

INTERVAL ENFORCEABLE PROPERTIES OF FINITE GROUPS

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ABSTRACT. We propose a classification of group properties according to whether they can be deduced from the assumption that a group’s subgroup lattice contains an interval isomorphic to some lattice. We are able to classify a few group properties as being “interval enforceable” in this sense, and we establish that other properties satisfy a weaker notion of “core-free interval enforceable.” We also show that if there exists a group property and its negation that are both core-free interval enforceable, this would settle an important open question in universal algebra.

1. INTRODUCTION

The study of subgroup lattices has a long history that began with Richard Dedekind [7] and Ada Rottlaender [21], and continued with important contributions by Reinhold Baer, Øystein Ore, Michio Suzuki, Roland Schmidt, and many others (see Schmidt [22]). Much of this work focuses on the problem of deducing properties of a group G from assumptions about the structure of its lattice of subgroups, $\text{Sub}(G)$, or, conversely, deducing lattice theoretical properties of $\text{Sub}(G)$ from assumptions about G .

Historically, less attention was paid to the local structure of the subgroup lattice of a finite group, perhaps because it seemed that very little about G could be inferred from knowledge of, say, an *upper interval*, $\llbracket H, G \rrbracket = \{K \mid H \leq K \leq G\}$, in the subgroup lattice of G . Recently, however, this topic has attracted more attention (see, e.g., [1, 2, 4, 6, 11, 13, 15, 16]), mostly owing to its connection with one of the most important open problems in universal algebra, the *Finite Lattice Representation Problem* (FLRP). This is the problem of characterizing the lattices that are (isomorphic to) congruence lattices of finite algebras (see, e.g., [5, 8, 16, 17]). There is a remarkable theorem relating this problem to intervals in subgroup lattices of finite groups.

Theorem 1.1 (Pálffy and Pudlák [18]). *The following statements are equivalent:*

- (A) *Every finite lattice is isomorphic to the congruence lattice of a finite algebra.*
- (B) *Every finite lattice is isomorphic to an interval in the subgroup lattice of a finite group.*

If these statements are true (resp., false), then we say the FLRP has a positive (resp., negative) answer. Thus, if we can find a finite lattice L for which it can be

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proved that there is no finite group G with $L \cong \llbracket H, G \rrbracket$ for some $H < G$, then the FLRP has a negative answer.

In this paper we propose a new classification of group properties according to whether or not they can be deduced from the assumption that $\text{Sub}(G)$ has an upper interval isomorphic to some finite lattice. We believe that discovering which group properties can (or cannot) be connected to the local structure of a subgroup lattice is itself a worthwhile endeavor, but we will also describe how this classification could provide a solution of the FLRP.

Suppose \mathcal{P} is a *group theoretical property*¹ and suppose there exists a finite lattice L such that if G is a finite group with $L \cong \llbracket H, G \rrbracket$ for some $H \leq G$, then G has property \mathcal{P} . We call such a property \mathcal{P} *interval enforceable* (IE). If the lattice involved is germane to the discussion, we say that \mathcal{P} is *interval enforceable by* L . An *interval enforceable class of groups* is a class of groups all of which have a common interval enforceable property.

Although it depends on the lattice L , generally speaking it is difficult to deduce very much about a group G from the assumption that an upper interval in $\text{Sub}(G)$ is isomorphic to L . It becomes easier if, in addition to the hypothesis $L \cong \llbracket H, G \rrbracket$, we assume that the subgroup H is *core-free* in G ; that is, H contains no nontrivial normal subgroup of G . Properties of G that can be deduced from these assumptions are what we call *core-free interval enforceable* (cf-IE).

Extending this idea, we consider finite collections \mathcal{L} of finite lattices and ask what can be proved about a group G if one assumes that each $L_i \in \mathcal{L}$ is isomorphic to an upper interval $\llbracket H_i, G \rrbracket \leq \text{Sub}(G)$, with each H_i core-free in G . Clearly, if $\text{Sub}(G)$ has such upper intervals, and if corresponding to each $L_i \in \mathcal{L}$ there is a property \mathcal{P}_i that is cf-IE by L_i , then G must have all of the properties \mathcal{P}_i . A related question is the following: Given a set \mathcal{P} of cf-IE properties, is the conjunction $\bigwedge \mathcal{P}$ cf-IE? Corollary 3.8 answers this question affirmatively.

