Fairly Dividing Mixtures of Goods and Chores under Lexicographic Preferences

Hadi Hosseini
Pennsylvania State University
University Park, PA, USA
hadi@psu.edu

Sujoy Sikdar
Binghamton University
Binghamton, NY, USA
ssikdar@binghamton.edu

Rohit Vaish
Indian Institute of Technology Delhi
New Delhi, India
rvaish@iitd.ac.in

Lirong Xia
Rensselaer Polytechnic Institute
Troy, NY, USA
xial@cs.rpi.edu

ABSTRACT

We study fair allocation of indivisible goods and chores among agents with *lexicographic* preferences—a subclass of additive valuations. In sharp contrast to the goods-only setting, we show that an allocation satisfying *envy-freeness up to any item* (EFX) could fail to exist for a mixture of *objective* goods and chores. To our knowledge, this negative result provides the *first* counterexample for EFX over (any subdomain of) additive valuations. To complement this non-existence result, we identify a class of instances with (possibly subjective) mixed items where an EFX and Pareto optimal allocation always exists and can be efficiently computed. When the fairness requirement is relaxed to *maximin share* (MMS), we show positive existence and computation for *any* mixed instance. More broadly, our work examines the existence and computation of fair and efficient allocations both for mixed items as well as chores-only instances, and highlights the additional difficulty of these problems vis-à-vis their goods-only counterparts.

KEYWORDS

Fair Division

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1 INTRODUCTION

Fair division of indivisible items encompasses a wide array of real-world applications such as inheritance division [18], allocation of public housing units [12], course allocation [19], and distribution of medical equipment and human resources [3, 9, 43]. These applications often require dealing with resources that can simultaneously be seen as *goods* by some agents, generating positive utility, and as *chores* by others, generating negative utility. For example, medical supplies such as vaccines or ventilators [43] may result in negative utilities for some regions due to storage or maintenance costs, while being generally seen as positively valued resources by others. Another example is the practice of including a service charge in restaurant bills: It is positively valued by the restaurant staff, but has negative value for customers who did not like the food.

A standard solution concept in the study of fairness is *envy-freeness* [24, 26], which requires that no agent prefers another agent's allocation to its own. With indivisible (or discrete) resources, envy-freeness cannot always be guaranteed, motivating the study of its relaxations. A well-studied, and arguably most desirable, relaxation is *envy-freeness up to any item* (EFX), which states that any pairwise envy can be eliminated by removing *any* item; more specifically, by removing any item considered as a *good* from the envied agent's bundle and *any* item seen as a *chore* from the envious agent's bundle [4, 20].

For goods-only problems with additive valuations, the existence and computation of an EFX allocation—except for a few special cases [21, 41, 44]—remains a major open question. Moreover, EFX is known to be incompatible with well-studied notions of economic efficiency such as *Pareto optimality* (PO). For chores-only problems or those involving a mixture of goods and chores, little is known about the existence and computation of EFX under additive valuations. Complicating matters further, many of the algorithmic techniques from the goods-only setting do not carry over to mixed items [4, 15, 16, 49].

One plausible approach for tackling such challenging problems is *domain restriction*. This approach has been widely adopted in the computational social choice literature to investigate structural and computational boundaries of collective decision-making [23, 25, 32]. In this vein, we focus on *lexicographic preferences*, a subdomain of additive valuations, to study existential and computational questions regarding EFX allocations. Lexicographic preferences provide a succinct language for representing complex preferences [39, 45], and have been widely-studied in psychology [31], machine learning [46], and social choice theory [47].

Lexicographic preferences arise in a variety of settings where preferences over alternatives are formed based on priorities. For example, members of a team developing a web application for a course project may have different priorities over being assigned roles such as front-end or back-end developer, designer and project manager, etc. An agent with previous web development experience may consider developer roles to be good and others as chores, and might prefer any combination of roles that include a development component over any combination that does not.

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Restricting preferences to the lexicographic domain has already proven fruitful for goods-only instances. Indeed, Hosseini et al. [34] have shown that for the goods problem under lexicographic preferences, an EFX and PO allocation always exists and can be computed efficiently. Furthermore, they also characterized the class of fair (EFX) and economically efficient (PO) mechanisms satisfying other desirable economic properties such as strategyproofness. Despite these positive results, the chores-only and the mixed item problems have largely remained unexplored due to several additional challenges that we describe next.

Challenges of Mixed Items: The mixed items problem presents many new challenges compared to the goods problem. First, for indivisible goods, several well-studied variations of *picking sequences* [6, 14, 17, 32] satisfy EFX under lexicographic preferences [34]. However, for mixed items, these variants may violate EFX even for two agents with lexicographic preferences, as we illustrate in Example 1 below. Second, for goods-only instances under lexicographic preferences, any allocation computed by a picking sequence satisfies Pareto optimality [34]. By contrast, for mixed items, sequencibility does not imply Pareto optimality, which makes the mixed items setting challenging from the perspective of algorithm design.

Example 1. Suppose there are two agents $1, 2$ and four items $o_1, \ldots, o_4$. Each agent i has an importance ordering $\rhd_i$ which is a strict linear order over the individual items, as shown below:

$$1: \underline{o_1^-} \rhd \underline{o_2^+} \rhd o_3^+ \rhd o_4^+$$
$$2: o_2^+ \rhd o_1^- \rhd \underline{o_3^+} \rhd \underline{o_4^-}$$

The superscripts + or − denote whether the agent considers the item to be a good or a chore, respectively. Thus, the item o_4 is a good for agent 1 but a chore for agent 2, while o_2 and o_3 are "common goods" and o_1 is a "common chore". The above instance contains *subjective* mixed items because there is an item, namely o_4, for which agents differ on whether it is a good or a chore.

An agent's preference over bundles of items is given by the *lexicographic extension* of its importance ordering $\rhd$ as follows: Agent 1 prefers any bundle that does not contain the chore o_1 (including the empty bundle) to any bundle that does, subject to which it prefers any bundle containing the good o_2 to any bundle that does not, and so on. Similarly, agent 2 prefers any bundle containing the good o_2 to any other bundle that does not, subject to which any bundle without the chore o_1 is preferred over any bundle with it, and so on.

