximation guarantee (i.e., our analysis is almost tight), and conjecture that no algorithm can.

For envy-freeness, we consider a similar additive approximation, EF-r, where an agent's utility must not increase by more than r when swapping places with another agent. We make a connection to discrepancy theory (Chen et al. 2014) to show that a EF-$O(\sqrt{\frac{n}{k}} \cdot \log k)$ partition always exists, and it can be computed efficiently. We conjecture that a EF-2 partition may always exists for any k.

Finally, in Section 5, we consider a classical variation of our model, where the only requirement is to create k non-empty groups but the groups can be of arbitrary sizes. We study both the core and envy-freeness in this case and provide several tight approximation bounds.

Related Work

Our work can be viewed as a hedonic game with symmetric, binary, and additively separable preferences, and with the restriction that the partition produced have exactly k almost equal-sized parts. Hedonic games with restrictions on the number of groups have been studied before, but under other objectives, such as swap stability (Bilò, Monaco, and Moscardelli 2022), Pareto optimality (Cseh, Fleiner, and Harján 2019), and an alternative variant of the core (Sless et al. 2018). As noted in the introduction, our model is a generalization of the stable roommates problem of partitioning $2n$ agents into n pairs, where the widely studied notion of stability coincides with the core. In this problem, with asymmetric preferences a solution in the core does not always exist — unlike in the bipartite version, referred to as the *stable marriage problem*, in which it is guaranteed to exist (Gale and Shapley 1962) — but can be found in polynomial time when it does (Irving 1985). When preferences are symmetric, however, a solution in the core always exists and can be found efficiently; for instance, one can repeatedly match and remove a pair of agents with the highest utility. The three-dimensional version of this problem — partitioning $3n$ agents into groups of size 3 each — has also received significant attention. In this case, even with symmetric additive preferences, a solution in the core may not exist (Arkin et al. 2009), and checking whether it does is NP-hard (Chen and Roy 2021). However, if we further restrict the preferences to be binary, then McKay and Manlove (2021) show that a solution in the core always exists and can be found efficiently. Our problem can be seen as a multidimensional generalization of the roommate problem with symmetric binary additive preferences.

Envy-freeness has been studied recently in the hedonic games literature (Peters 2016; Barrot and Yokoo 2019), again with possibly negative utilities. Another concept similar to envy-freeness is *Nash-stability* (Bogomolnaia and Jackson 2002; Olsen, Bækgaard, and Tambo 2012), which requires that no agent be happier by *joining* another part (rather than by swapping places with an agent in another part).[3] In our graph theoretic framework, this is equivalent to asking that each node have at least as many neighbors in its own part as in any other part. This has been studied extensively in graph theory using terms such as satisfactory partitions (Bazgan, Tuza, and Vanderpooten 2010), friendly partitions (Aharoni, Milner, and Prikry 1990), and internal partitions (Ban and Linial 2016), but under only the restriction that each part is non-empty. This problem is also studied in the case where the parts are required to be of almost the same size (Bazgan, Tuza, and Vanderpooten 2010). However, since such partitions do not always exist, this literature primarily focuses on the computational complexity of checking the existence of such partitions and approximating the most satisfactory partitions.

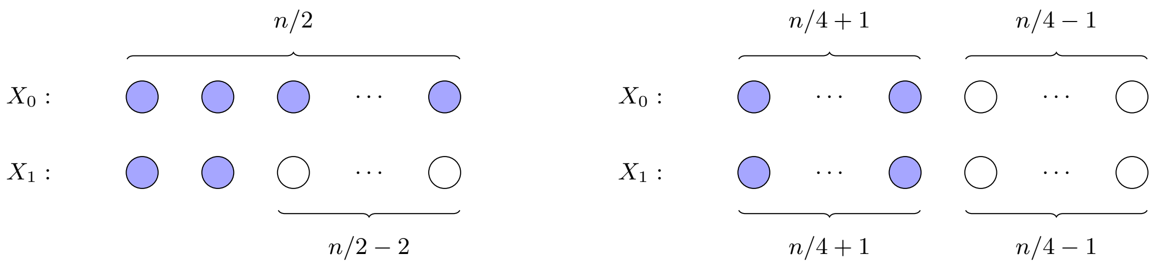
Instead, our focus is on providing worst-case guarantees on the necessary violation of envy-freeness, as is commonly done in the literature on fair resource allocation (Lipton et al. 2004; Caragiannis et al. 2019; Aziz et al. 2019). We make a connection to discrepancy theory (Chen et al. 2014) to establish an $O(\sqrt{n})$ bound. In discrepancy theory, the goal is to distribute each agent's friends as evenly as possible between the parts, so that not only does an agent not have many more friends in another part than her own part, she also does not have many more friends in her own part than in any other part. The latter restriction, a flipped version of the satisfactory partition problem, has also been studied separately as the co-satisfactory or unfriendly partition problem (Aharoni, Milner, and Prikry 1990). Manurangsi and Suksompong (2021) use discrepancy theory in a similar problem with n agents partitioned into k groups, but with the agents having utilities over goods being allocated to the groups, not over the other agents.

2 Preliminaries

For $t \in \mathbb{N}$, let $[t] = \{0, \ldots, t-1\}$. We consider a set $V = [n]$ of agents who are members of a social network. The network is represented by an undirected graph $G(V, E)$, where the agents are the nodes and an edge $(i, i') \in E$ indicates friendship between agents i and i'. This induces the utility function of agent i, denoted $u_i : V \to \{0, 1\}$, where $u_i(i') = 1$ if $(i, i') \in E$ and 0 otherwise. Let $N_G(i)$ denote the set of neighbors of agent i in G, i.e., $N_G(i) = \{i' \in V :$

[2]That is, an agent with utility u must receive utility more than $\alpha u + \beta$ after deviating.

[3]The two differ only when the other part consists entirely of the agent's friends.



(a) 2-partition in the core

(b) EF 2-partition

Figure 1: An instance, that consists of $K_{n/2+2}$ (blue nodes) and $n/2 - 2$ isolated agents (white nodes), where core and envy-freeness are incompatible.

$(i, i') \in E\}$. We refer to $d_G(i) = |N_G(i)|$ as the degree of agent i. We omit G when it is clear from the context.

A *k-partition* of V is given by $X = (X_0, \ldots, X_{k-1})$, where $X_j \cap X_{j'} = \emptyset$ for all distinct $j, j' \in [k]$; $X_j \neq \emptyset$ for all $j \in [k]$; and $\cup_{j \in [k]} X_j = V$. We may refer to an individual group X_j as a *part*. With slight abuse of notation, we denote by $X(i)$ the part X_j to which agent i belongs (i.e., $i \in X_j$). We assume that $n \geqslant k$, so a k-partition exists. A k-partition is called *balanced* if $\lfloor n/k \rfloor \leqslant |X_j| \leqslant \lceil n/k \rceil$ for all $j \in [k]$, and called *imbalanced* otherwise. Hereinafter, whenever we refer to a k-partition, we mean a balanced k-partition, unless explicitly specified otherwise. The utility of agent i for $S \subseteq V$ is denoted by, with slight abuse of notation, $u_i(S)$. We assume that utilities are additive, i.e., $u_i(S) = \sum_{i' \in S} u_i(i') = |S \cap N(i)|$.

In this work, we focus on two fairness criteria. The first one is the *core* which, informally, requires that there be no group of agents (coalition) of size $\lfloor n/k \rfloor \leqslant |S| \leqslant \lceil n/k \rceil$ such that every agent in the coalition prefers to be in that coalition than in her own part; such a coalition is called "blocking".

Definition 1. Fix $\alpha \geqslant 1$ and $\beta \geqslant 0$. A coalition $S \subseteq V$ is called (α, β)-blocking for a k-partition X if

$$u_i(S) > \alpha \cdot u_i(X(i)) + \beta$$

for every $i \in S$. A k-partition X is said to be in the (α, β)-*core* if there is no (α, β)-blocking coalition S with $\lfloor n/k \rfloor \leqslant |S| \leqslant \lceil n/k \rceil$. When $\alpha = 1$ and $\beta = 0$, we simply use the terms blocking coalition, and core.

Another fairness criterion we focus on is envy-freeness.

Definition 2. For $r \geqslant 0$, a k-partition X is called *envy-free up to r*, denoted EFr or EF-r, if, for every pair of agents $i, i' \in V$, $u_i(X(i)) \geqslant u_i(X(i') \cup \{i\} \setminus \{i'\}) - r$. When $r = 0$, we simply refer to this as envy-freeness (EF).