In this paper, we will identify some group properties that are cf-IE, and others that are not. We will see that the cf-IE properties found thus far are negations of common group properties (for example, “not solvable,” “not almost simple,” “not alternating,” “not symmetric”). Moreover, we prove that in these special cases the corresponding group properties (“solvable,” “almost simple,” “alternating,” “symmetric”) that are not cf-IE. This and other considerations suggest that a group property and its negation cannot both be cf-IE. As yet, we are unable to prove this. A related question is whether, for every group property \mathcal{P} , either \mathcal{P} is cf-IE or $\neg\mathcal{P}$ is cf-IE.

Our main result (Theorem 3.6) connects the foregoing ideas with the FLRP, as follows:

Statement (B) of Theorem 1.1 is equivalent to the following statement:

- (C) Fix $n \geq 2$ and let $\mathcal{L} = \{L_1, \dots, L_n\}$ be any collection of finite lattices at least two of which have more than two elements. For each $i = 1, 2, \dots, n$, let \mathfrak{X}_i denote the class that is core-free interval enforceable by L_i . Then there exists a finite group $G \in \bigcap_{i=1}^n \mathfrak{X}_i$ such that for each $L_i \in \mathcal{L}$ we have $L_i \cong \llbracket H_i, G \rrbracket$ for some subgroup H_i that is core-free in G .

¹This and other italicized terms in the introduction will be defined more formally in Section 2.

Remark. By (C), the FLRP would have a negative answer if we could find a collection $\mathfrak{X}_1, \dots, \mathfrak{X}_n$ of cf-IE classes such that $\bigcap_{i=1}^n \mathfrak{X}_i$ is empty.

Core-free interval enforceable properties are related to permutation representations of groups. If H is a core-free subgroup of G , then G has a faithful permutation representation $\varphi : G \hookrightarrow \text{Sym}(G/H)$. Let $\langle G/H, \varphi(G) \rangle$ denote the algebra comprised of the right cosets G/H acted upon by right multiplication by elements of G ; that is, $\varphi(g) : Hx \mapsto Hxg$. It is well known that the congruence lattice of this algebra (i.e., the lattice of systems of imprimitivity) is isomorphic to the interval $\llbracket H, G \rrbracket$ in the subgroup lattice of G .² This puts statement (C) into perspective. If the FLRP has a positive answer, then no matter what we take as our finite collection \mathcal{L} —for example, we might take \mathcal{L} to be *all* finite lattices with at most N elements for some large $N < \omega$ —we can always find a *single* finite group G such that every lattice in \mathcal{L} is isomorphic to the interval in $\text{Sub}(G)$ above a core-free subgroup. As a result, this group G must have so many faithful representations $G \hookrightarrow \text{Sym}(G/H_i)$ with systems of imprimitivity isomorphic to L_i , one such representation for each distinct $L_i \in \mathcal{L}$. Moreover, the group G having this property can be chosen from the class $\bigcap_{i=1}^n \mathfrak{X}_i$, where $\mathfrak{X}_1, \dots, \mathfrak{X}_n$ is an arbitrary collection of cf-IE classes of groups.

2. NOTATION AND DEFINITIONS

In this paper, *all groups and lattices are finite*. We use \mathfrak{G} to denote the class of all finite groups. Given a group G , we denote the set of subgroups of G by $\text{Sub}(G)$. The algebra $\langle \text{Sub}(G), \wedge, \vee \rangle$ is a lattice where the \wedge (“meet”) and \vee (“join”) operations are defined for all H and K in $\text{Sub}(G)$ by $H \wedge K = H \cap K$ and $H \vee K = \langle H, K \rangle =$ the smallest subgroup of G containing both H and K . We will refer to the set $\text{Sub}(G)$ as a lattice, without explicitly mentioning the \wedge and \vee operations.

By $H \leq G$ (resp., $H < G$) we mean H is a subgroup (resp., proper subgroup) of G . For $H \leq G$, the *core of H in G* , denoted by $\text{core}_G(H)$, is the largest normal subgroup of G contained in H . If $\text{core}_G(H) = 1$, then we say that H is *core-free in G* . For $H \leq G$, by the *interval $\llbracket H, G \rrbracket$* we mean the set $\{K \mid H \leq K \leq G\}$, which is a sublattice of $\text{Sub}(G)$. With this notation, $\text{Sub}(G) = \llbracket 1, G \rrbracket$. When viewing $\llbracket H, G \rrbracket$ as a sublattice of $\text{Sub}(G)$, we sometimes refer to it as an *upper interval*. Given a lattice L and a group G , the expression $L \cong \llbracket H, G \rrbracket$ will mean that there exists a subgroup $H \leq G$ such that L is isomorphic to the interval $\{K \mid H \leq K \leq G\}$ in the subgroup lattice of G .

