MATROIDS WITH DIFFERENT CONFIGURATIONS AND THE SAME
G-INVARIANT

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ABSTRACT. From the configuration of a matroid (which records the size and rank of the
cyclic flats and the containments among them, but not the sets), one can compute several
much-studied matroid invariants, including the Tutte polynomial and a newer, stronger
invariant, the $G$-invariant. To gauge how much additional information the configuration
contains compared to these invariants, it is of interest to have methods for constructing
matroids with different configurations but the same $G$-invariant. We offer several such
constructions along with tools for developing more.

1. INTRODUCTION

The configuration of a matroid, which Eberhardt [9] introduced, is obtained from its
lattice of cyclic flats (that is, flats that are unions of circuits) by recording the abstract
lattice structure along with just the size and rank of each cyclic flat, not the set. Eberhardt
proved that from the configuration of a matroid $M$, one can compute its Tutte polynomial,

$$T(M; x, y) = \sum_{A \subseteq E(M)} (x - 1)^{r(M) - r(A)} (y - 1)^{|A| - r(A)}.$$ 

The data recorded in the Tutte polynomial is the multiset of size-rank pairs, $(|A|, r(A))$, over all $A \subseteq E(M)$. The Tutte polynomial is one of the most extensively studied invariants
of a matroid (see, e.g., [6, 10]).

Strengthening Eberhardt’s result, Bonin and Kung [2, Theorem 7.3] showed that from
the configuration of a matroid, one can compute its $G$-invariant. Derksen [7] introduced the
$G$-invariant and showed that the Tutte polynomial can be computed from it. The perspective
on the $G$-invariant that we use is the reformulation introduced in [2]: this invariant records
the multiset of sequences of sizes of the sets in flags (maximal chains of flats) of the
matroid. (Section 2 gives a more precise formulation.) Akin to the universality property
of the Tutte polynomial among matroid invariants that satisfy deletion-contraction rules,
Derksen and Fink [8] showed that the $G$-invariant is a universal valuative invariant for
subdivisions of matroid base polytopes.

Reflecting on the proof of [2, Theorem 7.3] reveals that the chains of cyclic flats in the
configuration play the key role; the lattice structure is secondary. So if one can construct
pairs of non-isomorphic lattices for which one can relate their chains via bijections, one
might be able to produce pairs of matroids with different configurations and the same
$G$-invariant. That is the idea that we develop in this paper and use to shed light on how
much stronger the configuration is compared to the $G$-invariant. Since the Tutte polynomial
can be computed from the $G$-invariant, our results also contribute to the theory of Tutte-
equivalent matroids (see [5]).
In Section 2, we review the relevant background and previously known examples of matroids with different configurations but the same $G$-invariant. The core of the paper is Section 3, where we develop the tools that we apply in Sections 4 and 5 to give the constructions of interest. These tools and the strategy in the proofs of Theorems 4.1 and 5.1 are likely to be useful to obtain more such constructions.

2. Notation, Background, and Prior Results

Our notation and terminology for matroid theory follow Oxley [11]. Let $[n]$ denote the set $\{1, 2, \ldots, n\}$. Let $\hat{0}$ denote the least element of a lattice $L$, and let $\hat{1}$ denote its greatest element. If we need to clarify in which lattice an interval is formed, we use a subscript, as in $[a, b]_L$. Likewise, we may use $0_L$ and $1_L$. For a lattice $L$, we let $L^o$ denote $L$ with $\hat{0}$ and $\hat{1}$ removed, so $L^o$ is the open interval $(\hat{0}, \hat{1})$.

Given a matroid $M$, a subset $A$ of $E(M)$ is cyclic if $A$ is a (possibly empty) union of circuits, or, equivalently, the restriction $M|A$ has no coloops. It follows that if $A$ and $B$ are cyclic flats, then so are $\text{cl}(A \cup B)$ and the flat obtained from $A \cap B$ by removing the coloops of $M|A \cap B$; these are the join and meet of $A$ and $B$ in the lattice $Z(M)$ of cyclic flats of $M$. We will use the following elementary result about cyclic flats.

Lemma 2.1. Let $M$ be a matroid with $\emptyset, E(M) \in Z(M)$. If $X$ is any cyclic flat of $M$, then $Z(M|X)$ is the interval $[\emptyset, X]$ in $Z(M)$, and

\[
Z(M|X) = \{ F - X : F \in Z(M) \text{ and } X \subseteq F \},
\]

so the lattice $Z(M|X)$ is isomorphic to the interval $[X, E(M)]$ in $Z(M)$.

The configuration of a matroid $M$ with no coloops is the triple $(L, s, \rho)$, where $L$ is a lattice and $s : L \to \mathbb{Z}$ and $\rho : L \to \mathbb{Z}$ are functions such that there is an isomorphism $\phi : L \to Z(M)$ for which $s(x) = |\phi(x)|$ and $\rho(x) = r(\phi(x))$ for all $x \in L$. (Many triples can satisfy these properties, but they all contain the same data, so we view them as the same.) Many non-isomorphic matroids can have the same configuration. For instance, consider paving matroids, that is, matroids where all flats that are properly contained in hyperplanes are independent; any two paving matroids of the same rank, on the same number of elements, and with the same number of dependent hyperplanes of each size have the same configuration, and many non-isomorphic paving matroids can share these parameters.

The configuration of $M$ gives the configurations of certain minors of $M$, as the next lemma states.

Lemma 2.2. Let $M$ be a matroid with $\emptyset, E(M) \in Z(M)$. If $X \in Z(M)$, then the size and rank of each set in $Z(M|X)$ and $Z(M|X)$ can be found from the configuration of $M$. So, from the configuration of $M$, we get the configuration of each minor $M|X/Y$ with $X, Y \in Z(M)$ and $Y \subseteq X$.

The following result from [4] explains why we do not impose any conditions on the lattices that we consider other than that they are finite.

Lemma 2.3. For each finite lattice $L$, there is a matroid $M$ for which $Z(M)$ is isomorphic to $L$.