Consider the picking sequence 1221 wherein agent 1 picks its favorite item first, followed by back-to-back turns for agent 2 to pick its favorite remaining item, before agent 1 picks the leftover item. The allocation induced by this picking sequence is underlined in the above instance: First, agent 1 picks o_2 (its favorite good), followed by agent 2 picking o_3 (its favorite remaining good) and then o_4 (the chore it dislikes less between o_1 and o_4), and finally agent 1 is left to pick its most-disliked chore o_1.

It is easy to verify that this allocation is neither EFX nor Pareto optimal. Indeed, agent 2 continues to envy agent 1 even after the perceived chore o_4 is removed from its own bundle. Moreover, the above allocation is Pareto dominated by an allocation that gives all items to agent 2. □

Contributions. We undertake a systematic examination of the existential and computational boundaries of fair division under lexicographic preferences. The key conceptual takeaway from our work is that the mixed items problem can be significantly more challenging—both structurally and computationally—than its goods-only counterpart. Below we list some important points of distinction between these models that emerge from our study (also see Table 1).

- **Envy-freeness**: We show that the problem of determining the existence of an envy-free allocation is NP-complete even for lexicographic chores-only instances (Theorem 1). By contrast, for goods, this problem has a polynomial-time algorithm [34]. Since lexicographic preferences are a subclass of additive valuations, our intractability result extends to the latter domain and strengthens the known hardness results for this problem.

- **EFX**: Our main result is that an EFX allocation can fail to exist even for instances with *objective* mixed items (i.e., where each item is either a good for all agents or a chore for all agents) under lexicographic preferences (Theorem 2). This result provides the *first* counterexample for EFX over (any subdomain of) additive valuations (Corollary 2), and complements the ongoing research effort in understanding the existence of such solutions. By contrast, an EFX allocation always exists for goods under lexicographic preferences [34], and we show a similar positive result for the chores-only problem (see the full version [35]).

- **EFX and PO**: Given the failure of existence of EFX (and thus EFX+PO) allocations even for objective mixed items, we identify a natural domain restriction where EFX+PO allocations are guaranteed to exist even with *subjective* mixed items and are efficiently computable (Theorem 3). Notably, our algorithm returns PO solutions despite the failure of the equivalence between PO and sequencibility for mixed items as observed in Example 1.

- **MMS**: Under lexicographic preferences, EFX is a strictly stronger notion than *maximin share* or MMS (Proposition 4). When EFX is weakened to MMS, we show universal existence and efficient computation for *any* mixed instance (Theorem 4).

In addition, we consider other notions of fairness and efficiency (such as EF1 and rank-maximality) and paint a comprehensive picture of the existential and computational landscape of fair division under lexicographic preferences. We refer the reader to the full version of the paper [35] for all missing proofs and detailed algorithms.

2 RELATED WORK

Fair division of indivisible items has been most extensively studied in a model where the resources are *goods*. In this model, it is known that an allocation satisfying envy-freeness up to one good (EF1)—a property weaker than EFX—can be computed in polynomial time under additive [20] as well as the significantly more general class of monotone valuations [40]. Furthermore, under additive valuations, EF1 is known to be compatible with PO [20], and an EF1+PO allocation can be computed in pseudo-polynomial time [10].

Guarantee(s)		Goods		Chores		Mixed Items		Special Cases
		existence	computation	existence	computation	existence	computation	
	EF	✗	P†	✗	NP-c (Thm. 1)	✗	NP-c (Thm. 1)	
	EFX	✓	P†	✓	P*	✗ (Thm. 2)	Open	✓ (Thm. 3; Cor. 3)
	EF1	✓	P§	✓	P§	✓	P§	
	MMS	✓	P†	✓	P*	✓	P (Thm. 4)	
PO +	EF	✗	P†	✗	NP-c*	✗	NP-c*	
	EFX	✓	P†	✓	P*	✗ (Thm. 2)	Open	
	EF1	✓	P§	✓	P (Cor. 1)	Open	Open	✓ (Thm. 3; Cor. 3)
	MMS	✓	P†	✓	P*	Open	Open	
RM +	EF	✗	P†	✗	NP-c*	✗	NP-c*	
	EFX	✗	NP-c†	✗	NP-c*	✗	NP-c†	
	EF1	✗	NP-c†	✗	NP-c*	✗	NP-c†	
	MMS	✗	P†	✗*	P*	✗	Open	

Table 1: Summary of results for lexicographic preferences. For existence results, a ✓ indicates guaranteed existence while a ✗ indicates that existence might fail (even for *objective* instances for mixed items). PO and RM refer to Pareto optimality and Rank maximality, respectively. For computational results, P and NP-c refer to polynomial time and NP-complete, respectively. Results marked by † follow from Hosseini et al. [34], and those with § follow from Aziz et al. [4]. Results marked by ⋆ are in the full version of this paper [35]. Our contributions are highlighted by shaded boxes.

For the stronger property of EFX, the existence question for goods under additive valuations is a major open problem. Unfortunately, EFX is known to also be incompatible with PO for non-negative additive valuations [44]. Interestingly, these obstacles disappear when the preference domain is restricted to lexicographic preferences. In this domain, not only does an EFX and PO allocation always exist, but such an allocation can also be efficiently computed. Furthermore, there is a family of algorithms that can guarantee EFX and PO alongside strategyproofness and other desirable properties [34]. By contrast, under additive valuations, achieving strategyproofness together with EF1 is known to be impossible even for two agents [1]. It is relevant to note that the domain restriction approach towards EFX has been quite successful. Indeed, an EFX allocation is guaranteed to exist when agents have identical monotone valuations [44], or submodular valuations with binary marginals [7, 48], or additive valuations with at most two distinct values [2, 27].