By a *group theoretical class*, or *class of groups*, we mean a collection \mathfrak{X} of groups that is closed under isomorphism: if $G_0 \in \mathfrak{X}$ and $G_1 \cong G_0$, then $G_1 \in \mathfrak{X}$. A *group theoretical property*, or simply *property of groups*, is a property \mathcal{P} such that if a group G_0 has property \mathcal{P} and $G_1 \cong G_0$, then G_1 has property \mathcal{P} .³ Thus if $\mathfrak{X}_{\mathcal{P}}$ denotes the collection of all groups having the group property \mathcal{P} , then $\mathfrak{X}_{\mathcal{P}}$ is a

²See [14, Lemma 4.20] or [9, Theorem 1.5A].

³It seems there is no single standard definition of *group theoretical class*. While some authors (e.g., [10], [3]) use the same definition we use here, others (e.g. [19], [20]) require that every group theoretical class contains the one element group. In the sequel we consider negations of group properties, and we would like these to qualify as group properties. Therefore, we don’t require that every group theoretical class contains the one element group.

class of groups, and belonging to a particular class of groups is a group theoretical property.

If \mathcal{K} is a class of algebras (e.g., a class of groups), then we say that \mathcal{K} is *closed under homomorphic images* and we write $\mathbf{H}(\mathcal{K}) = \mathcal{K}$ provided $\varphi(G) \in \mathcal{K}$ whenever $G \in \mathcal{K}$ and φ is a homomorphism of G .

Let \mathfrak{L} denote the class of all finite lattices, and \mathfrak{G} the class of all finite groups. Let \mathcal{P} be a group theoretical property and $\mathfrak{X}_{\mathcal{P}}$ the associated class of all groups with property \mathcal{P} . We call \mathcal{P} (and $\mathfrak{X}_{\mathcal{P}}$)

- *interval enforceable* (IE) provided

$$(\exists L \in \mathfrak{L}) (\forall G \in \mathfrak{G}) (L \cong \llbracket H, G \rrbracket \longrightarrow G \in \mathfrak{X}_{\mathcal{P}})$$

- *core-free interval enforceable* (cf-IE) provided

$$(\exists L \in \mathfrak{L}) (\forall G \in \mathfrak{G}) (L \cong \llbracket H, G \rrbracket \bigwedge \text{core}_G(H) = 1 \longrightarrow G \in \mathfrak{X}_{\mathcal{P}})$$

- *minimal interval enforceable* (min-IE) provided there exists $L \in \mathfrak{L}$ such that if $L \cong \llbracket H, G \rrbracket$ for some group $G \in \mathfrak{G}$ of minimal order (with respect to $L \cong \llbracket H, G \rrbracket$), then $G \in \mathfrak{X}_{\mathcal{P}}$.

In this paper we will have little to say about min-IE properties. Nonetheless, we include this class in our list of new definitions because properties of this type arise often (see, e.g., [13]), and a primary aim of this paper is to formalize various notions of interval enforceability that we believe are useful in applications.

3. RESULTS

Clearly, if \mathcal{P} is an interval enforceable property, then it is also core-free interval enforceable. There is an easy sufficient condition under which the converse holds. Suppose \mathcal{P} is a group property, let $\mathfrak{X}_{\mathcal{P}}$ denote the class of all groups with property \mathcal{P} , and let $\mathfrak{X}_{\mathcal{P}}^c$ denote the class of all groups that do not have property \mathcal{P} .

Lemma 3.1. *Suppose \mathcal{P} is a core-free interval enforceable property. If $\mathbf{H}(\mathfrak{X}_{\mathcal{P}}^c) = \mathfrak{X}_{\mathcal{P}}^c$, then \mathcal{P} is an interval enforceable property.*

Proof. Since \mathcal{P} is cf-IE, there is a lattice L such that

$$(3.1) \quad L \cong \llbracket H, G \rrbracket \bigwedge \text{core}_G(H) = 1 \longrightarrow G \in \mathfrak{X}_{\mathcal{P}}.$$

Under the assumption $\mathbf{H}(\mathfrak{X}_{\mathcal{P}}^c) = \mathfrak{X}_{\mathcal{P}}^c$ we prove

$$(3.2) \quad L \cong \llbracket H, G \rrbracket \longrightarrow G \in \mathfrak{X}_{\mathcal{P}}.$$

If (3.2) fails, then there is a group $G \in \mathfrak{X}_{\mathcal{P}}^c$ with $L \cong \llbracket H, G \rrbracket$. Let $N = \text{core}_G(H)$. Then $L \cong \llbracket H/N, G/N \rrbracket$ and H/N is core-free in G/N so, by hypothesis (3.1), $G/N \in \mathfrak{X}_{\mathcal{P}}$. But $G/N \in \mathfrak{X}_{\mathcal{P}}$, since $\mathfrak{X}_{\mathcal{P}}^c$ is closed under homomorphic images. \square