For the proof techniques we plan to use, we need the following additional terminology. The *cut size* of a k-partition X, denoted $\mathrm{cut}(X)$, is the number of edges between its different parts, i.e., $\mathrm{cut}(X) = |\{(i, i') \in E : X(i) \neq X(i')\}|$. A k-partition with the smallest cut size is called a *min k-cut*. Note that

$$\mathrm{cut}(X) = \sum_{i \in V} (|N(i)| - u_i(X(i))) = 2|E| - \sum_{i \in V} u_i(X(i)).$$

Hence, min k-cut also maximizes the social welfare among all k-partitions. Some of our results show that such solutions also satisfy good approximations of the core. Give disjoint sets of nodes A and B, $E(A, B)$ denotes the set of edges with one endpoint in A and the other in B.

Let us also introduce standard graph theory terminology. We denote by K_n, K_{n_1,n_2} and K_{n_1,n_2,n_3} the complete undirected graph of n vertices; the complete bipartite graph with n_1 and n_2 vertices on the two sides; and the complete tripartite graph with n_1, n_2, and n_3 vertices on the three sides, respectively.

Core vs. Envy-freeness

While both core and envy-freeness are notions of fairness, they are quite different desiderata and incompatible with each other in general. In fact, in our setting, there are instances in which every partition in the core achieves the worst possible approximation with respect to envy-freeness, and every envy-free partition achieves the worst possible approximation with respect to the core.

To see that, consider a graph that consists of the clique $K_{\frac{n}{2}+2}$ and $\frac{n}{2} - 2$ isolated nodes, where n is a multiple of 4 and $k = 2$. The only 2-partitions in the core are the ones in which $\frac{n}{2}$ nodes from the clique form one group, say X_0, and the remaining nodes form the other group, say X_1. On the other hand, the only envy-free 2-partitions are the ones in which each group contains $\frac{n}{4} + 1$ nodes of the clique along with $\frac{n}{4} - 1$ isolated nodes. These two types of partitions are illustrated in Figure 1.

Intuitively, the two partitions are complete opposites of each other: the former divides the clique as unequally as possible between the two groups, while the latter divides the clique exactly equally. It can be checked that each type of partition achieves the worst approximation to the other fairness notion among all partitions. The decision of which of the two notions (and correspondingly, partitions) is more desirable depends on the application at hand. Hence, we study both these notions separately in this paper.

3 Core

In this section, we study k-partitions in the (approximate) core. We start from the important case that $k = 2$, which has received particular attention in the literature on satisfactory partitions (Bazgan, Tuza, and Vanderpooten 2010). First, we point out an interesting open question:

Open Question 1. *Does every graph admit a* 2*-partition in the core?*

While the existence of 2-partitions in the core is unsettled, we show that the $(2,0)$-core is always non-empty, and in particular, contains every min 2-cut.

Theorem 1. *For* $k = 2$*, a min* 2*-cut is in the* $(2,0)$*-core.*

Proof. Let $X = (X_0, X_1)$ be a min 2-cut. Suppose for contradiction that there exists a $(2,0)$-blocking coalition S of size $\lceil n/2 \rceil$ or $\lfloor n/2 \rfloor$. Let $X_0^* = X_0 \cap S$ and $X_1^* = X_1 \cap S$.

For each agent $i \in X_0^*$, $i \in S$ implies $u_i(S) > 2 \cdot u_i(X_0)$, which in turn implies $|N(i) \cap X_1^*| > 2 \cdot |N(i) \cap X_0 \setminus X_0^*|$. Summing over all $i \in X_0^*$, we obtain

$$E(X_0^*, X_1^*) > 2 \cdot E(X_0^*, X_0 \setminus X_0^*).$$

Similarly, for each agent $i \in X_1^*$, we have $|N(i) \cap X_0^*| > 2 \cdot |N(i) \cap X_1 \setminus X_1^*|$. Summing over all $i \in X_1^*$, we get

$$E(X_0^*, X_1^*) > 2 \cdot E(X_1^*, X_1 \setminus X_1^*).$$

Combining the two equations, we have

$$\begin{aligned} E(X_0^*, X_1^*) > 2 \cdot \max\{&E(X_0^*, X_0 \setminus X_0^*), \\ &E(X_1^*, X_1 \setminus X_1^*)\} \\ \geqslant E(X_0^*, &X_0 \setminus X_0^*) + E(X_1^*, X_1 \setminus X_1^*). \quad (1) \end{aligned}$$

Now, consider the 2-partition $X' = (S, V \setminus S)$. We will show that $\mathrm{cut}(X) > \mathrm{cut}(X')$, which will contradict X being a min 2-cut. We have

$$\begin{aligned} \mathrm{cut}(X) &= E(X_0, X_1) \\ &= E(X_0^*, X_1^*) + E(X_0^*, X_1 \setminus X_1^*) \\ &\quad + E(X_1^*, X_0 \setminus X_0^*) + E(X_0 \setminus X_0^*, X_1 \setminus X_1^*) \\ &\geqslant E(X_0^*, X_1^*) + E(X_0^*, X_1 \setminus X_1^*) \\ &\quad + E(X_1^*, X_0 \setminus X_0^*) \\ &> E(X_0^*, X_0 \setminus X_0^*) + E(X_1^*, X_1 \setminus X_1^*) \\ &\quad + E(X_0^*, X_1 \setminus X_1^*) + E(X_1^*, X_0 \setminus X_0^*) \\ &= \mathrm{cut}(X'), \end{aligned}$$

where the strict inequality uses Equation (1). This is the desired contradiction. □

While Theorem 1 is a strong existential result, it does not come with an efficient algorithm as finding a min 2-cut (also known as the minimum bisection problem) is NP-hard (Garey and Johnson 1979). This leads to our next open problem:

Open Question 2. *Can a* 2*-partition in the* $(2,0)$*-core be computed in polynomial time?*

As a slight remedy, we will later show that at least a 2-partition in the $(3,0)$-core can be computed efficiently.

Next, we focus on $k \geqslant 3$ and show that the core can be empty in this case.

Theorem 2. *When* $k \geqslant 3$*, there exists an instance in which no* k*-partition is in the* $(\alpha,0)$*-core for any* $\alpha \geqslant 1$*, and also there exists an instance in which no* k*-partition is in the* $(1,\beta)$*-core for* $\beta < k/2 - 2$*.*

Proof. Fix $k \geqslant 3$. For the first claim, consider a cycle with $n = k+1 \geqslant 4$ nodes. Fix an arbitrary k-partition X. Note that X must consist of one part with two nodes and $k-1$ parts with a single node each. Without loss of generality, let X_0 be the part with $|X_0| = 2$. Note that in a cycle of length at least 4, the size of the smallest maximal matching is at least 2. Hence, there must exist agents $i, i' \notin X_0$ that are connected by an edge. Since the coalition $\{i, i'\}$ is allowed to deviate, they can both go from receiving utility 0 to receiving utility 1, implying that X is not in the $(\alpha,0)$-core for any $\alpha > 0$.

For the second claim, consider the graph G formed by $k+1$ disjoint cliques of size $k-1$ each, denoted $C_0, \ldots, C_k$. Hence, $n = k^2 - 1$. Let X be any k-partition of G. First, we claim that there exists $\ell^* \in [k+1]$ such that $|C_{\ell^*} \cap X_j| \leqslant (k+1)/2$ for all $j \in [k]$. If this is not true, then for every $\ell \in [k+1]$, there exists at least one $j_\ell \in [k]$ with $|C_\ell \cap X_{j_\ell}| > (k+1)/2$. Note that such j_ℓ must be unique. Further, because $|X_j| \leqslant \lceil n/k \rceil \leqslant k+1$ for all $j \in [k]$, we must have $j_\ell \neq j_{\ell'}$ for distinct $\ell, \ell' \in [k+1]$. However, this is not possible as there are $k+1$ cliques but only k parts. Now, for every agent $i \in C_{\ell^*}$, we have $u_i(X(i)) \leqslant (k-1)/2$. On the other hand, C_{ℓ^*} is a feasible deviating coalition as $|C_{\ell^*}| = k-1 = \lfloor n/k \rfloor$. Further, for every $i \in C_{\ell^*}$, we have $u_i(C_{\ell^*}) = k-2 \geqslant u_i(X(i)) + (k-3)/2$. Hence, C_{ℓ^*} is a $(1, k/2-2)$-blocking coalition, as desired. □

While above we show that the core can be empty when $k \geqslant 3$, these examples are somewhat unsatisfactory as they crucially rely on n not being divisible by k, which leads to another interesting open question:

Open Question 3. *Does every graph with* n *nodes admit a* k*-partition in the core, if* k *divides* n*?*

When $n < k^2 + k$, note that any deviating coalition has size at most $\lceil n/k \rceil \leqslant k+1$, which means that no agent can improve her utility by an additive factor of more than k when deviating. Hence, every k-partition is trivially in the $(1,k)$-core.