Given a matroid $M$ on $E$ with rank function $r$ and a permutation $\pi$, say $e_1, e_2, \ldots, e_n$, of $E$, the rank sequence $\underline{r}(\pi) = r_1 r_2 \ldots r_n$ is given by

\[
r_i = r(\{e_1, e_2, \ldots, e_i\}) - r(\{e_1, e_2, \ldots, e_{i-1}\}).
\]
Thus, \( \{ e_i : r_i = 1 \} \) is a basis of \( M \). Let \( k = r(M) \). Each rank sequence \( r(\pi) \) is an \((n,k)\)-sequence, that is, a sequence of \( k \) ones and \( n-k \) zeroes. For each \((n,k)\)-sequence \( r \), let \( [r] \) be a formal symbol, and let \( \mathcal{G}(n,k) \) be the vector space over a field of characteristic zero consisting of all formal linear combinations of such symbols. The \( \mathcal{G} \)-invariant of \( M \) is defined by

\[
\mathcal{G}(M) = \sum_{\text{permutations } \pi \text{ of } E} [r(\pi)].
\]

In this paper we use a reformulation of \( \mathcal{G}(M) \) developed in [2]. An \((n,k)\)-composition is a sequence \( a = (a_0, a_1, \ldots, a_k) \) of integers where \( a_0 \geq 0 \) and \( a_i > 0 \) for \( i \in [k] \) such that \( a_0 + a_1 + \cdots + a_k = n \). Let \( M \) be a matroid as above. A flag of \( M \) is a sequence \( X = (X_0, X_1, \ldots, X_k) \) where \( X_i \) is a rank-\( i \) flat of \( M \) and \( X_i \subseteq X_{i+1} \) for \( i < k \). The composition of a flag \( X \) is \( a \) where \( a_0 = |X_0| \) and \( a_i = |X_i - X_{i-1}| \) for \( i \in [k] \). Thus, \( a \) is an \((n,k)\)-composition. Let \( \nu(M; a) \) be the number of flags of \( M \) with composition \( a \). The catenary data of \( M \) is the \( \binom{n}{k} \)-dimensional vector \( (\nu(M; a)) \) that is indexed by \((n,k)\)-compositions.

A special basis of \( \mathcal{G}(n,k) \), called the \( \gamma \)-basis, is defined in [2]; its vectors \( \gamma(a) \) are indexed by the \((n,k)\)-compositions \( a \). By the next result [2, Theorem 3.3], the catenary data of \( M \) is equivalent to \( \mathcal{G}(M) \).

**Theorem 2.4.** The \( \mathcal{G} \)-invariant of \( M \) is determined by its catenary data and conversely. In particular,

\[
\mathcal{G}(M) = \sum_{(n,k)-\text{compositions } a} \nu(M; a)\gamma(a).
\]

By [2, Theorem 7.3], if \( M \) has no coloops, then \( \mathcal{G}(M) \) can be computed from the configuration of \( M \). If \( M \) has coloops, then \( \mathcal{G}(M) \) can be computed from \( \mathcal{G}(M \setminus X) \) and \( |X| \) where \( X \) is the set of coloops; a similar remark applies to loops. Thus, we focus on matroids \( M \) with neither loops nor coloops, that is, \( \emptyset, E(M) \in \mathcal{Z}(M) \). Analogous to the notation \( L^n \) defined above, we let \( \mathcal{Z}^c(M) \) denote the set of nonempty, proper cyclic flats of \( M \). Thus, \( \mathcal{Z}^c(M) \) is empty if and only if \( M \) is a uniform matroid.

Prior to this work, the matroids with different configurations but the same \( \mathcal{G} \)-invariant that we were aware of were:

- Dowling lattices of a given rank exceeding three, using non-isomorphic groups of the same order [2].
- the free \( m \)-cones of non-isomorphic matroids that have the same \( \mathcal{G} \)-invariant, along with tipless, baseless, and tipless/baseless variations [3], and
- the duals of any such examples.

(The effect of taking the dual of a matroid on the \( \mathcal{G} \)-invariant, in the original formulation, is simple: reverse the order within each rank sequence, and then switch 0s and 1s.)

Another construction is easy to treat using catenary data: given a matroid \( M \) and a positive integer \( t \), construct the extension \( M_t \) of \( M \) by, for each \( e \in E(M) \), adding a set \( A_e \) of \( t \) elements parallel to \( e \), with \( A_e \) disjoint from all other such sets and from \( E(M) \). (Contracting the tip of a free \( m \)-cone of \( M \) yields \( M_{tn} \).) Note that all flats of \( M_t \) are cyclic, \( \mathcal{Z}(M_t) \) is isomorphic to the lattice of flats of \( M \), and each flag \((Y_0,Y_1,\ldots,Y_k)\) of \( M_t \) corresponds to a flag \((X_0,X_1,\ldots,X_k)\) of \( M \) where \( X_i \subseteq Y_i \) and \( |Y_i| = |X_i|(t+1) \) for each \( i \). So if \( M \) and \( N \) are non-isomorphic and have the same \( \mathcal{G} \)-invariant, then \( M_t \) and \( N_t \) have the same catenary data, and so the same \( \mathcal{G} \)-invariant, but different configurations.

For any positive integer \( n \), there is a positive integer \( m \) so that there are at least \( n \) non-isomorphic groups of order \( m \), so Dowling lattices yield sets of arbitrarily many matroids
with different configurations (specifically, non-isomorphic lattices of cyclic flats) but the same \( G \)-invariant. Our constructions yield other large sets of matroids of this type for which the lattices of cyclic flats are simpler and smaller (see Examples 1 and 2).

3. The tools

The first lemma generalizes an argument from the proof of [2, Theorem 7.3]. The join \( F_1 \lor F_2 \) mentioned below is the join in the lattice \( \mathcal{Z}(M) \) of cyclic flats.