In [16], Péter Pálffy gives an example of a lattice that cannot occur as an upper interval in the subgroup lattice finite solvable group. (We give other examples in Section 3.3.) In his Ph.D. thesis [4], Alberto Basile proves that if G is an alternating or symmetric group, then there are certain lattices that cannot occur as upper intervals in $\text{Sub}(G)$. Another class of lattices with this property is described by Aschbacher and Shalev in [1]. Thus, two classes of groups that are known to be at least cf-IE are the following:

- $\mathfrak{X}_0 = \mathfrak{S}^c =$ nonsolvable finite groups;
- $\mathfrak{X}_1 = \{G \in \mathfrak{G} \mid (\forall n < \omega) (G \neq A_n \bigwedge G \neq S_n)\}$,

where A_n and S_n denote, respectively, the alternating and symmetric groups on n letters. Note that both classes \mathfrak{X}_0 and \mathfrak{X}_1 satisfy the hypothesis of 3.1. Explicitly, $\mathfrak{X}_0^c = \mathfrak{S}$, the class of solvable groups, is closed under homomorphic images, as is the class \mathfrak{X}_1^c of alternating and symmetric groups. Therefore, by Lemma 3.1, \mathfrak{X}_0 and \mathfrak{X}_1 are IE classes. By contrast, suppose there exists a finite lattice L such that

$$L \cong \llbracket H, G \rrbracket \bigwedge \text{core}_G(H) = 1 \longrightarrow G \text{ is subdirectly irreducible.}$$

Lemma 3.1 does not apply in this case since the class of subdirectly reducible groups is obviously not closed under homomorphic images.⁴ In Section 3.3 below we describe lattices with which we can prove that the following classes are at least cf-IE:

- \mathfrak{X}_2 = the subdirectly irreducible groups;
- \mathfrak{X}_3 = the groups having no nontrivial abelian normal subgroups;
- $\mathfrak{X}_4 = \{G \in \mathfrak{S} \mid C_G(M) = 1 \text{ for all } 1 \neq M \trianglelefteq G\}$.

We noted above that \mathfrak{X}_2 fails to satisfy the hypothesis of 3.1. The same can be said of \mathfrak{X}_3 and \mathfrak{X}_4 . That is, $\mathbf{H}(\mathfrak{X}_i^c) \neq \mathfrak{X}_i^c$ for $i = 2, 3, 4$. To verify this take $H \in \mathfrak{X}_i$, $K \in \mathfrak{X}_i^c$, and consider $H \times K$. In each case ($i = 2, 3, 4$) we see that $H \times K$ belongs to \mathfrak{X}_i^c , but the homomorphic image $(H \times K)/(1 \times K) \cong H$ does not.

3.1. Negations of interval enforceable properties. If a lattice L is isomorphic to an interval in the subgroup lattice of a finite group, then we call L *group representable*. Recall, Theorem 1.1 says that the FLRP has a negative answer if we can find a finite lattice that is not group representable.

Suppose there exists a property \mathcal{P} such that both \mathcal{P} and its negation $\neg\mathcal{P}$ are interval enforceable by the lattices L and L_c , respectively. That is $L \cong \llbracket H, G \rrbracket$ implies G has property \mathcal{P} , and $L_c \cong \llbracket H_c, G_c \rrbracket$ implies G_c does not have property \mathcal{P} . Then clearly the lattice in Figure 1 could not be group representable. As the next

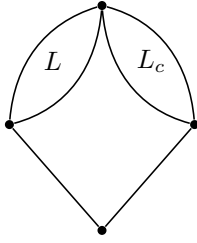


FIGURE 1.

result shows, however, if a group property and its negation are interval enforceable by the lattices L and L_c , then already at least one of these lattices is not group representable.

Lemma 3.2. *If \mathcal{P} is a group property that is interval enforceable by a group representable lattice, then it is not the case that $\neg\mathcal{P}$ is interval enforceable by a group representable lattice.*

⁴Recall, for groups *subdirectly irreducible* is equivalent to having a unique minimal normal subgroup. Every algebra, in particular every group G , has a subdirect decomposition into subdirectly irreducibles, say, $G \hookrightarrow G/N_1 \times \cdots \times G/N_n$, so there are always subdirectly irreducible homomorphic images.