Proposition 1. *When* $n < k^2 + k$*, every* k*-partition is in the* $(1,k)$*-core.*

From Theorem 2, we know that one cannot obtain a purely multiplicative guarantee of the form $(\alpha,0)$-core for any $\alpha \geqslant 1$ and cannot obtain an additive guarantee of the form $(1,\beta)$-core for any $\beta \leqslant k/2-2$. Thus, we conclude that the guarantee in Proposition 1 is asymptotically tight with respect to these two ways of approximation when $n < k^2 + k$.

Next, we consider the case of $n \geqslant k^2 + k$. Interestingly, while a purely multiplicative approximation of the core cannot be guaranteed in general, we show that this is possible when we know $n \geqslant k^2 + k$. Specifically, the next result shows that a k-partition in the $(2k-1,0)$-core always exists and can be found in polynomial time, if $n \geqslant k^2 + k$. In this case, we in fact show that every min k-cut is in the $(2k-1,0)$-core, but we can also use a local search procedure, presented as Algorithm 1, to obtain the same approximation guarantee efficiently. At a high level, the algorithm works as follows. It starts from an arbitrary k-partition and draws a directed edge from agent i to agent i', with

Algorithm 1: Local Min-Cut

1: $X \leftarrow$ an arbitrary k-partition
2: **while** true **do**
3: Build a directed graph $G' = (V', E')$ with $V' = V$ and $E' = \{(i, i') : u_i(X(i')) > u_i(X(i)) + 1\}$
4: **if** there is a cycle $(i_0, i_1, \ldots, i_{s-1}, i_0)$ in G' **then**
5: **for** $\ell \in [s]$ **do**
6: $X(i_\ell) \leftarrow X(i_\ell) \setminus \{i_\ell\}$
7: $X(i_{\{\ell+1 \mod s\}}) \leftarrow X(i_{\{\ell+1 \mod s\}}) \cup \{i_\ell\}$
8: **end for**
9: **else if** $\exists (i, i')$ s.t. $u_{i'}(X(i')) = 0$ and $u_i(X(i')) > u_i(X(i))$ **then**
10: **if** $(i, i') \notin E$ or $u_i(X(i')) > u_i(X(i)) + 1$ **then**
11: $X(i) \leftarrow X(i) \cup \{i'\} \setminus \{i\}$
12: $X(i') \leftarrow X(i') \cup \{i\} \setminus \{i'\}$
13: **end if**
14: **else**
15: break
16: **end if**
17: **end while**
18: **return** X

$X(i) \neq X(i')$, if i envies i' by more than one. If there exists a directed cycle, say $(i_0, i_1, \ldots, i_{s-1}, i_0)$, it shifts the agents along the cycle, i.e., i_0 is moved to $X(i_1)$, i_1 is moved to $X(i_2)$ and so on, while i_{s-1} is moved to $X(i_0)$. Then, it updates the directed edges and continues eliminating cycles in this fashion. When there are no cycles left, it searches for pairs of agents, i and i', with $X(i) \neq X(i')$, such that i' has zero utility for her group and a positive utility for i's group, i envies i', and the envy is by more than one if i and i' are not neighbors. If such a pair exists, it swaps i and i'. Then, the algorithm updates the directed edges, search for cycles or such pairs, and eliminates them until until no cycles or such pairs are left. Throughout the procedure, the cut size strictly decreases, and we establish that the approximation guarantee holds at any local minimum.

Theorem 3. *When $n \geqslant k^2 + k$, every min k-cut is in the $(2k-1, 0)$-core, and Algorithm 1 returns a k-partition in the $(2k-1, 0)$-core in polynomial time.*

Proof. First, we show that Algorithm 1 terminates in polynomial time by arguing that $\mathrm{cut}(X)$ strictly decreases in every iteration of the while loop. If we find a cycle in Line 4, then during the cyclic shift of nodes along this cycle, each node gains at least 1 utility. Since the social welfare strictly increases, $\mathrm{cut}(X)$ strictly decreases. Similarly, if we find two agents i and i' such that i' has no neighbors in $X(i')$ but i has at least two more neighbors in $X(i')$ than in $X(i)$, then swapping i and i' also strictly decreases the cut size. Further, if i' is not a neighbor of i, then we only need i to have at least one more neighbor in $X(i')$ than in $X(i)$. Hence, in any case, $\mathrm{cut}(X)$ strictly reduces in every iteration of the while loop, resulting in termination in polynomial time.

Let X be either a min k-cut or the output of Algorithm 1. Suppose for contradiction that there is a $(2k-1, 0)$-blocking coalition S of size $\lceil n/k \rceil$ or $\lfloor n/k \rfloor$. We first show the following lemma.

Lemma 1. *For $i \in S$, if $u_i(S \cap X_j) \leqslant u_i(X(i)) + 1$ for each $j \in [k]$, then $u_i(X(i)) = 0$.*

Proof. Suppose there exists $i \in S$ with $u_i(S \cap X_j) \leqslant u_i(X(i)) + 1$ for each $j \in [k]$ but $u_i(X(i)) \geqslant 1$. Then,

$$\begin{aligned} u_i(S) &= \textstyle\sum_{j \in [k]} u_i(S \cap X_j) \\ &\leqslant (k-1)(u_i(X(i)) + 1) + u_i(X(i)) \\ &\leqslant 2(k-1) \cdot u_i(X(i)) + u_i(X(i)) \\ &= (2k-1) \cdot u_i(X(i)), \end{aligned}$$

which contradicts S being a $(2k-1, 0)$-blocking coalition. □

Suppose that there exists $i \in S$ such that $u_i(S \cap X_j) > u_i(X(i)) + 1$ for some $j \in [k]$. Let G' be the directed graph constructed from X according to Line 3 of Algorithm 1. Then, there must be an edge from i to every node in X_j in G', as $u_i(X(i)) + 1 < u_i(S \cap X_j) \leqslant u_i(X_j)$. Further, since $u_i(S \cap X_j) > 0$, $S \cap X_j \neq \emptyset$. Hence, i has an edge to some node in S in G'. Note that there can be no cycle in G': if X is the output of Algorithm 1, this would contradict the while loop terminating, and if X is a min k-cut, a cyclic shift of nodes like in Algorithm 1 would reduce the cut size, which would be a contradiction. Since there is no cycle in G', consider the longest path in G' starting at i and only containing nodes in S. Suppose it is $(i, i_1, \ldots, i_t, i')$. Then, i' must satisfy the condition of Lemma 1, otherwise by the same reasoning as before, there would exist $j' \in [k]$ such that $S \cap X_{j'} \neq \emptyset$ and i' has edges to all nodes in $X_{j'}$ in G'. This would either lead to a cycle or a longer path in G' starting at i and only containing nodes in S, which is a contradiction. Since i' satisfies the condition of Lemma 1, we have $u_{i'}(X(i')) = 0$. We also have $u_{i_t}(X(i')) > u_{i_t}(X(i_t)) + 1$. If X is returned by Algorithm 1, we get a contradiction because Algorithm 1 would have continued by swapping i_t and i' in Line 9. If X is a min k-cut, then swapping i_t and i' would reduce the cut size, which would also be a contradiction.

We have established that all $i \in S$ satisfy the condition from Lemma 1. Hence, $u_i(X(i)) = 0$ for all $i \in S$. However, since $n \geqslant k^2 + k$, we have $|S| \geqslant \lfloor n/k \rfloor \geqslant k+1$, which implies that there exist $i_1, i_2 \in S$ with $X(i_1) = X(i_2)$, which contradicts $u_{i_1}(X(i_1)) = u_{i_2}(X(i_2)) = 0$. Hence, there is no such $(2k-1, 0)$-blocking coalition S. □

In the proof of Lemma 1, note that if we assumed the deviating coalition S to be a $(k, k-1)$-blocking coalition, then we would obtain a contradiction regardless of whether $u_i(X(i)) = 0$ or $u_i(X(i)) \geqslant 1$. Since the next part of the proof, which establishes that all $i \in S$ must satisfy the condition of Lemma 1, does not assume $n \geqslant k^2 + k$, we have that Algorithm 1 always finds a solution in the $(k, k-1)$-core. In particular, for $k = 2$, we can efficiently guarantee $(3, 1)$-core. Recall that Theorem 1 provides a slightly better guarantee of $(2, 0)$-core, but not in polynomial time.

Corollary 1. *For $k = 2$, Algorithm 1 returns a 2-partition in the $(3, 1)$-core in polynomial time.*

While it is an open question whether Algorithm 1 provides the best possible guarantee, we show, using an intricate instance, that our approximation analysis of min k-cuts in Theorem 3 is almost tight from a multiplicative point of view. Missing proofs can be found in the appendix.