**Lemma 3.1.** Assume that the function \( g : \mathcal{Z}^0(M) \to 2^{2^E(M)} \) has the property that if \( g(F_1) \cap g(F_2) \neq \emptyset \), then \( F_1 \lor F_2 \in \mathcal{Z}^0(M) \) and \( g(F_1) \cap g(F_2) \subseteq g(F_1 \lor F_2) \). Then

\[
\left| \bigcup_{F \in \mathcal{Z}^0(M)} g(F) \right| = \sum_{S \subseteq \mathcal{Z}^0(M), S \neq \emptyset} (-1)^{|S|+1} \left| \bigcap_{F \in S} g(F) \right| = \sum_{S \subseteq \mathcal{Z}^0(M) \text{ nonempty chains}} (-1)^{|S|+1} \left| \bigcap_{F \in S} g(F) \right|.
\]

Before proving the lemma, we note an example of such a function \( g \). For a matroid \( M \), let \( g_M : \mathcal{Z}^0(M) \to 2^{2^E(M)} \) be given by

\[
(3.1) \quad g_M(F) = \{ X : X \subseteq E(M), |X| = r(M) - 1, \text{ and } \text{cl}_M(X \cap F) = F \}.
\]

It is routine to verify that \( g_M \) has the property in the hypothesis of the lemma. Later in this section we make heavy use of the function \( g_M \) for various matroids \( M \).

**Proof of Lemma 3.1.** The principle of inclusion/exclusion gives the equality of the first two expressions, so we focus on the two sums. Let \( F_1 \) and \( F_2 \) be incomparable flats in \( \mathcal{Z}^0(M) \) with \( g(F_1) \cap g(F_2) \neq \emptyset \), so \( F_1 \lor F_2 \) properly contains both of them. Now \( g(F_1) \cap g(F_2) = g(F_1) \cap g(F_2) \cap g(F_1 \lor F_2) \) by the assumed property. If \( F_1 \) and \( F_2 \) are in a subset \( S \) of \( \mathcal{Z}^0(M) \), and if \( S' \) is the symmetric difference \( S \triangle \{ F_1 \lor F_2 \} \), then \( (-1)^{|S|} = \pm (-1)^{|S'|} \) and

\[
\bigcap_{F \in S} g(F) = \bigcap_{F \in S'} g(F),
\]

so such terms in the first sum could cancel. To cancel all such terms, take a linear extension \( \leq \) of the order \( \subseteq \) on \( \mathcal{Z}^0(M) \) and, if a subset \( S \) of \( \mathcal{Z}^0(M) \) contains incomparable cyclic flats, let \( F_1 \) and \( F_2 \) be such a pair for which \( (F_1, F_2) \) is least in the lexicographic order that \( \leq \) induces on \( \mathcal{Z}^0(M) \times \mathcal{Z}^0(M) \); in the first sum, cancel the term that arises from \( S \) with the one that arises from \( S \triangle \{ F_1 \lor F_2 \} \). Any incomparable cyclic flats \( F_1 \) and \( F_2 \) in a set \( S \) that remains after cancellation satisfy \( g(F_1) \cap g(F_2) = \emptyset \); such terms contribute zero to the first sum and so can be omitted. The result of all such cancellations and omissions is the sum on the right side. \( \square \)

Let \( (X_0, X_1, \ldots, X_r) \) be a flag of a matroid \( M \) with \( \emptyset, E(M) \in \mathcal{Z}(M) \). If, for each \( X_i \), we remove the coloops of \( M \) from \( X_i \), we obtain a chain of cyclic flats. The (possibly empty) chain obtained by removing \( \emptyset \) and \( E(M) \) from this chain is the reduced cyclic chain of the flag. For a chain \( C \) in \( \mathcal{Z}^0(M) \), let \( \text{flag}(C) \) denote the set of all flags of \( M \) whose reduced cyclic chain is \( C \). For a set \( T \) of chains in \( \mathcal{Z}^0(M) \), let \( \text{flag}(T) \) be the union of all sets \( \text{flag}(C) \) where \( C \in T \). For a set \( S \) of flags, let \( \text{comp}(S) \) be the multiset of compositions of the flags in \( S \). Thus, \( \text{comp}(\text{flag}(T)) \) is the multiset of all compositions of all of the flags of \( M \) whose reduced cyclic chain is in the set \( T \) of chains in \( \mathcal{Z}^0(M) \). Let \( \iota(N) \) denote the number of independent hyperplanes (that is, hyperplanes that are independent sets) of a matroid \( N \).

Part of the proof of [2, Theorem 7.3] establishes the following lemma.
Lemma 3.2. Assume that $\emptyset, E(M) \in Z(M)$. Let $C = \{F_1 \subset F_2 \subset \cdots \subset F_t\}$ be a chain in $Z^o(M)$. Set $F_0 = \emptyset$ and $F_{t+1} = E(M)$. Let $L$ be the set of all lists of length $r(M)$, with no repeated entries, that are obtained as follows:

- for each $j \in [t+1]$, pick an independent hyperplane $H_j$ of $M|F_j/F_{j-1}$,
- consider lists in which the entries are the sets $F_1, F_2, \ldots, F_t$, and $E(M)$ along with the singleton subsets of $H_1, H_2, \ldots, H_{t+1}$,
- such a list is in $L$ if and only if, for each $j \in [t+1]$, all singleton subsets of $H_j$ occur before $F_j$.

Mapping $L \in L$ to the sequence $\phi(L)$, the $i$th entry of which is the union of the first $i$ sets in $L$, for $0 \leq i \leq r(M)$, defines a bijection $\phi : L \to \text{flag}(C)$.

Thus, the multiset $\text{comp}(\text{flag}(C))$ is determined by the sizes and ranks of $F_1, F_2, \ldots, F_t$, and $E(M)$, along with $i(M|F_1), i(M|F_j/F_{j-1})$ for $2 \leq j \leq t$, and $i(M/F_t)$.

The number of independent hyperplanes of a matroid can be deduced from its $G$-invariant [2, Proposition 5.5] and so from its configuration.

Corollary 3.3. Let $M$ and $M'$ be matroids, both having neither loops nor coloops. Let $C = \{F_1 \subset F_2 \subset \cdots \subset F_t\}$ be a chain in $Z^o(M)$, and $C' = \{F'_1 \subset F'_2 \subset \cdots \subset F'_t\}$ a chain in $Z^o(M')$. Assume that the following pairs of minors have the same configuration:

- the restrictions $M|F_i$ and $M'|F_i'$,
- for each $i$ with $2 \leq i \leq t$, the minors $M|F_i/F_{i-1}$ and $M'|F'_i/F'_{i-1}$, and
- the contractions $M/F_i$ and $M'/F'_i$.