Proof. Assume \mathcal{P} is interval enforceable by the group representable lattice L , and let $H \leq G$ be groups for which $L \cong \llbracket H, G \rrbracket$. If $\neg\mathcal{P}$ is interval enforceable by the group representable lattice L_c , then there exist $H_c \leq G_c$ satisfying $L_c \cong \llbracket H_c, G_c \rrbracket$. Consider the group $G \times G_c$. This has upper intervals $L \cong \llbracket H \times G_c, G \times G_c \rrbracket$ and $L_c \cong \llbracket G \times H_c, G \times G_c \rrbracket$ and therefore, by the interval enforceability assumptions, the group $G \times G_c$ has the properties \mathcal{P} and $\neg\mathcal{P}$ simultaneously, which is a contradiction. \square

To take a concrete example, nonsolvability is IE. However, solvability is obviously not IE. For, if $L \cong \llbracket H, G \rrbracket$ then for any nonsolvable group K we have $L \cong \llbracket H \times K, G \times K \rrbracket$, and of course $G \times K$ is nonsolvable. Note that here (and in the proof of Lemma 3.2) the group $H \times K$ at the bottom of the interval is not core-free. So a more interesting question is whether a property and its negation can both be cf-IE. Again, if such a property were found, a lattice of the form in Figure 1 would give a negative answer to the FLRP, though this requires additional justification to address the core-free aspect (see Section 3.3).

This leads to the following question: If \mathcal{P} is core-free interval enforceable by a group representable lattice, does it follow that $\neg\mathcal{P}$ is not core-free interval enforceable by a group representable lattice? We provide an affirmative answer in some special cases, such as when \mathcal{P} means “not solvable” or “not almost simple.” Indeed, Lemma 3.3 implies that the class of solvable groups, and more generally any class of groups that omits certain wreath products, cannot be core-free interval enforceable by a group representable lattice.

Lemma 3.3. *Suppose \mathcal{P} is core-free interval enforceable by a group representable lattice. Then, for any finite nonabelian simple group S , there exists a wreath product group of the form $W = S \wr \bar{U}$ that has property \mathcal{P} .*

Proof. Let L be a group representable lattice such that if $L \cong \llbracket H, G \rrbracket$ and $\text{core}_G(H) = 1$ then $G \in \mathfrak{X}_{\mathcal{P}}$. Since L is group representable, there exists a \mathcal{P} -group G with $L \cong \llbracket H, G \rrbracket$. We apply an idea of Hans Kurzweil (see [12]) twice. Fix a finite nonabelian simple group S . Suppose the index of H in G is $|G : H| = n$. Then the action of G on the cosets of H induces an automorphism of the group S^n by permutation of coordinates. Denote this representation by $\varphi : G \rightarrow \text{Aut}(S^n)$, and let the image of G be $\varphi(G) = \bar{G} \leq \text{Aut}(S^n)$. The wreath product under this action is the group

$$U := S \wr_{\varphi} G = S^n \rtimes_{\varphi} G = S^n \rtimes \bar{G},$$

with multiplication given by

$$(s_1, \dots, s_n, x)(t_1, \dots, t_n, y) = (s_1 t_{x(1)}, \dots, s_n t_{x(n)}, xy),$$

for $s_i, t_i \in S$ and $x, y \in \bar{G}$. (For the remainder of the proof, we suppress the semidirect product symbol and write, for example, $S^n \bar{G}$ instead of $S^n \rtimes \bar{G}$.)

An illustration of the subgroup lattice of such a wreath product appears in Figure 2. Note that the interval $\llbracket D, S^n \rrbracket$, where D denotes the diagonal subgroup of S^n , is isomorphic to $\text{Eq}(n)'$, the dual of the lattice of partitions of an n -element set. The dual lattice L' is an upper interval of $\text{Sub}(U)$, namely, $L' \cong \llbracket D\bar{G}, U \rrbracket$.⁵

It is important to note (and we prove below) that if H is core-free in G – equivalently, if $\ker \varphi = 1$ – then the foregoing construction results in the subgroup $D\bar{G}$ being core-free in U . Therefore, by repeating the foregoing procedure, with

⁵These facts, which were proved by Kurzweil in [12], are discussed in greater detail in [8, Section 2.2].