Guaranteeing fairness and efficiency becomes more challenging when some items are chores. For such *mixed items* problems, Aziz et al. [4] showed that under additive valuations, an EF1 allocation can be computed efficiently by the double round-robin algorithm. On the other hand, establishing the (non-)existence of EFX allocations for mixed items under additive valuations has been an open question, which we answer in this paper. Whether EF1 can be achieved alongside PO for mixed items seems to be a challenging problem, and it is not known whether such allocations always exist for three or more agents under additive valuations. A notable exception is the chores-only problem with bivalued additive valuations, where an EF1 and PO allocation can be computed in polynomial time [22, 28].

With additive valuations, an MMS allocation could fail to exist for both the goods-only setting [38] and the chores-only setting [5]. This has given rise to several cardinal [5, 29, 30] and ordinal [8, 33] approximation techniques. For goods-only and chores-only problems with additive valuations, MMS allocations are only known to always exist for restricted domains such as personalized bivalued valuations, and allocations that are MMS and PO can be computed in polynomial time under the restrictions of factored bivalued valuations and weakly lexicographic valuations (allowing for ties between items) [22]. For mixed items under additive valuations, no multiplicative approximation of MMS can be achieved [37]. These negative results motivate the study of existence and computation of MMS (and its combination with efficiency notions) under restricted domains such as lexicographic preferences as we do in Section 4.4.

The term "mixed" has also been used to refer to mixture of indivisible and divisible resources in the literature [11, 15]. In this paper we only consider mixture of indivisible items (goods and chores).

3 PRELIMINARIES

Model. For any $k \in \mathbb{N}$, we define $[k] \coloneqq \{1, \ldots, k\}$. An instance of the allocation problem with *mixed items* is a tuple $\langle N, M, G, C, \rhd \rangle$ where $N \coloneqq [n]$ is a set of n *agents* and M is a set of m *items* $\{o_1, \ldots, o_m\}$. Here, $G \coloneqq (G_1, \ldots, G_n)$ and $C \coloneqq (C_1, \ldots, C_n)$ are collections of subsets of M, where, for each $i \in [n]$, $G_i \subseteq M$ is the set of *goods* and $C_i = M \setminus G_i$ is the set of *chores* for agent i, respectively. Additionally, $\rhd \coloneqq (\rhd_1, \ldots, \rhd_n)$ is a *importance profile* that specifies for each agent $i \in N$ an *importance ordering* $\rhd_i \in \mathcal{L}$ over the individual items in M in the form of a linear order; here $\mathcal{L}$ is the set of all (strict and complete) linear orders over M (all goods and chores). For example, we write $o_1^+ \rhd_i o_2^- \rhd_i o_3^+$ to indicate that agent i considers items o_1 and o_3 as goods and the item o_2 a chore, and ranks o_1 above o_2 and o_2 above o_3 in its importance ordering.[1]

[1]Not to be interpreted as "agent i *prefers* chore o_2 over good o_3"; see the paragraph on 'Lexicographic Preferences' for the exact definition.

We use $\triangleright_i(k)$ to denote the k-th ranked item in the importance ordering of agent i, $\triangleright_i(k, S)$ to specify the k-th ranked item for agent i among items in set S, and $\triangleright_i([k], S) := \{\triangleright_i(1, S), \triangleright_i(2, S), \ldots, \triangleright_i(k, S)\}$ to denote the set of k top-ranked items in S. Thus, in the above example, $\triangleright_i(1) = o_1$, $\triangleright_i(1, \{o_2, o_3\}) = o_2$, and $\triangleright_i([2], \{o_1, o_2, o_3\}) = \{o_1, o_2\}$.

In an instance with **objective** mixed items, each item is either a good for all agents or a chore for all agents. That is, for any pair of agents $i, j \in N$, we have $G_i = G_j$ and $C_i = C_j$. In a *goods-only* (respectively, *chores-only*) instance, every item is a good (respectively, a chore) for all agents, i.e., for every agent $i \in N$, we have $G_i = M$ (respectively, $C_i = M$).

Bundles. A *bundle* is any subset $X \subseteq M$ of the items. Given any bundle $X \subseteq M$, we will write $X^{i+} := X \cap G_i$ and $X^{i-} := X \cap C_i$ to denote the sets of goods and chores in X, respectively, according to agent i.

Allocations. An *allocation* $A = (A_1, \ldots, A_n)$ is an n-partition of M, where $A_i \subseteq M$ is the bundle assigned to agent i. We will write $\Pi(M)$ to denote the set of all n-partitions of M. We say that an allocation A is *partial* if $\bigcup_{i \in N} A_i \subset M$, and *complete* if $\bigcup_{i \in N} A_i = M$. Unless stated explicitly otherwise, an 'allocation' will refer to a complete allocation.

One of the conceptual contributions of our work is to formalize the notion of lexicographic preferences for mixed items.

Lexicographic Preferences. We will assume that agents' preferences over bundles are given by the lexicographic extension of their importance orderings $\triangleright := (\triangleright_1, \ldots, \triangleright_n)$. Recall that each importance ordering $\triangleright_i$ is itself a linear order over the individual items. An agent's preference over the bundles is obtained by lexicographically extending its importance ordering $\triangleright_i$ taking into account whether an item is considered a good or a chore.

Informally, this means that an agent with importance ordering $o_1^+ \triangleright o_2^- \triangleright o_3^+$ prefers any bundle that contains the good o_1 over any bundle that does not, subject to that, it prefers a bundle that *does not* contain the chore o_2 over any other bundle that contains o_2, and so on. The importance ordering $o_1^+ \triangleright o_2^- \triangleright o_3^+$ over individual items induces the ranking $\succ_i$ over the bundles given by $\{o_1^+, o_3^+\} \succ \{o_1^+\} \succ \{o_1^+, o_2^-, o_3^+\} \succ \{o_1^+, o_2^-\} \succ \{o_3^+\} \succ \emptyset \succ \{o_2^-, o_3^+\} \succ \{o_2^-\}$, where $\emptyset$ denotes the empty bundle.