Then $\text{comp}(\text{flag}(M(C)) = \text{comp}(\text{flag}(M'(C')))$. 

Corollary 3.3 and Lemmas 3.5 and 3.6 are the key tools for the results in the rest of the paper. We next prove a result that we use in the proofs of those lemmas.

Lemma 3.4. Let $M$ and $M'$ be matroids of rank $r$ for which $|E(M)| = |E(M')|$. Assume that $M$ and $M'$ have neither loops nor coloops. Let $C = \{F_1 \subset F_2 \subset \cdots \subset F_t\}$ be a chain in $Z^o(M)$, and $C' = \{F'_1 \subset F'_2 \subset \cdots \subset F'_t\}$ a chain in $Z^o(M')$, for which the following pairs of minors have the same configuration:

- the restrictions $M|F_i$ and $M'|F'_i$, and
- for each $i$ with $2 \leq i \leq t$, the minors $M|F_i/F_{i-1}$ and $M'|F'_i/F'_{i-1}$.

Let $g_M$ and $g_{M'}$ be given by equation (3.1). Then

$$\left| \bigcap_{i \in [t]} g_M(F_i) \right| = \left| \bigcap_{i \in [t]} g_{M'}(F'_i) \right|.$$  

(3.2)

Proof. We get each set in $g_M(F_1) \cap g_M(F_2) \cap \cdots \cap g_M(F_t)$ exactly once by following the steps below, allowing for all possible choices:

- choose integers $a_1, a_2, \ldots, a_t, a_{t+1}$ with $a_1 + a_2 + \cdots + a_t + a_{t+1} = r - 1$, and with $a_i \geq r_M(F_i)$ and $a_i \geq r(F_i) - r(F_{i-1})$ for $2 \leq i \leq t$, and $a_{t+1} \geq 0$;
- choose
  - (i) a spanning set $W_1$ of $M|F_1$ where $|W_1| = a_1$,
  - (ii) for each $i$ with $2 \leq i \leq t$, a spanning set $W_i$ of $M|F_i/F_{i-1}$ where $|W_i| = a_i$,
  - (iii) any set $W_{t+1} \subseteq E(M) - F_t$ where $|W_{t+1}| = a_{t+1};$
- then $W_1 \cup W_2 \cup \cdots \cup W_{t+1} \in g_M(F_1) \cap g_M(F_2) \cap \cdots \cap g_M(F_t)$.

A similar sequences of choices yields all sets in $g_M(F'_1) \cap g_{M'}(F'_2) \cap \cdots \cap g_{M'}(F'_t)$. From this, equality (3.2) follows since, by the hypothesis, the restrictions $M|F_i$ and $M'|F'_i$ have
the same configuration and so the same number of spanning sets of size \(a_1\), and, for each 
\(i\) with \(2 \leq i \leq t\), the minors \(M[F_i]/F_{i-1}\) and \(M'[F'_i]/F'_{i-1}\) have the same configuration 
and so the same number of spanning sets of size \(a_i\), and those assumptions along with the hypothesis 
\(|E(M)| = |E(M')|\) also give \(|E(M) - F_i| = |E(M') - F'_i|\).

For a matroid \(M\), let \(\text{ch}(Z^\circ(M))\) be the set of non-empty chains in \(Z^\circ(M)\).
The next two lemmas and their proofs have a similar flavor and could be merged. We treat them separately for clarity.

**Lemma 3.5.** Let the rank-\(r\) matroids \(M\) and \(M'\) on \(n\) elements have neither loops nor 
coloops. Assume that there is a bijection \(\sigma : \text{ch}(Z^\circ(M)) \rightarrow \text{ch}(Z^\circ(M'))\) such that for 
each chain \(S = \{X_1 \subseteq X_2 \subseteq \cdots \subseteq X_i\} \in \text{ch}(Z^\circ(M))\),

(a) its image \(\sigma(S) = \{X'_1 \subseteq X'_2 \subseteq \cdots \subseteq X'_i\}\) has \(|S|\) elements, and

(b) the restrictions \(M[X_i]\) and \(M'[X'_i]\) have the same configuration, as do, for each \(i\) 
with \(2 \leq i \leq t\), the minors \(M[F_i]/F_{i-1}\) and \(M'[X'_i]/X'_{i-1}\).

Then \(\iota(M) = \iota(M')\) and, for the empty chain \(\emptyset\), \(\text{comp}(\text{flag}_M(\emptyset)) = \text{comp}(\text{flag}_{M'}(\emptyset))\).

**Proof.** Let \(g_M\) and \(g_{M'}\) be given by equation (3.1). Then

\[
\iota(M) = \binom{n}{r-1} - \sum_{F \in Z^\circ(M)} g_M(F),
\]

and similarly for \(M'\), so in order to show that \(\iota(M) = \iota(M')\), it suffices to show that

\[
\left| \sum_{F \in Z^\circ(M)} g_M(F) \right| = \left| \sum_{F \in Z^\circ(M')} g_{M'}(F) \right|.
\]

By Lemma 3.1, it suffices to show that

\[
\sum_{S \in \text{ch}(Z^\circ(M))} (-1)^{|S|+1} \left| \bigcap_{F \in S} g_M(F) \right| = \sum_{S \in \text{ch}(Z^\circ(M'))} (-1)^{|S|+1} \left| \bigcap_{F \in S} g_{M'}(F) \right|.
\]

This holds by applying Lemma 3.4 to each pair of chains \((S, \sigma(S))\) for \(S \in \text{ch}(Z^\circ(M))\).