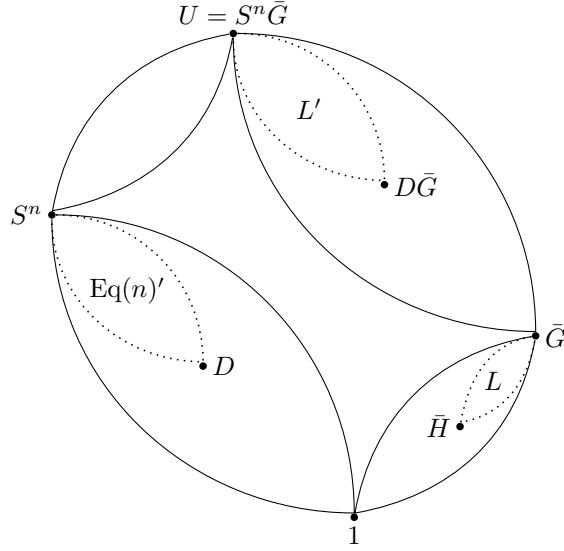


FIGURE 2. Hasse diagram illustrating some features of the subgroup lattice of the wreath product U .

$H_1 = D\bar{G}$ denoting the (core-free) subgroup of U such that $L' \cong \llbracket H_1, U \rrbracket$, we find that $L = L'' \cong \llbracket D_1\bar{U}, S^m\bar{U} \rrbracket$, where $m = |U : H_1|$, and D_1 denotes the diagonal subgroup of S^m . Since $D_1\bar{U}$ will be core-free in $S^m\bar{U}$ then, it follows by the original hypothesis that $S^m\bar{U} = S \wr \bar{U}$ must have property \mathcal{P} .

To complete the proof, we check that starting with a core-free subgroup $H \leq G$ in the Kurzweil construction just described results in a core-free subgroup $D\bar{G} \leq U$. Let $N = \text{core}_U(D\bar{G})$. Then, for all $w = (d, \dots, d, x) \in N$ and for all $u = (t_1, \dots, t_n, g) \in U$, we have $uwu^{-1} \in N$. Fix $w = (d, \dots, d, x) \in N$. We will choose $u \in U$ so that the condition $uwu^{-1} \in N$ implies x acts trivially on $\{1, \dots, n\}$. First note that if $u = (t_1, \dots, t_n, 1)$, then

$$\begin{aligned} uwu^{-1} &= (t_1, \dots, t_n, 1)(d, \dots, d, x)(t_1^{-1}, \dots, t_n^{-1}, 1) \\ &= (t_1 d t_{x(1)}^{-1}, \dots, t_n d t_{x(n)}^{-1}, 1) \in N, \end{aligned}$$

and this implies that $t_1 d t_{x(1)}^{-1} = t_2 d t_{x(2)}^{-1} = \dots = t_n d t_{x(n)}^{-1}$. Suppose by way of contradiction that $x(1) = j \neq 1$. Then, since x is a permutation (hence, one-to-one), $x(k) \neq j$ for each $k \in \{2, 3, \dots, n\}$. Pick one such k other than j . (This is possible since $n = |G : H| > 2$; for otherwise $H \trianglelefteq G$ contradicting $\text{core}_G(H) = 1$.) Since $u \in U$ is arbitrary, we may assume $t_1 = t_k$ and $t_{x(1)} = t_j \neq t_{x(k)}$. But this contradicts $t_1 d t_{x(1)}^{-1} = t_k d t_{x(k)}^{-1}$. Therefore, $x(1) = 1$. The same argument shows that $x(i) = i$ for each $1 \leq i \leq n$, and we see that $w = (d, \dots, d, x) \in N$ implies $x \in \ker \varphi = 1$. This puts N below D , and the only normal subgroup of U that lies below D is the trivial group. \square

By the foregoing result we conclude that a class of groups that does not include wreath products of the form $S \wr G$, where S is an arbitrary finite nonabelian simple

group, is not a core-free interval enforceable class. The class of solvable groups is an example.

3.2. Dedekind's rule. When A and B are subgroups of a group G , by AB we mean the set $\{ab \mid a \in A, b \in B\}$, and we write $A \vee B$ or $\langle A, B \rangle$ to denote the subgroup of G generated by A and B . Clearly $AB \subseteq \langle A, B \rangle$; equality holds if and only if A and B *permute*, by which we mean $AB = BA$.

We will need the following well known result:⁶

Theorem 3.4 (Dedekind's rule). *Let G be a group and let A, B and C be subgroups of G with $A \leq B$. Then,*

$$(3.3) \quad A(C \cap B) = AC \cap B, \quad \text{and}$$

$$(3.4) \quad (C \cap B)A = CA \cap B.$$

For $A \in \llbracket H, G \rrbracket$, let $A^{\perp(H,G)}$ denote the set of complements of A in the interval $\llbracket H, G \rrbracket$. That is,

$$A^{\perp(H,G)} := \{B \in \llbracket H, G \rrbracket \mid A \cap B = H, \langle A, B \rangle = G\}.$$

Clearly $H^{\perp(H,G)} = \{G\}$ and $G^{\perp(H,G)} = \{H\}$. Recall that an *antichain* of a partially ordered set is a subset of pairwise incomparable elements.