Formally, given any two non-identical bundles X and Y, let $z := \triangleright_i(1, X \Delta Y)$ be the the most important item according to $\triangleright_i$ in their symmetric difference.[2] We say that agent i prefers bundle X over bundle Y, denoted as $X \succ_i Y$, if and only if either $z \in G_i \cap X$ or $z \in C_i \cap Y$. That is, if z is a good, agent i prefers the bundle containing z, and otherwise if z is a chore, then agent i prefers the bundle that does not contain z. For any agent $i \in N$, and any pair of bundles $X, Y \subseteq M$, we will write $X \succeq_i Y$ if either $X \succ_i Y$ or $X = Y$.

Envy-Freeness and its Relaxations. An allocation A is (a) *envy-free* (EF) if for every pair of agents $i, h \in N$, $A_i \succeq_i A_h$, (b) *envy-free up to one item* (EF1) if for every pair of agents $i, h \in N$ such that $A_i^{i-} \cup A_h^{i+} \neq \emptyset$, there exists an item $o \in A_i^{i-} \cup A_h^{i+}$ such that either $A_i \succeq_i A_h \setminus \{o\}$ or $A_i \setminus \{o\} \succeq_i A_h$, and (c) *envy-free up to any item* (EFX) if for every pair of agents $i, h \in N$ such that $A_i^{i-} \cup A_h^{i+} \neq \emptyset$, it holds for *every* item $o \in A_h^{i+} \cup A_i^{i-}$, that (i) if $o \in A_h^{i+}$, then $A_i \succeq_i A_h \setminus \{o\}$ and (ii) if $o \in A_i^{i-}$, then $A_i \setminus \{o\} \succeq_i A_h$. In the full version [35], we define two relaxations of EFX, which we denote as EFX-c and EFX-g. where only chores (respectively, only goods) can be removed. Interestingly, our counterexample for EFX (Theorem 2) holds even for EFX-c while an EFX-g allocation always exists.

[2]Here, Δ is the symmetric set difference operator, i.e. $X \Delta Y = (X \setminus Y) \cup (Y \setminus X)$.

Maximin Share. An agent's maximin share is its most preferred bundle that it can guarantee itself as a divider in an n-person cut-and-choose procedure against adversarial opponents [19]. Formally, the maximin share of agent i is given by $\text{MMS}_i := \max_{i P \in \Pi(M)} \min_i \{P_1, \ldots, P_n\}$, where $\min_i\{\cdot\}$ and $\max_i\{\cdot\}$ denote the least-preferred and most-preferred bundles with respect to $\succ_i$. An allocation A satisfies *maximin share* (MMS) if each agent receives a bundle that it weakly prefers to its maximin share, i.e., for every agent $i \in N$, $A_i \succeq_i \text{MMS}_i$.

Pareto Optimality. Given a importance profile $\triangleright$, an allocation A is said to be *Pareto optimal* (PO) if there is no other allocation B such that $B_i \succeq_i A_i$ for every agent $i \in N$ and $B_h \succ_h A_h$ for some agent $h \in N$. To avoid vacuous solutions such as leaving all chores unassigned, we will always require a Pareto optimal allocation to be complete.

Rank-Maximality. A *rank-maximal* (RM) allocation [36, 42] is one that maximizes the number of agents who receive their highest-ranked good (i.e., ranked first in importance ordering among all goods), subject to which it maximizes the number of agents who receive their second-highest good, and so on, subject to which it maximizes the number of agents who receive their lowest-ranked chore (i.e., ranked last in importance ordering among all chores), subject to which it maximizes the number of agents who receive the second-lowest chore, and so on.

Given an allocation A, its *signature* refers to a tuple $(n_1^+, n_2^+, \ldots, n_m^+, n_1^-, n_2^-, \ldots, n_m^-)$ where $n_k^+ = |\{i \in N : \triangleright_i(k, G_i) \in A_i\}|$ is the number of agents who receive their k-th highest ranked good and $n_k^- = |\{i \in N : \triangleright_i(m-k, C_i) \in A_i\}|$ is the number of agents who receive their k-th lowest ranked chore (equivalently, $(m-k)$-th highest ranked chore). An allocation A is rank-maximal if its signature is lexicographically maximized.

Picking Sequence. A *picking sequence* of length k is an ordered tuple $\langle s_1, s_2, \ldots, s_k \rangle$ where, for each $i \in [k]$, $s_i \in N$ denotes the agent who picks its favorite available item, that is, its top-ranked remaining good (if one exists) or otherwise its bottom-ranked remaining chore as per its importance ordering $\triangleright_i$. A *sequencible* allocation is one that can be simulated via a picking sequence.

For goods-only instances with additive preferences, every PO allocation is sequencible [14]. In the lexicographic domain, sequenciblity also implies PO for the goods problem [34].[3] In Proposition 1, we show that the equivalence between PO and sequenciblity also holds for lexicographic chores.

Proposition 1 (PO $\Leftrightarrow$ sequencible for chores). *Under lexicographic preferences, an allocation of chores is* PO *if and only if it is sequencible.*

[3]Note that under additive preferences, sequenciblity does not imply PO. For example, the round robin algorithm does not guarantee PO.

Given that an EF1 allocation for chores can be computed through a picking sequence [4], an immediate implication of Proposition 1 is a polynomial-time algorithm for computing an EF1+PO allocation of chores under lexicographic preferences.

Corollary 1 (EF1+PO for chores). *Under lexicographic preferences an* EF1+PO *allocation of chores can be computed in polynomial time.*

However, when dealing with *mixed* items, sequencibility is no longer a sufficient condition for guaranteeing PO, even in the lexicographic domain.

Proposition 2 (PO and sequencibility for mixed items). *For mixed items under lexicographic preferences, Pareto optimality implies sequencibility, but the converse is not true even for objective mixed items.*

Proof. (sketch) To see why sequencibility does not imply PO, consider the objective mixed items instance with three items $\{o_1^+, o_2^+, o_3^-\}$ and two agents where agent 1's importance ordering is $o_1^+ \rhd o_2^+ \rhd o_3^-$, and agent 2's ordering is $o_3^- \rhd o_1^+ \rhd o_2^+$. The picking sequence $\langle 1, 2, 2\rangle$ allocates $\{o_1^+\}$ to agent 1 and $\{o_3^-, o_2^+\}$ to agent 2. However, this allocation is Pareto dominated by the allocation that gives all items to agent 1.