We now get \(\text{comp}(\text{flag}_M(\emptyset)) = \text{comp}(\text{flag}_{M'}(\emptyset))\) since the reduced cyclic chain of a 
flag is empty if and only if the composition of the flag is \((0, 1, 1, \ldots, 1, n - r + 1)\), and, 
by Lemma 3.2, the number of such flags in \(M\) is \((r - 1)! \iota(M)\), and likewise for \(M'\). \(\square\)

**Lemma 3.6.** Let \(M\) and \(M'\) be rank-\(r\) matroids on \(n\) elements with no loops and no 
coloops. Let \(C_1, C_2, \ldots, C_p\) be distinct (not necessarily disjoint) nonempty chains in 
\(Z^\circ(M)\) and let \(C'_1, C'_2, \ldots, C'_p\) be distinct (not necessarily disjoint) nonempty chains in 
\(Z^\circ(M')\) with \(|C_i| = |C'_i|\) for all \(i, j \in [p]\). Write \(C_i\) as \(\{F_{i,1} \subseteq F_{i,2} \subseteq \cdots \subseteq F_{i,t}\}\) and 
\(C'_i\) as \(\{F'_{i,1} \subseteq F'_{i,2} \subseteq \cdots \subseteq F'_{i,t}\}\). Assume that for all \(i, j \in [p]\),

(a) \(M[F_{i,1}]\) and \(M'[F'_{i,1}]\) have the same configuration, as do the minors \(M[F_{i,h}/F_{i,h-1}]\) 
and \(M'[F'_{i,h}/F'_{i,h-1}]\) for each \(h\) with \(2 \leq h \leq t\).

Also assume that there is a bijection \(\Phi : \bigcup_{i \in [p]} (\text{ch}(Z^\circ(M)/F_{i,t}) \times \{C_i\}) \rightarrow \bigcup_{i \in [p]} (\text{ch}(Z^\circ(M'/F'_{i,t})) \times \{C'_i\})\)

with the following property:

(b) if \(\Phi((\{X_1 \subseteq X_2 \subseteq \cdots \subseteq X_k\}, C_i)) = (\{X'_1 \subseteq X'_2 \subseteq \cdots \subseteq X'_k\}, C'_i)\), then 
k = k' and \(M[X_i]/F_{i,t}\) and \(M'[X'_i]/F'_{i,t}\) have the same configuration, as do the 
minors \(M[X_h/X_{h-1}]\) and \(M'[X'_h/X'_{h-1}]\) for each \(h\) with \(2 \leq h \leq k\).
Then \( \text{comp}(\text{flag}_M(\{C_1, C_2, \ldots, C_p\})) = \text{comp}(\text{flag}_{M'}(\{C'_1, C'_2, \ldots, C'_{p'}\})) \).

This result implies Corollary 3.3, but it applies more broadly, even for \( p = 1 \), since property (b) may hold for some bijection from \( \text{ch}(Z^\circ(M/F_{1,t})) \) onto \( \text{ch}(Z^\circ(M'/F'_{1,t})) \) even if \( M/F_{1,t} \) and \( M'/F'_{1,t} \) have different configurations (see the proof of Theorem 4.1). We may have \( F_{1,t} = F_{j,t} \) even if \( i \neq j \), so chains in \( \text{ch}(Z^\circ(M/F_{1,t})) \) may arise multiple times; the second entry in the Cartesian product distinguishes these occurrences. When \( p = 1 \), we can omit the second factor in the Cartesian product.

**Proof of Lemma 3.6.** By Lemma 3.2, we get each flag of \( M \) whose reduced cyclic chain is \( C_i \) exactly once by the following procedure:

- pick an independent hyperplane of \( M|F_{1,1} \) and take a permutation of its singleton subsets; insert the set \( F_{1,1} \) as the last entry of this list;
- treat each \( h \) with \( 2 \leq h \leq t \) in order; for \( h \), pick an independent hyperplane of \( M|F_{i,h}/F_{i,h-1} \) and insert its singleton subsets anywhere into the list we have so far, and then insert the set \( F_{i,h} \) as the last entry of this list;
- pick an independent hyperplane of \( M/F_{1,t} \) and insert its singleton subsets anywhere into the list we have so far, and then insert \( E(M) \) as the last entry of the list;

the flag that we get from the final list of sets has as its \( j \)th flat, for \( 0 \leq j \leq r \), the union of the first \( j \) sets in the list. The conditions above make it clear that the multiset of compositions of flags that result from any particular choice of independent hyperplanes of \( M|F_{1,1}, M|F_{i,h}/F_{i,h-1} \) for \( 2 \leq h \leq t \), and \( M/F_{1,t} \) does not depend on those sets; only their sizes (which are fixed) and the sizes of \( F_{i,1}, F_{i,2}, \ldots, F_{i,t} \) and \( E(M) \) matter.

A similar description applies to the flags of \( M' \) whose reduced cyclic chain is \( C'_i \). The numbers of independent hyperplanes of \( M|F_{1,1} \) and of \( M|F_{i,h}/F_{i,h-1} \) for \( 2 \leq h \leq t \) are determined by their configurations, so by condition (a) they are equal to the numbers of independent hyperplanes of the corresponding minors of \( M' \) using the chain \( C'_i \). The hypotheses do not imply that \( \iota(M/F_{1,t}) \) and \( \iota(M'/F_{1,t}) \) are equal, but for the conclusion in the theorem to hold, all that we need is

\[
\sum_{i \in [p]} \iota(M/F_{1,t}) = \sum_{i \in [p]} \iota(M'/F'_{1,t}).
\]

(3.3)

For each \( i \in [p] \), let \( g_{M/F_{1,t}} \), which we shorten to \( g_i \), be given by equation (3.1), and likewise for \( g'_i \), the shortened form of \( g_{M'/F'_{1,t}} \). Then

\[
\iota(M/F_{1,t}) = \left( r - r_{M}(F_{1,t}) - 1 \right) \bigg| \bigcup_{F \in Z^\circ(M/F_{1,t})} g_i(F),
\]

and similarly for \( \iota(M'/F'_{1,t}) \). Condition (a) implies that \( r_{M}(F_{1,t}) = r_{M'}(F'_{1,t}) \) for all \( i, j \in [p] \), so equation (3.3) will follow by showing that

\[
\sum_{i \in [p]} \bigg| \bigcup_{F \in Z^\circ(M/F_{1,t})} g_i(F) \bigg| = \sum_{i \in [p]} \bigg| \bigcup_{F \in Z^\circ(M'/F'_{1,t})} g'_i(F) \bigg|.
\]