Corollary 3.5. *Let $A \in \llbracket H, G \rrbracket$ and let \mathcal{B} be a nonempty subset of the set $A^{\perp(H,G)}$ of complements of A in $\llbracket H, G \rrbracket$. If every group in \mathcal{B} permutes with A , then \mathcal{B} is an antichain.*

Proof. If \mathcal{B} is a singleton, the result holds trivially. So assume B_1 and B_2 are distinct groups in \mathcal{B} . We prove $B_1 \not\leq B_2$. Indeed, if $B_1 \leq B_2$, then Theorem 3.4 implies

$$B_1 = B_1 H = B_1 (A \cap B_2) = B_1 A \cap B_2 = G \cap B_2 = B_2,$$

which is a contradiction. \square

3.3. Parachute lattices. We now prove the equivalence of statements (B) and (C) of Section 1.

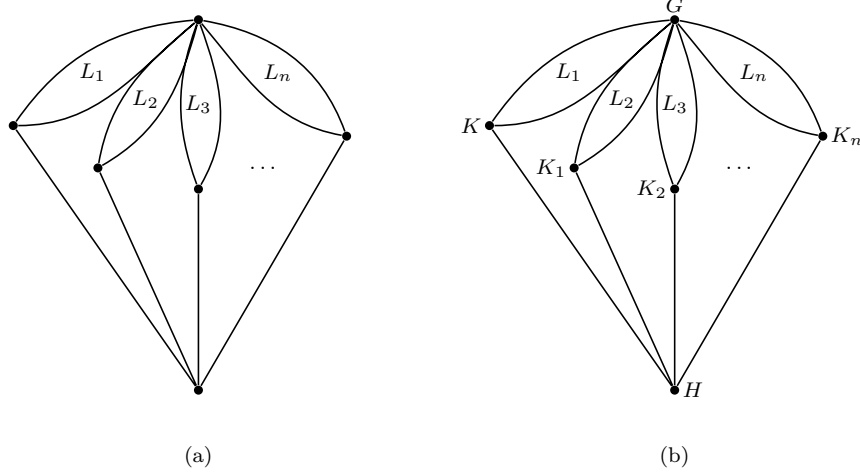
Theorem 3.6. *The following statements are equivalent:*

- (B) *Every finite lattice is isomorphic to an interval in the subgroup lattice of a finite group.*
- (C) *Suppose $n \geq 2$ and $\mathcal{L} = \{L_1, \dots, L_n\}$ is a set of finite lattices, at least two of which have more than two elements. For each $i = 1, 2, \dots, n$, let \mathfrak{X}_i denote the class that is core-free interval enforceable by L_i . Then there exists a finite group $G \in \bigcap_{i=1}^n \mathfrak{X}_i$ such that for each $L_i \in \mathcal{L}$ we have $L_i \cong \llbracket H_i, G \rrbracket$ for some subgroup H_i , where every $H_i \leq Y < G$ is core-free in G .*

Remark. By (C), the FLRP would have a negative answer if we could find a collection $\mathfrak{X}_1, \dots, \mathfrak{X}_n$ of cf-IE classes such that $\bigcap_{i=1}^n \mathfrak{X}_i$ is empty.

Proof. Obviously (C) implies (B). Assume (B) holds and assume the hypotheses of (C). Construct a new lattice, denoted $\mathcal{P} = \mathcal{P}(L_1, \dots, L_n)$, as shown in the Hasse diagram of Figure 3 (a), where the bottoms of the L_i sublattices are atoms

FIGURE 3. The parachute construction.



in \mathcal{P} . By (B), there exist groups $H < G$ with $\mathcal{P} \cong \llbracket H, G \rrbracket$. We can assume H is a core-free subgroup of G . (If not, replace G and H with G/N and H/N , where $N = \text{core}_G(H)$.) Let K, K_1, \dots, K_n be the subgroups in which H is maximal and for which $L_i \cong \llbracket K_i, G \rrbracket$, $1 \leq i \leq n$. (Figure 3 (b).) We will prove that, for each $1 \leq i \leq n$ every proper subgroup of G that contains K_i is core-free in G . It then follows that $G \in \mathfrak{X}_i$ for all $1 \leq i \leq n$, and so $G \in \bigcap_{i=1}^n \mathfrak{X}_i$.