Given an instance with mixed items, there always exists a Pareto optimal allocation (since there are only finitely many allocations and Pareto domination is a transitive relation). Furthermore, one such allocation can be computed in polynomial time; in particular, the *rank-maximal* allocation is Pareto optimal [35]. □

4 RESULTS

We start our investigation by considering the strongest fairness notion—*envy-freeness*. As we will see, this notion will provide us our first point of distinction between goods and chores.

4.1 Envy-Freeness

With indivisible items, a complete and envy-free allocation may not always exist. Thus, it is of interest to ask whether one can efficiently determine the existence of such solutions. This problem admits a polynomial-time algorithm in case of goods under lexicographic preferences [34], but turns out to be NP-complete for chores, and by extension, for mixed items (Theorem 1).

Theorem 1 (EF for chores). *Determining whether a chores-only instance with lexicographic preferences admits an envy-free allocation is* NP-complete.

To understand the reason behind the sharp contrast in the complexity of the goods and chores problems, notice that for goods under lexicographic preferences, an allocation is envy-free if and only if each agent gets its top-ranked item. One can efficiently check whether there exists a partial allocation satisfying this property via a straightforward matching computation (by considering a bipartite graph whose vertex sets are the agents and the items and an edge between each agent and its top-ranked item). Furthermore, if such a partial allocation exists, *any* completion of it is also envy-free.

By contrast, envy-freeness for chores entails that for every agent, the *worst* or least-preferred chore (i.e., highest-ranked in the importance ordering) in its own bundle is strictly preferred over the worst chore in any other agent's bundle. Thus, given an envy-free partial allocation, its completion may no longer be envy-free since, upon receiving more items, a different chore could become the worst.

We note that the allocation constructed in the forward direction in the proof of Theorem 1 is sequencible. Due to the equivalence between sequencibility and PO (Proposition 1), this implies that NP-hardness also holds for EF+PO. Furthermore, the EF+PO problem is actually NP-complete because EF and PO are both efficiently checkable properties; the latter because of its equivalence with sequencibility which can be checked in polynomial time.[4]

4.2 Envy-Freeness up to any Item (EFX)

Let us now turn our attention to a relaxation of envy-freeness called envy-freeness up to any item (EFX). Prior work has shown that an EFX and Pareto optimal allocation always exists for goods under lexicographic preferences [34]. In the full version [35], we show that a similar positive result can be achieved for the chores-only problem via the following simple procedure: Fix a priority ordering σ over agents. Let the first agent in σ pick its most preferred $m - n$ chores. Then, all agents (including the first agent) pick one chore each according to σ from the remaining items.

Our main result in this section is that the above positive results for goods-only and chores-only models fail to extend to the mixed items setting: We show that an EFX allocation may not exist even for *objective* mixed items, i.e., when each item is either a common good or a common chore (Theorem 2).

Theorem 2 (Non-existence of EFX). *There exists an instance with objective mixed items and lexicographic preferences that does not admit any* EFX *allocation.*

Since lexicographic preferences are a subclass of additive valuations, our counterexample also shows that an EFX allocation fails to exist under non-monotone and additive valuations (Corollary 2).[5] Our result complements that of Bérczi et al. [13] who showed that an EFX allocation could fail to exist for two agents with non-monotone, *non-additive*, and identical utility functions.

Corollary 2. *An* EFX *allocation can fail to exist for instances with non-monotone and additive valuations.*

The counterexample in the proof of Theorem 2 (given below) uses only *four* agents and *seven* items. Interestingly, for the said number of agents and items, an EFX allocation is guaranteed to exist for *goods-only* instances even under *monotone* valuations [41], which is significantly more general than additive (or lexicographic) preferences. It is also known that when agents belong to one of two given "types", an EFX allocation is guaranteed to exist for *goods-only* instances under *monotone* valuations [41]. Our result

[4]To verify sequencibility of a given allocation, consider the following procedure: Identify all chores that are allocated to agents who "prefer them the most" (i.e., chores that are lowest ranked in the importance orderings of their owners). Add these chores to the sequence and remove them from further consideration. Now, among the remaining chores, again identify the ones allocated in the "most preferred" manner (i.e., lowest ranked in the owner's importance ordering among the remaining chores). Again, add these chores to the sequence and remove them from further consideration. Repeat this process for as long as possible. It can be observed that the given allocation is sequencible if and only if the sequence constructed above includes all chores.

[5]A valuation function $v_i : 2^M \to \mathbb{R}$ is *non-monotone* if for some subsets $T \subset S \subseteq M$, we have $v_i(T) > v_i(S)$ and for some (possibly different) subsets $T' \subset S' \subseteq M$, we have $v_i(T') < v_i(S')$.

in Theorem 2, which also has two types of agents, demonstrates a barrier to extending this result in the non-monotone setting, even under lexicographic preferences.

Proof. (of Theorem 2) Consider an objective mixed items instance with four agents. Agents 1 and 2 have the same importance ordering, and so do agents 3 and 4, as shown below:

$$\begin{aligned} 1,2 &: \quad o_2^- \rhd o_3^- \rhd o_4^- \rhd o_1^+ \rhd o_5^- \rhd o_6^- \rhd o_7^- \\ 3,4 &: \quad o_5^- \rhd o_6^- \rhd o_7^- \rhd o_1^+ \rhd o_2^- \rhd o_3^- \rhd o_4^- \end{aligned}$$

Since the items are objective, we will find it convenient to use the phrases 'the good o_1' and 'the chore o_2' instead of just calling them 'items'.

Suppose, for contradiction, that an EFX allocation exists. Without loss of generality, suppose agent 1 gets the good o_1^+. Let A_i denote the bundle allocated to agent i. We will show a contradiction via case analysis, depending on the chores allocated to agent 1.

Case 1: Suppose $A_1 \cap \{o_2^-, o_3^-, o_4^-\} = \emptyset$. That is, agent 1's allocated chores are a (possibly empty) subset of $\{o_5^-, o_6^-, o_7^-\}$, which are all ranked below o_1^+ according to agent 1's importance ordering.