Theorem 4. *For $k \geqslant 3$, there exists an instance with $n \geqslant k^2 + k$ in which some min k-cut is not in the $(\alpha, 0)$-core for $\alpha < 2k - 2$.*

4 Envy-Freeness

We now turn our attention to finding k-partitions that are (approximate) envy-free. We start by showing that EF1 cannot always be guaranteed.

Theorem 5. *Even when $k = 2$, a 2-partition that is EF1 does not always exist.*

Proof. Consider the $K_{3,3,3}$ graph which consists of three set of three nodes each, denoted by $C_1 = \{c_{11}, c_{12}, c_{13}\}$, $C_2 = \{c_{21}, c_{22}, c_{23}\}$ and $C_3 = \{c_{31}, c_{32}, c_{33}\}$, respectively, and every node of each set is adjacent to every node in the other two sets.

For the sake of contradiction, assume that $X = (X_0, X_1)$ is a partition of the graph that is EF1. Since the graph is 6-regular, we can see that $|X_0| \geqslant 4$ and $|X_1| \geqslant 4$, as if an agent i is assigned to a part with only at most two of its neighbours, then the other four of its neighbours are assigned to the other part along with an agent i' which is not neighbour of i, and then i envies i' for more than one agent. Without loss of generality, we assume that $|X_0| = 4$. If X_0 contains three nodes of the same set, then we can easily see that this partition is not EF1, as each of them is assigned to the same group with at most one of its neighbours. As there are three sets and X_0 contains four agents, we see that two agents of the same set, say c_{11} and c_{12}, are assigned to X_0. Then these two agents are in the same part along with at most two of its neighbours, while all the remaining nodes are assigned to X_1. Then, c_{11} and c_{12} envy c_{13} for more than one agents, which is a contradiction. $\square$

To obtain non-trivial approximations to envy-freeness for higher values of k, that too via partitions, we turn to the literature on discrepancy theory. Intuitively, we want to color the elements of a set using k colors such that each predetermined subset has an approximately equal number of elements of each color. Formally, we are given a universe $\Omega = [n]$ and a set system $\mathcal{S} = \{S_0, \ldots, S_{m-1}\}$, where $S_i \subseteq [n]$ for each $i \in [m]$. The k-color discrepancy of a coloring $\chi : \Omega \to [k]$ on the set system $\mathcal{S}$ is defined as

$$\mathrm{disc}_k(\mathcal{S}, \chi) = \max_{j \in [k], i \in [m]} \left| |\chi^{-1}(j) \cap S_i| - |S_i|/k \right|.$$

The k-discrepancy of $\mathcal{S}$ is then the minimum k-color discrepancy over all χ: $\mathrm{disc}_k(\mathcal{S}) = \min_{\chi:\Omega\to[k]} \mathrm{disc}_k(\mathcal{S}, \chi)$. A celebrated result from this literature is that $\mathrm{disc}_k(\mathcal{S}) = O(\sqrt{\frac{n}{k} \ln(km/n)})$ for any set system $\mathcal{S}$ and a k-coloring achieving this bound can be computed in polynomial time (Chen et al. 2014, Corollary 44).

In our setting, with $\Omega = V = [n]$, a k-coloring $\chi : \Omega \to [k]$ induces a k-partition X given by $X_j = \chi^{-1}(j)$ for all $j \in [k]$.[4] Further, if we consider the set system $\mathcal{S}$ where $S_i = N_G(i)$ for each $i \in [n]$ (i.e., with $m = n$), then we are guaranteed that agent i can have at most $2\mathrm{disc}_k(\mathcal{S}, \chi)$ more neighbors in any other part than in her own part, implying EF-$2\mathrm{disc}_k(\mathcal{S}, \chi)$. The above discrepancy bound then immediately yields the existence of a k-partition that is EF-$O(\sqrt{\frac{n}{k} \ln k})$. However, this may not be balanced.

To fix this, we add another set $S_n = V$ to our set system; we now have $m = n + 1$, which does not asymptotically change the discrepancy bound. Now, we obtain a k-partition X that is also approximately balanced: $||X_j| - |X_{j'}|| = O(\sqrt{\frac{n}{k} \ln k})$ for all $j, j' \in [k]$. By arbitrarily moving $O(\sqrt{\frac{n}{k} \ln k})$ agents between parts, we can make it perfectly balanced, while only increasing the EF approximation by $O(\sqrt{\frac{n}{k} \ln k})$. Thus, we get the following.

Theorem 6. *For any $k \geqslant 2$, a k-partition that is EF-$O(\sqrt{\frac{n}{k} \ln k})$ is guaranteed to exist and can be computed in polynomial time.*

For discrepancy, the aforementioned upper bound is known to be almost tight: there is a lower bound of $\Omega(\sqrt{n/k})$ (Chen et al. 2014, Theorem 61). However, for our "one-sided" envy-freeness guarantee, achieving a constant approximation remains an open question.

Open Question 4. *Does every graph admit a k-partition that is EF2, for all $k \geqslant 2$?*

5 Beyond Balancedness

An interesting variation of our problem is to drop the requirement of balancedness and simply seek k non-empty groups, i.e., imbalanced k-partitions. This variation was first introduced by Gerber and Kobler (2000) and, since then, it has been given much attention (Bazgan, Tuza, and Vanderpooten 2010) due to its importance to real-life applications such as clustering (Flake, Tarjan, and Tsioutsiouliklis 2004; Shafique 2004).

In this section, we briefly consider this case and study both the core and envy-freeness for imbalanced k-partitions. For the core, we provide matching upper and lower bounds. For envy-freeness, we provide a complete picture for $k = 2$ by making a connection to the literature on satisfactory partitions, and point out interesting open questions for $k \geqslant 3$.

Core

Recall that core requires that there be no group of agents (coalition) such that every agent in the coalition prefers to be in that coalition than in her own part. In general, there is no direct correlation between the size of a coalition and the ease with which it can be blocking.[5] Hence, in the imbalanced case, we impose the same restriction on the size of a deviating coalition as we have on the size of a part in an imbalanced k-partition. Note that all parts in an imbalanced

[4] Technically, we also need to ensure $X_j \neq \emptyset$, but this is guaranteed due to the discrepancy bound.

[5] Smaller coalitions have the advantage of only having to improve the utility of fewer agents, whereas larger coalitions can include more friends of their members.

k-partition X are required to be non-empty, which implies $1 \leqslant |X_j| \leqslant n - k + 1$ for all $j \in [k]$; hence, we require a deviating coalition S to also satisfy $1 \leqslant |S| \leqslant n - k + 1$. This gives rise to the following variant of the core.

Definition 3. Fix $\alpha \geqslant 1$ and $\beta \geqslant 0$. A coalition $S \subseteq V$ is called (α, β)-blocking for an imbalanced k-partition X if

$$u_i(S) > \alpha \cdot u_i(X(i)) + \beta$$

for every $i \in S$. An imbalanced k-partition X is said to be in the (α, β)-*imbalanced core* if there is no (α, β)-blocking coalition S with $1 \leqslant |S| \leqslant n - k + 1$. When $\alpha = 1$ and $\beta = 0$, we simply use the terms blocking coalition, and imbalanced core.

Note that the differing size restrictions on the deviating coalitions technically makes our results for the core under imbalanced k-partitions incomparable to our results for the core under balanced k-partitions.

We show that for any k, an imbalanced partition in the $(1, k-2)$-imbalanced core always exists and can be found in polynomial time.

Theorem 7. *When $k \geqslant 2$, we can find an imbalanced k-partition in the $(1, k-2)$-imbalanced core in polynomial time, and in particular, when $k = 2$, we can efficiently find an imbalanced 2-partition in the imbalanced core. Moreover, when $k \geqslant 3$, there exists an instance in which no imbalanced k-partition is in the $(1, \beta)$-imbalanced core for any $\beta < k - 2$.*

Recall that in the proof of Theorem 2, we used an example with $n = k + 1$ to establish that there may not exist any (balanced) k-partitions in the $(\alpha, 0)$-core for any $\alpha \geqslant 1$ or $(1, \beta)$-core for any $\beta < k/2 - 2$. Because all imbalanced k-partitions are also balanced for $n = k+1$, the imbalanced core becomes equivalent to the core. Hence, the negative results of Theorem 2 carry over to the imbalanced case, though the additive lower bound in Theorem 7 is better.

This shows that the guarantee in Theorem 7 is tight in two ways: one can hope for neither a purely multiplicative approximation of the form $(\alpha, 0)$-imbalanced core for any $\alpha \geqslant 1$, nor a better additive approximation of the form $(1, \beta)$-imbalanced core for any $\beta < k - 2$.