By Lemma 3.1, it suffices to show that

\[
\sum_{i \in [p]} \sum_{S \in \text{ch}(Z^\circ(M/F_{1,t}))} (-1)^{|S|+1} \bigg| \bigcap_{F \in S} g_i(F) \bigg| = \sum_{i \in [p]} \sum_{S \in \text{ch}(Z^\circ(M'/F'_{1,t}))} (-1)^{|S|+1} \bigg| \bigcap_{F \in S} g'_i(F) \bigg|.
\]

Lemma 3.4 applies to the chains \( S \) and \( S' \) whenever \( \Phi((S, C_i)) = (S', C'_i) \) with \( i, j \in [p] \), so this equality holds. ∎
4. APPLICATION: A CONSTRUCTION MODIFYING A LATTICE

In this section we show how to extend a finite lattice in different ways to produce lattices in different configurations that yield the same $\mathcal{G}$-invariant.

We first construct the lattices that appear in Theorem 4.1. Let $a_1, a_2, \ldots, a_m$ be distinct elements of a finite lattice $L$ for which

- there is a $b \in L$ with $a_i \land a_j = b$ for all $i, j \in [m]$ with $i \neq j$, and
- for each $i \in [m-1]$, there is a lattice isomorphism $\tau_{m,i} : [0, a_m] \to [0, a_i]$ with $\tau_{m,i}(y) = y$ for all $y \in [0, b]$.

Set $\tau_{i,m} = \tau_{m,i}^{-1}$ and, for distinct $i, j \in [m-1]$, set $\tau_{i,j} = \tau_{m,j} \circ \tau_{i,m}$. Therefore $\tau_{i,j} : [0, a_i] \to [0, a_j]$ is a lattice isomorphism and $\tau_{i,j}(y) = y$ for all $y \in [0, b]$. Let $L_1, L_2, \ldots, L_n$ be finite lattices that are disjoint from each other and from $L$. Fix two functions $s : [n] \to [m]$ and $t : [n] \to [m]$. Form a lattice $L_s$ as follows:

- for $i \in [n]$, form $L'_{s_i}$ from $L_i$ by replacing $\hat{1}_{L_i}$ by $\hat{1}_{L_t}$ and $\hat{0}_{L_t}$ by $a_{s(i)}$,
- viewing lattices as relations, let $L_s$ be the transitive closure of $L \cup L'_{s_1} \cup L'_{s_2} \cup \cdots \cup L'_{s_n}$.

It is routine to check that $L_s$ is indeed a lattice. Define $L_t$ similarly. Thus, $L_s$ and $L_t$ have the same elements. The lattices $L_s$ and $L_t$ may be isomorphic, but in many examples they are not. We give examples after the proof of the next result.

**Theorem 4.1.** Let $L_s$ and $L_t$ be as defined above. Let $M_s$ and $M_t$ be matroids, with rank functions $r_s$ and $r_t$, respectively, neither having loops nor coloops, for which, for some lattice isomorphisms $\phi_s : L_s \to \mathcal{Z}(M_s)$ and $\phi_t : L_t \to \mathcal{Z}(M_t)$,

1. $|\phi_s(y)| = |\phi_t(y)|$ and $r_s(\phi_s(y)) = r_t(\phi_t(y))$ for all $y$ in $L_s$, and
2. if $y \in [0, a_m]$, then $|\phi_s(y)| = |\phi_s(\tau_{m,i}(y))|$ and $r_s(\phi_s(y)) = r_s(\phi_s(\tau_{m,i}(y)))$ for all $i \in [m-1]$.

Then $\mathcal{G}(M_s) = \mathcal{G}(M_t)$.

From the $\mathcal{G}$-invariant of a matroid, we can deduce the number of cyclic flats of each size and rank [2, Proposition 5.5], so condition (1) just says how this data lines up. Condition (2) is the only restrictive assumption on this data.

**Proof of Theorem 4.1.** By Theorem 2.4, to show that $\mathcal{G}(M_s) = \mathcal{G}(M_t)$, it suffices to show that $M_s$ and $M_t$ have the same catenary data. For that, it suffices to partition the set of chains in $\mathcal{Z}^\circ(M_s)$ into sets $P_1, P_2, \ldots, P_d$ and partition the set of chains in $\mathcal{Z}^\circ(M_t)$ into sets $Q_1, Q_2, \ldots, Q_d$ so that, for each $h \in [d]$, one of Corollary 3.3, Lemma 3.5, or Lemma 3.6 gives $\text{comp}(\text{flag}_{M_s}(P_h)) = \text{comp}(\text{flag}_{M_t}(Q_h))$. We specify chains in $\mathcal{Z}^\circ(M_s)$ as chains in $L_s^\circ$; to get the corresponding chains in $\mathcal{Z}^\circ(M_s)$, apply $\phi_s$; we handle chains in $\mathcal{Z}^\circ(M_t)$ similarly. Let $\text{ch}(L^\circ_s)$ denote the set of nonempty chains in $L^\circ_s$; define $\text{ch}(L^\circ_t)$ similarly.

We start with some useful observations for verifying that certain minors have the same configuration, as required by Corollary 3.3 and Lemmas 3.5 and 3.6. These observations are cast in terms of an interval $[x, z]$ in $L_s$. The corresponding minor $M_s|_{\phi_s(z)/\phi_s(x)}$ of $M_s$ can be, if $x = 0$, the restriction to the first cyclic flat in a chain, or, if $z = 1$, the contraction by the last cyclic flat in a chain, or the minor determined by consecutive cyclic flats in a chain. Only restrictions of Corollary 3.3 use intervals of the form $[x, 1]$.

Properties (1) and (2) imply that, for all distinct integers $i, j \in [m]$ and all $y \in [0, a_i]$,

- (S) $|\phi_s(y)| = |\phi_s(\tau_{i,j}(y))| = |\phi_t(\tau_{i,j}(y))|$, and
- (R) $r_s(\phi_s(y)) = r_s(\phi_s(\tau_{i,j}(y))) = r_t(\phi_t(\tau_{i,j}(y)))$. 