This means that regardless of what agent 2 gets, it prefers the bundle A_1 to its own bundle A_2. Therefore, A_2 must be empty, as otherwise agent 2 will prefer A_1 even when some chore is removed from A_2. Thus, the chores o_2^-, o_3^-, and o_4^- must be allocated to agents 3 and 4, which means that one of these agents must get at least two of these chores. Suppose, without loss of generality, that agent 3 gets at least two chores. Then, agent 3 would prefer the empty bundle A_2 after any chore is removed from A_3, a contradiction to EFX.

Case 2: Suppose $A_1 \cap \{o_5^-, o_6^-, o_7^-\} = \emptyset$. That is, agent 1's allocated chores are a subset of $\{o_2^-, o_3^-, o_4^-\}$, which are all ranked above o_1^+ according to agent 1's importance ordering.

This means that regardless of how the remaining chores are assigned, both agents 3 and 4 will strictly prefer A_1 over their respective bundles (because their most important item in A_1 is o_1^+). Now, if agent 3 or 4 is assigned any item, which must be a chore, then even after removing this chore, it would still envy A_1. Therefore, agents 3 and 4 cannot be allocated any item. This means that agent 2 gets at least $\{o_5^-, o_6^-, o_7^-\}$, which implies that after any item (which must be a chore) is removed from agent 2's bundle, agent 2 envies agent 3 (who is not allocated any item). This contradicts EFX.

Case 3: If $A_1 \cap \{o_2^-, o_3^-, o_4^-\} \neq \emptyset$ and $A_1 \cap \{o_5^-, o_6^-, o_7^-\} \neq \emptyset$. That is, agent 1 gets at least one chore above good o_1^+ and at least one chore below o_1^+ according to its importance ordering.

Choose any $x \in A_1 \cap \{o_2^-, o_3^-, o_4^-\}$ and $y \in A_1 \cap \{o_5^-, o_6^-, o_7^-\}$. Then, because of EFX, agent 1 should not prefer any other agent's bundle after y is removed from A_1. This means that for any $i \in \{2, 3, 4\}$, A_i must contain a chore that is ranked higher than x according to agent 1's importance order. However, there are at most two chores perceived to be ranked higher than x by agent 1, which contradicts EFX. □

ALGORITHM 1: Finding an EFX+PO allocation when there is an agent whose top-ranked item is a good.

Input: A lexicographic mixed instance $\langle N, M, G, C, \rhd \rangle$
Output: An EFX+PO allocation A
Select an arbitrary agent $i \in N$ such that $\rhd_i(1) \in G_i$
Let $C' := \{o \in M : \forall j \in N \setminus \{i\}, o \in C_j\}$ `// The set of all common chores for the remaining agents.`
$A_i \leftarrow \rhd_i(1) \cup C'$
$N \leftarrow N \setminus \{i\}$
$M \leftarrow M \setminus A_i$
▷ `The remaining instance has no common chore.`
while *there exists an unallocated item* **do**
  if $|N| = 1$ **then**
    Assign all items to the remaining agent
  else
    Find the smallest $k \in \{1, 2, \ldots, |M|\}$ such that the set $S^k := \{i \in N : \rhd_i(k) \in G_i\}$ is non-empty `// set of agents whose` k^{th}`-ranked item is a good.`
    Select any agent $j \in S^k$
    $C' := \{o \in M : \forall i \in N \setminus \{j\}, o \in C_i\}$
    $A_j \leftarrow \{\rhd_j(k)\} \cup C'$
    $N \leftarrow N \setminus \{j\}$
    $M \leftarrow M \setminus A_j$
return A

4.3 EFX and Pareto optimality

We have seen that an EFX allocation may not exist for mixed items. This negative result prompts us to identify a subclass of lexicographic instances with subjective mixed items for which an EFX and Pareto optimal allocation is guaranteed to exist. Specifically, we will now require that there be an agent whose *top-ranked* item in its importance ordering is a good (Theorem 3).

Theorem 3 (EFX+PO when some agent has a top-ranked good). *Given a lexicographic mixed instance where some agent's top-ranked item is a good, an* EFX+PO *allocation always exists and can be computed in polynomial time.*

Proof. (sketch) Let us start by discussing why the allocation returned by our algorithm is EFX, followed by a similar discussion for PO.

Description of Algorithm and EFX Guarantee. Intuitively, the assumption about some agent's top-ranked item being a good allows us to deal with the common chores without violating EFX as follows (see Algorithm 1): An agent whose top-ranked item is a good can be assigned that item together with all items that are common chores for the rest of the $n-1$ agents. Since the preferences are lexicographic, this agent will not envy any other agent regardless of how the remaining items are allocated.

The first agent is now eliminated from the instance along with its assigned bundle. Observe that the reduced instance (with $n-1$ agents) has *no common chore*, that is, each item is considered as a good by at least one agent. The algorithm now uses the following strategy iteratively: It identifies an agent with the highest-ranking good (say agent j and good g), gives good g to agent j together with the common chores of the remaining $n-2$ agents, and then eliminates agent j.

Note that since agent j receives its highest-ranked good among the remaining items, it will not envy any agent that is eliminated *after* it, regardless of how the remaining items are assigned. Furthermore, by the 'no common chores' property, any item that is a chore for the rest of the agents must be a good for agent j. This means that agent j only receives those items that it considers to be goods. Thus, when evaluating EFX from agent j's perspective, we only need to look at the items in other agents' bundles that agent j considers to be goods. For any agent that was eliminated *before* j, there can be at most one such item (by virtue of assigning common chores), and thus EFX is maintained.

Guaranteeing PO. Suppose, for contradiction, that the allocation A returned by Algorithm 1 is Pareto dominated by the allocation B. We will argue by induction that for every agent i, we must have $A_i \subseteq B_i$, which would contradict Pareto optimality since A and B must be distinct. For ease of discussion, let us name the agents according to the order in which they are eliminated by Algorithm 1.