Envy-Freeness

Finally, we turn our attention to envy-freeness. Luckily, the definition of envy-freeness does not require any modification to make it meaningful for imbalanced k-partitions.

First, we use the following result from the literature on satisfactory partitions, restated in our framework, to establish the existence of an EF-2 imbalanced partition when $k = 2$.

Theorem 8 (Stiebitz 1996, Bazgan, Tuza, and Vanderpooten 2007)**.** *Given a graph $G = (V, E)$ and functions $a, b : V \to \mathbb{N}$ such that $d(i) \geqslant a(i) + b(i) + 1$ for every $i \in V$, there exists an imbalanced 2-partition $X = (X_0, X_1)$ of V such that $u_i(X_0) \geqslant a(i)$ for each $i \in X_0$ and $u_i(X_1) \geqslant b(i)$ for all $i \in X_1$, and it can be computed in polynomial time.*

In our case, we use functions $a(i) = b(i) = \lfloor (d(i) - 1)/2 \rfloor$ for all $i \in V$. Note that these satisfy the condition $d(i) \geqslant a(i) + b(i) + 1$. Hence, the above result allows us to efficiently compute a 2-partition X satisfying $u_i(X(i)) \geqslant \lfloor (d(i) - 1)/2 \rfloor$ for all $i \in V$. Since there are only two parts, this also implies that for all $i, i' \in V$,

$$\begin{aligned} u_i(X(i')) - u_i(X(i)) &\leqslant d(i) - 2 \cdot \lfloor (d(i) - 1)/2 \rfloor \\ &\leqslant d(i) - 2 \cdot (d(i) - 2)/2 = 2, \end{aligned}$$

which implies that X is EF-2.

Corollary 2. *An imbalanced 2-partition that is EF-2 always exists and can be computed in polynomial time.*

Theorem 8 admits an extension to $k > 2$ parts, but in our case, this only guarantees that $u_i(X(i)) \geqslant \lfloor (d(i) - k + 1)/k \rfloor$ for all $i \in V$ (Bazgan, Tuza, and Vanderpooten 2007). This does not meaningfully limit the number of neighbors that agent i has in another part and, therefore, fails to provide a non-trivial approximation to envy-freeness. That said, if one is interested in the slightly weaker guarantee of proportionality (Steinhaus 1948), which, in our setting, would require $u_i(X(i)) \geqslant d(i)/k$, then this would provide an additive 1-approximation.

For the satisfactory partition problem, where the goal is to indeed minimize $u_i(X(i')) - u_i(X(i))$, as in the equation above, it is easy to see that an additive error of 2 is the best possible. Consider dividing any clique with an odd number of nodes into two parts. An agent i in the smaller part will have at least two more neighbors in the larger part than in her own part. However, this does not hold for envy-freeness: if i envisions *swapping places* with an agent i' from the other part, then $X(i') \cup \{i\} \setminus \{i'\}$ will only contain one more neighbor of i than $X(i)$ does. Nonetheless, notice that the example that is used in the proof of Theorem 5 can also be used to show that EF-1 cannot always be guaranteed even in the imbalanced case when $k = 2$.

6 Discussion

In this paper, we considered the problem of partitioning n agents into k almost equal-sized groups, when the agents have binary preferences, induced by a social network. We designed algorithms which approximately satisfy two axiomatic fairness guarantees: the core and envy-freeness. Our work offers a number of exciting open questions. For example, is the core always non-empty when $k = 2$ or when k divides n? Does an EF-2 partition always exist? Does an imbalanced EF-2 partition always exist for any k?

There are two natural ways to extend our model. First, our agents have symmetric binary preferences, but one can consider preferences which are asymmetric and/or non-binary. Second, our agents only have preferences over other agents; the groups they are assigned to are apriori identical. A complementary model in the fair division literature considers assigning resources to groups of agents (Segal-Halevi and Suksompong 2019; Kyropoulou, Suksompong, and Voudouris 2020; Manurangsi and Suksompong 2021), where agents have preferences over the resources, but not over the other agents in their group. An extension of both models would require partitioning n agents into k groups and then allocating resources to these groups, when agents have preferences over both the resources being allocated and the other agents in their group.

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Appendix

A Proof of Theorem 4

Proof. Consider a graph G which consists of two disjoint cliques of size $2k-3$ each, denoted by A_1 and A_2; $k-1$ further disjoint cliques of size $2k-4$ each, denote by $B_1, \ldots, B_{k-1}$; and another disjoint clique of size 2, denoted by C. Note that $n = 2(2k-3)+(k-1)(2k-4)+2 = 2k^2-2k \geqslant k^2+k$ for $k \geqslant 3$. We start with the following lemma.

Lemma 2. *If X is a balanced min k-cut of G such that for some $j^* \in [k]$, there exist $V \subseteq X_{j^*}$ and a clique $V' \subseteq \cup_{j\in[k]} X_j \setminus X_{j^*}$ with $E(V', X_j \setminus V') = 0$ for every $j \in [k] \setminus j^*$, $E(V', V) = 0$, $E(X_{j^*} \setminus V, V') \geqslant E(X_{j^*} \setminus V, V)$, and $|V| = |V'|$, then swapping the nodes between V and V', using an arbitrary bijection, does not increase the cut size.*

Proof. Since V' is a clique, we easily see that the edges with two endpoints in different parts, except for part X_{j^*} are not increased. On the other hand, as $E(V', X_j \setminus V') = 0$ for any $j \in [k] \setminus j^*$, $E(V', V) = 0$ and $E(X_{j^*} \setminus V, V') \geqslant E(X_{j^*} \setminus V, V)$, we see that all the edges with one endpoint to X_{j^*} and the other endpoint to another part are not increased. Hence, cut is not increased. □

Let $X = (X_0, ..., X_{k-1})$ be an arbitrary balanced min k-cut of G. Suppose that the nodes of A_1 are spread among different parts. Then, there exists a part X_{j_1} that contains at least two nodes of A_1, as $2k-3 > k$ when $k > 3$. Let $S_1 = X_{j_1} \cap A_1$ and $V = X_{j_1} \setminus (S_1 \cup \{i_1\})$ where i_1 is an arbitrary node in $X_{j_1} \setminus S_1$ (such a node always exists as $n/k > |A_1| - 1 = 2k-4$). Notice that $\overline{S}_1 = A_1 \setminus S_1$ is a clique such that $E(\overline{S}_1, X_j \setminus \overline{S}_1) = 0$ for any $j \in [k] \setminus j_1$ and $E(\overline{S}_1, V) = 0$. Moreover, notice that $|\overline{S}_1| = |V|$ as $|A_1| = 2k-3$ and $|X_{j_1}| = 2k-2$. We also see that

$$\begin{aligned}&E(S_1 \cup \{i_1\}, X_{j_1} \setminus (S_1 \cup \{i_1\})) = \\ &E(S_1, X_{j_1} \setminus (S_1 \cup \{i_1\})) + E(i_1, X_{j_1} \setminus (S_1 \cup \{i_1\})) \leqslant 0 + |V|\end{aligned}$$

while

$$E(S_1 \cup \{i_1\}, \overline{S}_1) \geqslant 2 \cdot |\overline{S}_1|$$

as $|S_1| \geqslant 2$ and all the agents in S_1 are connected with all the agents in $\overline{S}_1$. From Lemma 2, we get that if we swap the nodes among V and $\overline{S}_1$, using an arbitrary mapping, the cut of the partition is not increased. Hence, there exists a balanced min k-cut in which all the nodes in A_1 are assigned to the same part X_{j_1}. Given this partition, suppose that the nodes of A_2 are spread among different parts. Then, there exists a part X_{j_2} different than X_{j_1} that contains at least two nodes of A_2, and by a similar argument as above we conclude in a balanced min k-cut in which all the nodes in A_1 are assigned to X_{j_1} and all the nodes in A_2 are assigned to X_{j_2}. Now, starting from this partition, suppose that the nodes of B_1 are spread among different parts. Then, as $|B_1| = 2k-4$, there exists a part $X_{j_1'}$ different that X_{j_1} and X_{j_2} which contains at least two nodes from B_1, when $k > 2$. Hence, by the same arguments as above we can conclude in a balanced min k-cut, in which all the nodes in A_1 are assigned to X_{j_1}, all the nodes in A_2 are assigned to X_{j_2}, and all the nodes in B_1 are assigned to $X_{j_1'}$. By continuing this way and as $|B_\ell| = 2k-4$ for any $\ell \in \{1, ..., k-1\}$, we conclude that there exists a balanced min k-cut, in which all the nodes in A_1 are assigned to X_{j_1}, all the nodes in A_2 are assigned to X_{j_2}, and all the nodes in B_ℓ, for $\ell \in \{1, ..., k-3\}$, are assigned to $X_{j_\ell'}$. Now, the last part different that X_{j_1}, X_{j_2} and $X_{j_\ell'}$ for $\ell \in \{1, ..., k-3\}$, denoted by $X_{j_{k-2}'}$, contains at least two nodes from B_{k-2} or B_{k-1}. Without loss of generality, we assume that $|X_{j_{k-2}'} \cap B_{k-2}| \geqslant 2$. By doing the same arguments as before, we find a balanced min k-cut partition $X' = (X_0', ..., X_{k-1}')$ in which all the nodes of each clique A_1, A_2, B_1,...,B_{k-2} are assigned to the same group. Let $Q = A_1 \cup A_2 \cup B_1 \cup ... \cup B_{k-2}$. Then notice that for each $j \in [k]$, $|X_j' \cap Q| \geqslant 2k-4$. Hence, the nodes of B_{k-1} and C are spread across different parts and each part contains at most two nodes of B_{k-2}.