Consider an interval \([x, z]_{L_i}\) with \(x \neq z\). The next three items treat all intervals that arise when we apply Corollary 3.3 and Lemmas 3.5 and 3.6.

- If there is no \(i \in [m]\) with \(x \leq a_i < z\), then \(M_s|\phi_s(x)\phi_s(x)\) and \(M_t|\phi_t(z)/\phi_t(x)\) have the same configuration.

This holds since \([x, z]_{L_i}\) is also an interval of \(L_i\) and the equalities in property (1) hold for all \(y\) in \([x, z]_{L_i}\). This next statement gives addition information for some of the intervals to which the last statement applies.

- If \(z \leq a_i\) for some \(i \in [m]\), then, for all \(j \in [m]\) with \(j \neq i\), the minors \(M_s|\phi_s(z)/\phi_s(x)\) and \(M_t|\phi_t(τ_{i,j}(z))/\phi_t(τ_{i,j}(x))\) have the same configuration.

This holds since properties (S) and (R) apply to all \(y \in [x, z]\).

- If \(x \leq a_i\) and \(z \in L_i^b\) where \(s(h) = i\) and \(t(h) = j\), then
  - if \(i = j\), then the minors \(M_s|\phi_s(z)/\phi_s(x)\) and \(M_t|\phi_t(z)/\phi_t(x)\) have the same configuration, while
  - if \(i \neq j\), then the minors \(M_s|\phi_s(z)/\phi_s(x)\) and \(M_t|\phi_t(z)/\phi_t(τ_{i,j}(x))\) have the same configuration.

This holds by property (1) and, for the second part, properties (S) and (R) applied to all \(y \in [x, a_i]\).

To treat the empty chain via Lemma 3.5, consider \(σ : ch(L_0^n) → ch(L_0^n)\) given by, for \(C ∈ ch(L_0^n)\),

\[
σ(C) = \begin{cases} 
(C - L) ∪ τ_{s(h),t(h)}(C ∩ L), & \text{if } C ∩ L_b^0 \neq ∅ \text{ and } s(h) \neq t(h), \\
C, & \text{otherwise}.
\end{cases}
\]

It is routine to check that \(σ\) is a bijection. Condition (a) clearly holds. The observations in the second paragraph show that condition (b) holds, so Lemma 3.5 applies.

A chain \(C\) is in the symmetric difference \(ch(L_0^n)△ch(L_0^n)\) if and only if (i) \(C ⊄ L_i\), (ii) \(C ∩ L ⊄ [0, b]\), and (iii) \(s(h) \neq t(h)\) for the \(h\) with \(C - L ⊂ L_i^b\). Restricting \(σ\) gives a bijection \(σ : ch(L_0^n) - ch(L_0^n) → ch(L_0^n) - ch(L_0^n)\). Corollary 3.3 applies to the chains \(φ_s(C)\) and \(φ_t(σ(C))\) for each \(C ∈ ch(L_0^n) - ch(L_0^n)\); the observations in the second paragraph show that conditions (a)–(c) hold.

We now focus on chains in \(ch(L_0^n) ∩ ch(L_0^n)\). Let \(max(C)\) denote the greatest element in a chain \(C\). If \(C\) be a nonempty chain of both \(L_0^n\) and \(L_0^n\). If \(i \notin [m]\) has \(C ⊄ [0, a_i]\), then Corollary 3.3 applies to \(φ_s(C)\) and \(φ_t(C)\), with the observations in the second paragraph showing that conditions (a)–(c) hold. If \(C ⊂ [0, b]\), then Lemma 3.6 applies to \(φ_s(C)\) for \(p = 1\): restrict the map \(σ\) defined above to \(ch((max(C), 1)_{L_0^n})\) to get a bijection \(Φ : ch((max(C), 1)_{L_0^n}) → ch((max(C), 1)_{L_0^n})\); conditions (a) and (b) hold by the observations in the second paragraph. Now consider a chain \(C\) for which there is exactly one \(i \in [m]\) with \(C ⊂ [0, a_i]\). The images of \(C\) under the maps \(τ_{i,j}\), along with \(C\) itself, give \(m\) chains \(C_1, C_2, \ldots, C_m\) with \(C_j ⊂ [0, a_j]\) and \(τ_{j,h}(C_j) = C_h\) for all distinct \(j, h \in [m]\). We apply Lemma 3.6 to the chains \(φ_s(C_1), φ_s(C_2), \ldots, φ_s(C_m)\) in \(Z^o(M_s)\), and \(φ_t(C_1), φ_t(C_2), \ldots, φ_t(C_m)\) in \(Z^o(M_t)\). By the observations in the second paragraph, condition (a) in that lemma holds. Note that if \(D ∈ ch((max(C_h), 1)_{L_0^n})\) and \(D ∩ L_0^0 ≠ ∅\), then \(s(j) = h\). The map

\[
Φ : \bigcup_{h ∈ [m]} (ch((max(C_h), 1)_{L_0^n}) × \{C_h\}) → \bigcup_{h ∈ [m]} (ch((max(C_h), 1)_{L_0^n}) × \{C_h\})
\]
Figure 1. The lattice in Example 1.

given by

\[ \Phi((D, C_h)) = \begin{cases} 
((D - L) \cup \tau_{t(j)}(D \cap L), C_{t(j)}), & \text{if } D \cap L_j \neq \emptyset \text{ and } t(j) \neq h, \\
(D, C_h), & \text{otherwise,} 
\end{cases} \]

is easily seen to be a bijection that, by the observations in the second paragraph, when we apply \( \phi_s \) and \( \phi_t \), satisfies property (b) in Lemma 3.6.