Recall from the above discussion on EFX that for each agent i, the most important item in its bundle under A, namely $\rhd_i(1, A_i)$, must be a good. We will first show by induction (over i) that every agent i must retain the item $\rhd_i(1, A_i)$ in B_i. Indeed, agent 1 must retain $\rhd_1(1, A_1)$ in B_1 because it is agent 1's most important item in M and is a good for agent 1. Suppose each agent $h \in \{1, \ldots, i-1\}$ retains $\rhd_h(1, A_h)$ in B_h. Then, by virtue of choosing an agent with the highest-ranking good (see Lines 11–14 in Algorithm 1), agent i's most important item in A_i, namely $\rhd_i(1, A_i)$, is also its most important "achievable" good, i.e., the most important item in the set $G_i \setminus \{\rhd_1(1, A_1), \rhd_2(2, A_2) \ldots, \rhd_{i-1}(1, A_{i-1})\}$. Therefore, due to lexicographic preferences, $\rhd_i(1, A_i)$ must be retained in B_i, implying the induction hypothesis.

A similar inductive argument in the reverse direction (i.e., $n, n-1, \ldots, 2, 1$) implies that for every agent i, we have $A_i \subseteq B_i$. Indeed, the last agent, namely agent n, must retain all of its items since every item in A_n is a good for agent n, and every item in $M \setminus \big(A_n \cup \{\rhd_1(1, A_1), \ldots, \rhd_{n-1}(1, A_{n-1})\}\big)$ is a chore. Thus, $A_n \subseteq B_n$.

Next, suppose $A_k \subseteq B_k$ for all agents $k \in \{n, n-1, \ldots, i+1\}$, where $i > 1$. We want to show that $A_i \subseteq B_i$. Since $i > 1$, all items in A_i are goods for agent i. If $A_i \setminus B_i \neq \emptyset$, then in order for B_i to be more preferable than A_i, there must be a good $g \in B_i \setminus A_i$ such that g has a higher importance than any item in $A_i \setminus B_i$. This, however, is not possible, since agent i gets its most important "achievable" good in A_i, i.e., the most important good in the set $G_i \setminus \{\rhd_1(1, A_1), \rhd_2(2, A_2) \ldots, \rhd_{i-1}(1, A_{i-1})\}$. Thus, $A_i \subseteq B_i$ for all $i \in \{2, 3, \ldots, n\}$. This, in turn, implies that $A_1 \subseteq B_1$, thereby finishing the induction and giving the desired contradiction. □

Another subclass of lexicographic instances where an EFX+PO allocation is guaranteed to exist is when every item is considered a good by at least one agent, i.e., there are no *common chores*.

Corollary 3 (EFX+PO for mixed instances without common chores). *Given a lexicographic mixed instance without any common chore, an* EFX+PO *allocation always exists and can be computed in polynomial time.*

Corollary 3 and our counterexample for EFX in Theorem 2 together raise an interesting question: Under lexicographic preferences, EFX allocation always exists with *zero* common chores (Corollary 3), but fails to exist with *six* common chores (Theorem 2). What happens for intermediate values 1, 2, 3, 4 or 5 common chores?

4.4 Maximin Share (MMS)

In light of the failure in guaranteeing EFX even for objective mixed items, we investigate the existence of MMS allocations for mixed items. We show that not only does an MMS allocation exist for *subjective* mixed items under lexicographic preferences, but also that such an allocation can be computed efficiently.

We start by characterizing MMS bundles by examining the structure of an agent's maximin share. Given a lexicographic mixed instance, an agent's maximin share is identified by its top-ranked item: If agent i's top-ranked item is a good, MMS_i is an empty set if the number of goods is less than the number of agents (i.e., $|G_i| < n$), or else it is the set of the least-preferred $|G_i| - n + 1$ goods. Otherwise, when agent i's top-ranked item is a chore, then MMS_i is uniquely defined by the union of the top-ranked item (worst chore) and all the goods.

Proposition 3 (Characterizing MMS for mixed items). *Given an instance $\langle N, M, G, C, \rhd \rangle$ with lexicographic mixed items, the maximin share of agent i can be defined based on whether its top-ranked item is a good or a chore, as follows:*

$$MMS_i = \begin{cases} G_i \setminus \rhd_i([n-1], G_i), & \text{if } \rhd_i(1) \in G_i \wedge |G_i| \geq n \\ \emptyset, & \text{if } \rhd_i(1) \in G_i \wedge |G_i| < n \\ \rhd_i(1, C_i) \cup G_i, & \text{if } \rhd_i(1) \in C_i. \end{cases}$$

Proof. The MMS partition of any agent $i \in N$ is uniquely defined based on whether its top-ranked item $\rhd_i(1)$ is a good or a chore:

Case 1. Top ranked item is a good, that is, $\rhd_i(1) \in G_i$: There are two cases according to the size of G_i.

(a) If $|G_i| \geq n$: the MMS partition for i is defined as

$$\{\{\rhd_i(1, G_i) \cup C_i\}, \{\rhd_i(2, G_i)\}, \ldots, \{\rhd_i(n-1, G_i)\}, G_i \setminus \{\rhd_i([n-1], G_i)\}\}.$$

The MMS partition for i is the least-preferred bundle. Since preferences are lexicographic, we have $\text{MMS}_i = G_i \setminus \bigcup_{l \in [n-1]} \{\rhd_i(l, G_i)\} = G_i \setminus \rhd_i([n-1], G_i)$.

(b) If $|G_i| < n$: the MMS partition for i is uniquely defined as

$$\{\{\rhd_i(1, G_i) \cup C_i\}, \{\rhd_i(2, G_i)\}, \ldots, \{\rhd_i(|G_i|, G_i)\}, \{\}, \ldots, \{\}\}.$$

Therefore, $\text{MMS}_i = \emptyset$.

Case 2. Top ranked item is a chore, that is, $\rhd_i(1) \in C_i$: The MMS partition is uniquely defined as

$$\{\{\rhd_i(1, C_i) \cup G_i\}, \{\rhd_i(2, C_i)\}, \ldots, \{\rhd_i(n, C_i)\}\}.$$

Note that if $|C_i| < n$, then $\{\rhd_i(k, C_i)\} = \emptyset$ for all $k < |C_i|$. The MMS for agent i is the least-preferred partition above. Since preferences are lexicographic, $\text{MMS}_i = \{\rhd_i(1, C_i) \cup G_i\}$. □

Although EFX may not always exist for mixed items (Theorem 2), we show that whenever such an allocation exists, it also satisfies

ALGORITHM 2: Algorithm for finding an MMS allocation for mixed items.