Now, we can see that if $C = \{c_1, c_2\}$ and $B_{k-1} = \{b_1, \ldots, b_{2k-4}\}$, then X'' given by $X_0'' = A_1 \cup \{c_1\}$, $X_1'' = A_2 \cup \{c_2\}$, and $X_{j+1}'' = B_j \cup \{b_{2j-1}, b_{2j}\}$ for $j \in \{1, \ldots, k-2\}$ is a balanced min k-cut. But then, the coalition $S = C \cup B_{k-1}$ is a $(2k-3, 0)$-blocking coalition, as the utility of each agent in C increases by an infinite multiplicative factor when deviating with S, while that of each agent in B_{k-1} increases by a multiplicative factor of $2k-3$ when deviating with S. □

B Proof of Theorem 7

Proof. We show Algorithm 2 finds a 2-partition in the imbalanced core in polynomial time, while when $k > 2$, the same algorithm finds a partition in the $(1, k-2)$-imbalanced core.

For contradiction, assume that there is a blocking coalition S for the k-partition X computed by Algorithm 2 with $1 \leqslant |S| \leqslant n-k+1$ each of whose agents increased their utility by at least an additive factor of $k-1$.

First, we suppose that G is connected. Notice that every connected graph admits a spanning tree, and that the graph stays connected when deleting a leaf from this tree. Hence, Algorithm 2 is well-defined in this case, and we obtain the guarantee that X_{k-1} is a connected subgraph of G.

Algorithm 2: (Approximate) Imbalanced Core

if G is connected **then**
    for $r = 0, \ldots, k-2$ **do**
        $i_r \leftarrow$ a leaf node in a spanning tree of $G \setminus \cup_{t\in[r]} X_t$
        $X_r \leftarrow \{i_r\}$
    end for
else
    $X_0 \leftarrow$ any connected component of G
    for $r = 1, \ldots, k-2$ **do**
        if $V \setminus \cup_{t\in[r]} X_t \neq \emptyset$ **then**
            $X_r \leftarrow \{i\}$, for an arbitrary $i \in V \setminus \cup_{t\in[r]} X_t$
        else
            $X_r \leftarrow \{i\}$, for an arbitrary $i \in X_0$
            $X_0 \leftarrow X_0 \setminus \{i\}$
        end if
    end for
end if
if $V \setminus \cup_{t\in[k-1]} X_t \neq \emptyset$ **then**
    $X_{k-1} = V \setminus \cup_{t\in[k-2]} X_t$
else
    $X_{k-1} = \{i\}$, for an arbitrary $i \in X_0$
    $X_0 \leftarrow X_0 \setminus \{i\}$
end if
return $X = (X_0, \ldots, X_{k-1})$

We claim that $S \cap X_{k-1} \neq \emptyset$ and $X_{k-1} \setminus S \neq \emptyset$. To see the former claim, note that if $|S| \leqslant k-1$, then $u_i(S) \leqslant k-2 \leqslant u_i(X(i)) + k - 2$ for any $i \in S$, which would be a contradiction. Hence, we must have $|S| \geqslant k$, which implies $S \cap X_{k-1} \neq \emptyset$. To see the latter claim, note that $|S| \leqslant n-k+1$. Also, $|X_{k-1}| = n-k+1$. Thus, if $S \supseteq X_{k-1}$, then we would have $S = X_{k-1}$. This would imply $u_i(S) = u_i(X(i))$ for all $i \in S$, which would again be a contradiction. Hence, we must have $X_{k-1} \setminus S \neq \emptyset$.

Fix $i_1^* \in S \cap X_{k-1}$ and $i_2^* \in X_{k-1} \setminus S$. Because X_{k-1} is a connected subgraph of G, there exists a path from i_1^* to i_2^* using only the nodes in X_{k-1}. Consider the first edge of this path to travel out of S; say this edge is (i', i'') with $i' \in S \cap X_{k-1}$ and $i'' \in X_{k-1} \setminus S$. When deviating from X_{k-1} to S, agent i' loses at least one neighbor (namely i'') from X_{k-1} and may gain up to $k-1$ neighbors (the nodes in $\cup_{r\in[k-1]} X_r$). This implies $u_{i'}(S) \leqslant u_{i'}(X_{k-1}) + k - 2$, which is a contradiction.

Next, suppose G is not connected. Since no connected component can contain all nodes of G, the algorithm must have moved at most $k-2$ nodes from X_0 to $\cup_{t\in\{1,\ldots,k-1\}} X_t$. Hence, none of the agents who are in X_0 in the final solution can join coalition S as their utility cannot improve by more than an additive factor of $k-2$ when doing so. Further, if there exists $i \in S \cap X_{k-1}$, then $u_i(S) \leqslant u_i(X_{k-1}) + \sum_{r=1}^{k-2} u_i(X_r) \leqslant u_i(X_{k-1}) + k - 2$ (as we have already established $S \cap X_0 = \emptyset$), which is again a contradiction. Hence, we must have $S \subseteq \cup_{r\in\{1,\ldots,k-2\}} X_r$, implying that $|S| \leqslant k-2$. But then, $u_i(S) \leqslant k-3 < u_i(X(i)) + k - 2$ for all $i \in S$, which is again a contradiction.

For the lower bound, consider the complete graph K_n with $n \geqslant k \cdot (k-1)$. Let X be any k-partition of this graph. Due to the pigeonhole principle, there exists $r^* \in [k]$ such that $|X_{r^*}| \geqslant n/k \geqslant k-1$. Hence, the coalition $S = \cup_{r\in[k]\setminus\{r^*\}} X_j$ is allowed to deviate as $|S| \leqslant n-k+1$. Since each X_r part of this coalition is non-empty, we have $u_i(S) \geqslant u_i(X(i)) + k - 2$ for each $i \in S$, implying that X is not in the $(1, \beta)$-core for any $\beta < k-2$. $\square$

C Trees

In this section, we consider the special case where the network is a tree. We introduce some more graph theory terminology. We refer to the complete bipartite graph $K_{1,n-1}$ as a *star* and P_n denotes a path graph with n vertices.

Trees in the Balanced Core

Let us begin with 2-partitions in the core. Recall that for general graphs, we left non-emptiness of the core as an open question and proved that every balanced min 2-cut is in the $(2, 0)$-core. For trees, we show that every balanced min 2-cut is in the core. Moreover, the NP-hard problem of finding a balanced min 2-cut in general graphs is known to be polynomial-time solvable for trees (**?**).

Theorem 9. *When $k = 2$ and the network is a tree, every balanced min 2-cut is in the core. We can compute a solution in polynomial time.*

Proof. Let $X = (X_0, X_1)$ be a balanced min 2-cut. For the sake of contradiction, assume that there exists a blocking coalition S; we do not even need S to be of size $\lceil n/2 \rceil$ or $\lfloor n/2 \rfloor$ to derive a contradiction.

Let $X_0^* = X_0 \cap S$ and $X_1^* = X_1 \cap S$. Notice that for each agent $i \in X_0^*$, we have $u_i(S) \geqslant u_i(X_0) + 1$, which implies that $u_i(X_1^*) \geqslant u_i(X_0 \setminus S) + 1$. Summing over all $i \in X_0^*$, we have that $|E(X_0^*, X_1^*)| \geqslant |E(X_0^*, X_0 \setminus S) + |X_0^*|$.

Similarly, for each agent $i \in X_1^*$, we have $u_i(X_0^*) \geqslant u_i(X_1 \setminus S) + 1$. Summing over all $i \in X_1^*$, we have $|E(X_0^*, X_1^*)| \geqslant |E(X_1^*, X_1 \setminus S)| + |X_1^*|$.