Choose Y such that $K_j \leq Y < G$. We will prove Y is core-free. If $N = \text{core}_G(Y)$ were nontrivial, then since H is core-free, we would have $K_j \leq NH \leq Y$. Now, NH permutes with all $X \in \llbracket H, G \rrbracket$, since for such X we have $XNH = NXH = NHX$. Therefore, if N is nontrivial, then the set $(NH)^{\perp(H,G)}$, the complements of NH in $\llbracket H, G \rrbracket$, forms an antichain by Corollary 3.5. This contradicts the assumption that at least two of the lattices L_i have more than two elements. \square

By a *parachute lattice*, denoted $\mathcal{P}(L_1, \dots, L_m)$, we mean a lattice just like the one illustrated in Figure 3. We identify some special group properties that are core-free interval enforceable by a parachute lattice.

Lemma 3.7. *Let $\mathcal{P} = \mathcal{P}(L_1, \dots, L_n)$ with $n \geq 2$ and $|L_i| > 2$ for at least two i , and suppose $\mathcal{P} \cong \llbracket H, G \rrbracket$ with H core-free in G .*

- (i) *If $1 \neq N \trianglelefteq G$, then $NH = G$ and $C_G(N) = 1$.*
- (ii) *G is subdirectly irreducible and nonsolvable.*

Remark. If N is abelian, then $N \leq C_G(N)$, so (i) implies that every nontrivial normal subgroup of G is nonabelian.

Proof. (i) Assume $1 \neq N \trianglelefteq G$. As above, we let K_i denote the subgroups of G corresponding to the atoms of \mathcal{P} , and by the same argument used to prove Theorem 3.6, we see that every subgroup Y with $H \leq Y < G$ is core-free in G . Therefore, $NY = G$ for all $H \leq Y < G$. In particular, $NH = G$.

⁶See [20, p. 122], for example.

To prove that $C_G(N) = 1$, let $1 \neq M \leq N$ be a minimal normal subgroup of G contained in N . It suffices to prove $C_G(M) = 1$. Note that $C_G(M) \leq N_G(M) = G$. If $C_G(M)$ were nontrivial, then it would follow by (1) that $C_G(M)H = G$. Consider any $H < K < G$. Then $1 < M \cap K < M$ (strictly, by Dedekind's rule). Now $M \cap K$ is normalized by H and centralized (hence normalized) by $C_G(M)$. Therefore, $M \cap K \leq C_G(M)H = G$, contradicting the minimality of M .

To prove (ii) we first show that G has a unique minimal normal subgroup. Let M be a minimal normal subgroup of G and let $N \leq G$ be any normal subgroup not containing M . We show that $N = 1$. Since both subgroups are normal, the commutator subgroup $[M, N]$ lies in the intersection $M \cap N$, which is trivial by the minimality of M . Thus, M and N centralize each other. In particular, $N \leq C_G(M) = 1$, by (i). Finally, since G has a unique minimal normal subgroup that is nonabelian, G is nonsolvable. \square

Given two group theoretical properties \mathcal{P}_1 and \mathcal{P}_2 , we write $\mathcal{P}_1 \longrightarrow \mathcal{P}_2$ to denote that a group G has property \mathcal{P}_1 only if it also has property \mathcal{P}_2 . Thus, we clearly have

$$\mathcal{P}_1 \longrightarrow \mathcal{P}_2 \iff \mathfrak{X}_{\mathcal{P}_1} \subseteq \mathfrak{X}_{\mathcal{P}_2},$$

where, as above, $\mathfrak{X}_{\mathcal{P}_i}$ is the class of groups having property \mathcal{P}_i . The conjunction $\mathcal{P}_1 \wedge \cdots \wedge \mathcal{P}_n$ corresponds to the class

$$\bigcap_{i=1}^n \mathfrak{X}_{\mathcal{P}_i} = \{G \in \mathfrak{G} \mid G \text{ has property } \mathcal{P}_i \text{ for all } 1 \leq i \leq n\},$$

and the following is an immediate corollary of the parachute construction:

Corollary 3.8. *If $\mathcal{P}_1, \dots, \mathcal{P}_n$ are cf-IE properties, then so is $\mathcal{P}_1 \wedge \cdots \wedge \mathcal{P}_n$.*

By Theorem 3.6, Lemma 3.7, and Corollary 3.8, we see that the FLRP has a positive answer (that is, statement (B) is true) if and only if for every finite lattice L there is a finite group G satisfying all of the following:

- (i) $L \cong [H, G]$;
- (ii) G is nonsolvable, nonalternating, and nonsymmetric;
- (iii) $\text{core}_G(Y) = 1$ for all $H \leq Y < G$;
- (iv) G has a unique minimal normal subgroup M , which satisfies $C_G(M) = 1$; in particular, M is nonabelian and satisfies $MY = G$ for all $H \leq Y \leq G$.

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