Input: A lexicographic mixed instance $\langle N, M, G, C, \rhd \rangle$
Output: An MMS allocation A

1 Let $C' \coloneqq \{o \in M : \forall i \in N,\ o \in C_i\}$
▷ `Step 1: Assign chores according to top-ranked items`
2 **if** $\exists i \in N$ *such that* $\rhd_i(1) \in G_i$ **then**
3   Run Algorithm 1
4 **else** `// Else if` $\forall i \in N, \rhd_i(1) \in C_i$
5   Fix a priority ordering σ over n agents
6   **if** $|C'| \geq n$ **then**
7   Run a serial dictatorship where σ_1 picks its favorite (lowest ranked) $|C'| - n + 1$ chores
8   All remaining agents pick one chore each (lowest ranked chore among remaining chores)
9   **else**
10   Agents pick one chore (lowest ranked chore that remains) according to σ, and none if no chore is remaining
11   If there exists an agent who picked its worst chore (first in importance ordering), give that agent its remaining goods
▷ `Step 2: Serial dictatorship to assign remaining items`
12 Run a serial dictatorship according to any priority ordering; agents pick any number of goods among remaining items or nothing (if no item is a good for them).
13 **return** A

MMS. Note that the converse does not hold, that is, even for chores-only instances (where EFX always exists), MMS does not imply EFX (refer to the full version [35]).

Proposition 4 (EFX $\implies$ MMS for mixed items). *For mixed items under lexicographic preferences, an* EFX *allocation (whenever it exists) satisfies* MMS*, but the converse is not true.*

We develop an algorithm that computes an MMS allocation for *any* lexicographic instance—even with subjective mixed items—in polynomial time.

Description of algorithm. Our algorithm (Algorithm 2) first identifies the set C' of all common chores and proceeds in two steps: In **Step 1**, all common chores are allocated without violating MMS, and in **Step 2**, all remaining items are allocated as goods.

Step 1. *If there exists an agent whose top-ranked item is a good,* then run Algorithm 1 to achieve an EFX allocation. By Proposition 4, EFX implies MMS for mixed items.

Otherwise, if every agent's top item is a chore, a priority ordering σ over agents is fixed, and a serial dictatorship is run where agent σ_1 picks its most preferred (least important) $|C'| - n + 1$ chores, from the set of all common chores, C', and the remaining agents each pick one remaining chore from C'. Note that if $|C'| < n$, the first $n - |C'|$ agents pick one chore and the rest receive nothing. If an agent k receives its worst chore from C_k, it is given its remaining goods in G_k.

Step 2. All remaining items are allocated through a serial dictatorship. In each turn, an agent picks all remaining items it considers as goods, or picks nothing. All remaining items are only allocated as goods, and thus, do not violate MMS.

Theorem 4 (MMS for mixed items). *Given a lexicographic mixed instance, there is a polynomial-time algorithm that computes an* MMS *allocation even for subjective items.*

Proof. Algorithm 2 guarantees MMS for *any* lexicographic instance with mixed items. Let A be the output of the algorithm.

Case 1. There exists an agent i with top-ranked item as a good. That is, $\rhd_i(1) \in G_i$. Then, run Algorithm 1 that satisfies EFX (and PO). By Proposition 4, any EFX allocation is also MMS, thus, Algorithm 2 is MMS. In this case, the algorithm does not allocate any item in 'Step 2', thus, the allocation vacuously remains MMS.

Case 2. Every agent's top-ranked item is a chore. That is, $\forall i \in N,\ \rhd_i(1) \in C_i$. The proof relies on allocating items that are considered as chores by all agents, i.e., $C' \coloneqq \{o \in M : \forall i \in N,\ o \in C_i\}$. All remaining items in $M \setminus C'$ by construction are considered goods by at least one agent. Algorithm 2 proceeds to first allocate items in C'—via a serial dictatorship specified by σ—such that the first agent σ_1 either receives its least important chore (if $|C'| < n$) or its $|C'| - n + 1$ least important chores (if $|C'| \geq n$). All other agents pick a single chore from $C' \setminus A_{\sigma_1}$ or an empty set, which satisfies MMS.

Suppose agent h receives its most disliked (i.e., rank 1 in importance ordering) chore in C_h. Then, since C' did not contain any item that is considered good by any agent, agent h receives all goods in G_h (Line 11) and $A_h = \rhd_h(1, C_h) \cup G_h$. Notice that only the last agent to pick a chore from C' (according from σ) can receive its worst (top-ranked) chore. If an agent h does not receive $\rhd_h(1, C_h)$, then $A_h \succeq_h \rhd_h(1, C_h) \cup G_h$ by lexicographic preferences. Together, this implies implies that A satisfies MMS by Proposition 3. The allocation of remaining items only improves the outcome for all agents since all remaining items are assigned as goods in a serial dictatorship by Algorithm 2 (Line 12). Thus, all agents' allocations weakly improves. ◻

The significance of Theorem 4 stems from providing an efficient algorithm for computing an MMS allocation for any lexicographic mixed instance (including subjective instances). Yet, the problem of computing an MMS+PO allocation remains open even for objective lexicographic instances.

5 CONCLUDING REMARKS

We studied the interaction between fairness and efficiency for a mixture of indivisible goods and chores under lexicographic preferences. We showed that an EFX allocation may not always exist for mixed items. Nonetheless, we identified natural classes of lexicographic instances for which an EFX+PO allocation exists and can always be computed efficiently. We further proved that an MMS allocation always exists and can be computed efficiently even for subjective mixed instances.

Going forward, it will be interesting to resolve the computational complexity of checking the existence of EFX allocations for mixed items. Another relevant direction will be to explore the space of strategyproof mechanisms satisfying desirable fairness and efficiency guarantees.

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