Adding the two equations together, and noting that $|X_0^*| + |X_1^*| = |S|$, we obtain

$$\begin{aligned} 2 \cdot |E(X_0^*, X_1^*)| \geqslant & \, E(X_0^*, X_0 \setminus S) \\ & + E(X_1^*, X_1 \setminus S) + |S|. \end{aligned} \tag{2}$$

Notice that $X' = (S, V \setminus S) = (X_0^* \cup X_1^*, (X_0 \setminus S) \cup (X_1 \setminus S))$ is also a balanced 2-partition. Since $X = (X_0, X_1)$ is a balanced min 2-cut, we have

$$\begin{aligned} 0 & \leqslant \mathrm{cut}(X') - \mathrm{cut}(X) \\ & = E(X_0^*, X_0 \setminus S) + E(X_1^*, X_1 \setminus S) \\ & \quad - E(X_0^*, X_1^*) - E(X_0 \setminus S, X_1 \setminus S) \\ & \leqslant E(X_0^*, X_0 \setminus S) + E(X_1^*, X_1 \setminus S) - E(X_0^*, X_1^*) \\ & \leqslant |E(X_0^*, X_1^*)| - |S|, \end{aligned}$$

where the final step uses Equation (2).

Hence, we have that $|E(X_0 \cap S, X_1 \cap S)| \geqslant |S|$. Since S is a forest, it can have at most $|S| - 1$ edges, which is the desired contradiction. $\square$

For $k \geqslant 4$, we show that the core can be empty. In fact, we cannot hope for a multiplicative approximation guarantee of an $(\alpha, 0)$-core for any $\alpha \geqslant 1$. On the other hand, if we turn to additive approximations, we show that any balanced k-partition of a tree is naturally in the $(1, 1)$-core, which is the best we can hope for. We leave the case of $k = 3$ as an open question.

Theorem 10. *Every balanced k-partition of a tree is in the $(1, 1)$-core. For $k \geqslant 4$, there exists a tree for which no balanced k-partition is in the $(\alpha, 0)$-core for any $\alpha \geqslant 1$.*

Proof. Let X be any k-partition of a tree. Suppose for contradiction that there exists a $(1, 1)$-blocking coalition S. Note that S is a subgraph of a tree, so it must be a forest. Hence, there exists a leaf $i \in S$ with $u_i(S) \leqslant 1$, which contradicts S being a $(1, 1)$-blocking coalition.

Now, consider $G = (V, E)$ with $V = \{r, a_1, a_2, b_1, b_2, \ldots, b_{k-2}\}$ and $E = \{(r, a_1), (r, a_2), (a_1, b_1), \cup_{\ell \in \{2,\ldots,k-2\}} (a_2, b_\ell)\}$ as shown in Figure 2 for the lower bound. Note that $n = k + 1$. Let X be any k-partition. Note that it must consist of $k - 1$ parts with a single node each and one part with two nodes. Without loss of generality, assume that $|X_0| = 2$. Like in the proof of Theorem 2, we notice that the smallest maximal matching in this graph has two edges. Hence, there must exist agents $i, i' \notin X_0$ that are connected by an edge. Since the coalition $\{i, i'\}$ is allowed to deviate, agents i and i' can go from receiving utility 0 to utility 1, implying that the partition cannot be in (α, β)-core for any $\alpha \geqslant 1$ and $\beta < 1$. $\square$

Trees in the Imbalanced Case

We show we can approximate the imbalanced core much better than we could in the general graph. In particular, now a k-partition in the imbalanced core exists for $k \in \{2, 3\}$ (as opposed to just for $k = 2$ in the general case), and for $k > 3$, the best possible guarantee is the $(1, 1)$-imbalanced core (as opposed to the $(1, k-2)$-imbalanced core in the general case).

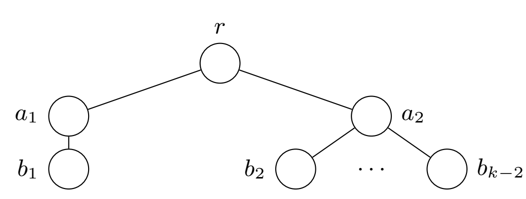

Figure 2: A tree in which no k-partition is in the $(\alpha, 0)$-imbalanced core for any $\alpha \geqslant 1$ and $k \geqslant 4$.

Our techniques extend to the case of forests; we consider trees for ease of exposition.

Theorem 11. *When $k \leqslant 3$ and the network is a tree, a k-partition in the imbalanced core always exists and can be found in polynomial time.*

Proof. For $k = 2$, this follows from Theorem 7.

Let $k = 3$ and (i_0, i_1) be a pair of nodes that are the farthest apart; note that both i_0 and i_1 must be leaves. Let p_0 and p_1 be the unique neighbors of i_0 and i_1, respectively. Let $X_0 = \{i_0\}$, $X_1 = \{i_1\}$, and $X_2 = V \setminus \{i_0, i_1\}$. Clearly, this can be computed in polynomial time. Suppose for contradiction that this is not in the imbalanced core and S is a blocking coalition. Note that if $i \in S \setminus \{i_0, i_1\}$, then $i \in \{p_0, p_1\}$, otherwise $u_i(X(i)) = |N(i)|$, preventing i from gaining by deviating with S.

Let L be the path between i_0 and i_1, and $|L|$ denote the number of edges in this path. Note that $n \geqslant 3$ implies $|L| \geqslant 2$. If $|L| = 2$, then the graph is a star. It is easy to check that the center of the star (equal to both p_0 and p_1) cannot gain from joining any coalition S of size at most $n - 2$, so there is no blocking coalition.

Next, suppose $|L| \geqslant 3$, so p_0 and p_1 are distinct. In particular, note that for each $t \in \{0, 1\}$, we have $u_{p_t}(X_2) = |N(p_t)| - 1$, so for p_t to deviate with S, we need $N(p_t) \subseteq S$.

When $|L| \geqslant 4$, each p_t has an adjacent node on L other than i_t and p_{1-t}. Since this node is adjacent to neither i_0 nor i_1, it is not in S. Hence, $p_0, p_1 \notin S$, which implies $i_0, i_1 \notin S$, which is a contradiction.

When $|L| = 3$, we have $L = (i_0, p_0, p_1, i_1)$. If p_0 and p_1 have no neighbors other than each other, i_0, or i_1, then the tree consists of only these four nodes; in this case, it is easy to see that the claimed partition is in the imbalanced core. Otherwise, without loss of generality, assume that p_0 has a neighbour $j \notin \{i_0, p_1\}$. From the previous argument, since j is not adjacent to i_0 or i_1, $j \notin S$. Since $u_{p_t}(X_2) = |N(p_t)| - 1$ for each $t \in \{0, 1\}$, this implies that p_0 would not join S, which in turn implies that p_1 would not join S. Then, $i_0, i_1 \notin S$ as well, which is a contradiction. Hence, the partition is in the imbalanced core. ☐

Finally, for $k \geqslant 4$, we show that the best approximation we can guarantee is the $(1, 1)$-imbalanced core.

Theorem 12. *Every k-partition of a tree is in the $(1, 1)$-imbalanced core. When $k \geqslant 4$, there exists a tree in which no k-partition is in the (α, β)-imbalanced core with any $\alpha \geqslant 1$ and $\beta < 1$.*

Proof. The proof for the positive result follows the same reasoning that we used in the proof of Theorem 10 to argue that every balanced k-partition of a tree is in the $(1, 1)$-core. Since any deviating coalition S is a subgraph of the tree, there must be $i \in S$ with $u_i(S) \leqslant 1$. Hence S cannot be a $(1, 1)$-blocking coalition.

Let us turn to the negative result for $k \geqslant 4$. Recall that in the proof of Theorem 10, we provided an example tree in which any balanced k-partition admits a deviating coalition of size 2 whose members go from receiving utility 0 to utility 1. Since this example used $n = k + 1$, a deviating coalition of size 2 is also allowed under the imbalanced core. Hence, this example shows the impossibility of achieving $(\alpha, 0)$-imbalanced core for any $\alpha \geqslant 1$. ☐

Trees and Envy Freeness

While we proved that EF-1 cannot be achieved for general graphs (Theorem 5), every tree has a balanced EF-1 partition.

Algorithm 3: EF1 Trees

$\forall j \in [k], X_j \leftarrow \emptyset$;
Phase 1:
for $i \in N$ **do**
  $X_{i \mod k} = X_{i \mod k} \cup i$
end for
Phase 2:
for $\ell = 2$ to d **do**
  for $i \in N$ with $level(i) = \ell$ that is envious for more than one agents **do**
    $i' \leftarrow$ an arbitrary child of i such that $X(i') = X(p(i))$
    $X(i') = X(i') \cup \{i\} \setminus \{i'\}$
    $X(i) = X(i) \cup \{i'\} \setminus \{i\}$
  end for
end for
return $X = (X_0, ..., X_{k-1})$

Theorem 13. *For any $k \geqslant 2$, we can find a balanced EF-1 k-partition for every tree, in polynomial time.*

Proof. We show that Algorithm 3 returns a balanced EF-1 k-partition for every tree, in polynomial time. The algorithm works as follows. Let d denote the depth of the tree. Without loss of generality, suppose the tree is labelled as following. Agent 0 is at level 1, agent 1 is the left most node of level 2, agent 2 is the second leftmost node of level 1, and so on, while agent $n - 1$ is the rightmost node of level d. Algorithm 3 first colors the nodes of the tree in a simple round-robin fashion to obtain EF-2 (in fact, it achieves a discrepancy bound of 2, whereby there are at most 2 more nodes of any color than of any other color), and then makes small edits to improve its guarantee to EF-1.

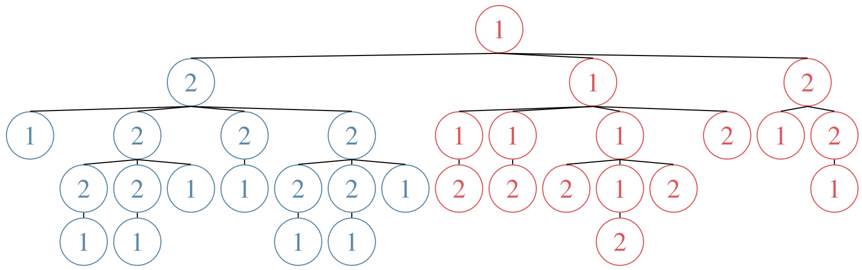

Figure 3: Instance that Algorithm 3 fails to provide weak Pareto Optimality, when k=2. Numbers illustrate the partition of Algorithm 3 and colors illustrate an EF-1 2-partition under which all agents improve their utility.

Suppose that at Line 6 of the algorithm, when $\ell = level(i)$, i is not envious for more than one agents. Then, when $\ell = level(i) + 1$, a child of i may be moved to the same part with i, but no child of i that is assigned to the same part with i is removed from it, while afterwards no neighbour of i is never moved to a different part. Hence, clearly, the partition remains EF-1 with respect to i.

Now, suppose i is envious for more than one agents. This means that before Line 5, $|X(i) \cap c(i)| = \lfloor |c(i)|/k \rfloor < |c(i,T)|/k$, and for some $i' \notin N(i)$, $|X(i') \cap c(i,T)| = \lceil |c(i,T)|/k \rceil$ and $X(i') = X(p(i))$. Then, i and one of her children that is assigned to $X(i')$ are swapped. Hence, i is currently assigned to the same group with at least $\lfloor |c(i,T)|/k \rfloor + 1$ of her neighbours while any other part still contains at most $\lceil |c(i,T)|/k \rceil$ neighbours of i. Thus, at Line 6 of the algorithm, when $\ell = level(i) + 1$, i is not envious for more than one agents, and by the same reasoning as above, we have that partition remains EF-1 with respect to i until the end of the algorithm. $\square$

There are cases that while Algorithm 3 returns an EF-1 balanced k-partition $X = (X_1, X_2)$, there exists an EF-1 balanced k-partition $X' = (X'_1, X'_2)$ under which all the agents receive higher utility. In other words, the algorithm fails to provide *weak Pareto Optimality*. For $k \geqslant 3$, simply consider the path graph P_{2k}, while for $k = 2$, consider the instance shown in Figure 3. The numbers in the nodes illustrate the part that each of them is assigned to according to Algorithm 3, and the red and blue nodes illustrate a balanced EF1 partition in which *all* the agents receive higher utility.

While the above algorithm efficiently computes a balanced EF-1 k-partition, this partition is not too desirable because it unnecessarily divides the friends of each agent between the different parts during the round-robin coloring; note that this coloring actually achieves a discrepancy bound of 2 . More concretely, in the appendix, we provide an instance in which a different balanced k-partition can provide strictly more utility to every agent. A more desirable partition with the same EF-1 guarantee is achieved via balanced min k-cut. While this is NP-hard to compute in general graphs even for $k = 2$, for trees, it is efficiently computable when $k = 2$, but NP-hard when k is part of the input (**?**). Recall that this partition minimizes the cut size and, hence, maximizes the social welfare.

Theorem 14. *For any $k \geqslant 2$ and when the network is a tree, every balanced min k-cut is EF-1.*

Proof. Let $X = (X_0, ..., X_{k-1})$ be a balanced min-k cut. Suppose for contradiction that there exists an agent i that is envious for more than one agents. This means that there exists $X_j \neq X(i)$ such that $X_j \cap N(i) > X(i) \cap N(i) + 1$. Let $i' = \arg\max_{t \in X_j} \text{level}(t)$, i.e. there is no other agent in X_j that is located in a higher level than i'. Hence, there is no child of i' in X_j. If we swap i and i', the movement of i' increases the number of edges that cross different parts by at most one, while the movement of agent i decreases the number of these edges by at least two. But, then $X = (X_0, ..., X_{k-1})$ would not be a balanced min-k cut which is a contradiction. $\square$

Finally, we consider the complexity of checking if a balanced EF k-partition exists in a given tree. We show that this is NP-hard when k is part of the input[6]. This is true even if the graph is a tree.

Theorem 15. *Checking if a given tree admits a balanced EF k-partition is NP-complete when k is part of the input.*

Proof. We reduce from the 3-Partition problem: Given $3k$ positive integers a_1,...,a_{3k} and A such that $A/4 < a_i < A/2$ for each $i \in [3k]$ and $\sum_{i \in [3k]} a_i = k \cdot A$, 3-Partition instance admits a solution if the numbers can be partitioned into triples such that each triple adds up to A. Notice that as all the integers are positive, $A \geqslant 3$.

Given an instance I of 3-Partition problem, we construct a tree $G_I = (V_I, E_I)$ as follows. For each a_i, we construct a star with root r_i and $2a_i - 1$ leaves. Notice, that as a_i-s are positive integers $2a_i - 1 \geqslant 1$, and thus each r_i has at least one leaf adjacent to it. Moreover, we add a star with root r^* and $2A - 1$ leaves, and each r_i is connected with r^*. Thus, $|V_i| = 2(k+1)A$. Figure 4 shows G_I given an instance I of 3-Partition problem.

[6]When k is a constant, the problem can be solved efficiently via dynamic programming.

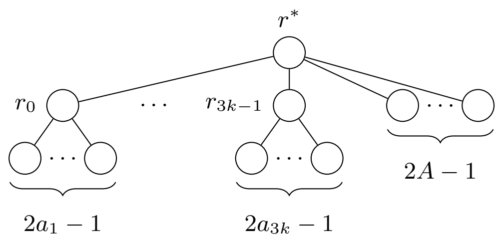

Figure 4: An example of G_I given an instance I of 3-Partition problem

We show that G_I admits an EF $k+1$-partition if and only if I admits a solution. We denote with $c(v, G_I)$ all the children of a node v in G_I. If I admits a solution, then each r_i along all of its children are assigned to the same part with some $r_{i'}$, if a_i and $a_{i'}$ are assigned to the same triple under the solution of I, and $X_0 = \{\{r^*\} \cup (c(r^*, G_I) \setminus_{\cup i \in [3k]} \{r_i\})\}$. Each X_j for $j \in \{1, ..., 3k-1\}$ contains exactly three r_i-s. We claim that $X = (X_0, ...X_{k-1})$ is an EF k-partition. Indeed, each node that has as parent some r_j or r^* is assigned to the same group with its unique neighbour, each r_j is assigned to the same group with all of its children, and as each of them has at least one child, they cannot envy any node that is assigned to the same group with r^*, and since $A \geqslant 3$, r^* does not envy any node that is assigned to the same group with three r_j-s.

Now, assume that $X = (X_0, ..., X_{k-1})$ is an EF k-partition. We see that there exists $j \in [k]$ such that $X_j = \{\{r^*\} \cup (c(r^*, T) \setminus_{\cup i \in [3k]} \{r_i\})\}$, as otherwise some node in $c(r^*, G_I) \setminus_{\cup i \in [3k]} r_i$ is not assigned to the same group with r^*, and then the only way for the partition to be EF is if no other agent is assigned to the same part with r^*, which is not possible. Similarly, each r_j should be assigned to the same group with each of its children. Thus, for each r_i and $r_{i'}$ that are assigned to the same part if we assign a_i and a_i' to the same triple, we find a solution for I. $\square$