Example 1. If the lattice \( L \) in the construction above is the lattice of flats of an \( m \)-point line and each \( L_i \) is a three-element chain, then \( L_s \) has the form illustrated in Figure 1, where some open intervals \( (a, \hat{1}) \) may be empty. The number of non-isomorphic lattices of this type is the number of integer partitions of \( n \) with at most \( m \) parts. One type of matroid for which its lattice of cyclic flats has this form is a rank-4 matroid with \( m \) three-point lines \( A_1, A_2, \ldots, A_m \), each pair of which spans the matroid, and where each cyclic plane contains just one cyclic line, namely, some \( A_i \). If the sizes of the \( n \) cyclic planes are fixed and distinct, then, up to isomorphism, \( \sum_{i \in [m]} S(n, i) \) matroids satisfy these condition, and their configurations are different. (Here, \( S(n, i) \) is the Stirling number of the second kind. For some pairs of configurations, the lattices are isomorphic but the assignments of sizes differ.) This produces huge sets of matroids with very simple but different configurations and the same \( G \)-invariant. For instance, for \( m = n \), the cyclic planes can have distinct sizes with only \( n(n + 7)/2 \) elements in the matroids, and the size of the set of matroids produced this way, with different configurations and the same \( G \)-invariant, is the \( n \)th Bell number. More such examples result by altering the sizes and ranks.

Example 2. Since a cyclic flat is both cyclic (a union of circuits) and a flat (an intersection of hyperplanes, the complements of which are circuits of the dual matroid), it follows that \( X \) is a cyclic flat of a matroid \( M \) if and only if \( E(M) - X \) is a cyclic flat of the dual matroid, \( M^* \). Thus, \( Z(M^*) \) is isomorphic to the order dual of \( Z(M) \). So a counterpart of Theorem 4.1 holds for the order duals of \( L_s \) and \( L_t \). An example of a matroid whose lattice of cyclic flats is isomorphic to the order dual of the lattice considered in the previous example is a rank-\( r \) matroid, with \( r \geq 4 \), in which the restriction to each of the cyclic hyperplanes \( A_1, A_2, \ldots, A_m \), which are pairwise disjoint and have the same cardinality, is a paving matroid, where any two cyclic flats of rank \( r - 2 \) in distinct cyclic hyperplanes span the matroid. It is conjectured that asymptotically almost all matroids are paving, and, while that is still unresolved (see [1] for recent results), the number of paving matroids is known to be enormous, so this construction produces huge sets of matroids with different configurations but the same \( G \)-invariant. Also, as in the previous example, as \( r \) grows, we have more options for the ranks of the cyclic flats \( A_i \) and for the cyclic flats \( X_j \) that they contain.
5. APPLICATION: A CONSTRUCTION USING PAVING MATROIDS

In Theorem 5.1 we show how to use the lattices of flats of paving matroids as the lattices in different configurations that yield the same $G$-invariant. Examples are given after the proof.

**Theorem 5.1.** Let $N_1$ and $N_2$ be non-isomorphic rank-$r$ paving matroids on a set $E$. For $i \in [2]$, let $H_i$ be the set of hyperplanes of $N_i$ and let $L_i$ be the lattice of flats of $N_i$. Assume that there are partitions $\{A_1, A_2, \ldots, A_p\}$ of $H_1 - H_2$ and $\{B_1, B_2, \ldots, B_p\}$ of $H_2 - H_1$, and, for each $j \in [p]$, a bijection $\alpha_j : E \to E$ such that $X \in A_j$ if and only if $\alpha_j(X) \in B_j$. Let $M_1$ and $M_2$ be matroids, with rank functions $r_1$ and $r_2$, respectively, for which there are lattice isomorphisms $\phi_i : L_i \to Z(M_i)$, for $i \in [2]$, such that

- if $X \in L_1 \cap L_2$, then $|\phi_1(X)| = |\phi_2(X)|$ and $r_1(\phi_1(X)) = r_2(\phi_2(X))$, and
- if $j \in [p]$ and $Y \in A_j$, then
  - $|\phi_1(Y)| = |\phi_2(\alpha_j(Y))|$ and $r_1(\phi_1(Y)) = r_2(\phi_2(\alpha_j(Y)))$, and
  - $|\phi_1(X)| = |\phi_1(\alpha_j(X))|$ and $r_1(\phi_1(X)) = r_1(\phi_1(\alpha_j(X)))$ for all $X \subseteq Y$ with $|X| < r - 1$.

Then $G(M_1) = G(M_2)$.

The hypotheses imply that $N_1$ and $N_2$ have the same configuration. Also, the conditions on $\phi_1$ and $\phi_2$ give the following equalities: if $Y \in A_j$ and $X \subseteq Y$ with $|X| < r - 1$, then

- $|\phi_2(X)| = |\phi_1(X)| = |\phi_1(\alpha_j(X))| = |\phi_2(\alpha_j(X))|$ and
- $r_2(\phi_2(X)) = r_1(\phi_1(X)) = r_1(\phi_1(\alpha_j(X))) = r_2(\phi_2(\alpha_j(X)))$.

**Proof of Theorem 5.1.** As in the previous proof, we give partitions $\{P_1, P_2, \ldots, P_d\}$ of the set of chains in $Z^0(M_1)$ and $\{Q_1, Q_2, \ldots, Q_d\}$ of the set of chains in $Z^0(M_2)$ so that, for each $h \in [d]$, we get $\text{comp(flag}_{M_1}(P_h)) = \text{comp(flag}_{M_2}(Q_h))$ from Corollary 3.3, Lemma 3.5, or Lemma 3.6. We can specify chains in $Z^0(M_i)$, for $i \in [2]$, as chains in $L_i^0$; to get the corresponding chain in $Z^0(M_j)$, apply $\phi_i$. Let $\text{ch}(L_i^0)$ denote the set of nonempty chains in $L_i^0$.

To treat the empty chain via Lemma 3.5, we need a bijection $\sigma : \text{ch}(L_1^0) \to \text{ch}(L_2^0)$ so that the composition $\phi_2 \circ \sigma \circ \phi_1^{-1}$ satisfies the conditions in Lemma 3.5. For a chain $C = \{Y_1 \subseteq Y_2 \subseteq \cdots \subseteq Y_t\}$ in $\text{ch}(L_1^0)$, let

$$\sigma(C) = \begin{cases} \alpha_j(C), & \text{if } Y_t \in A_j, \\ C, & \text{otherwise}, \end{cases}$$

where $\alpha_j(C) = \{\alpha_j(Y_h) : h \in [t]\}$. The hypotheses imply that $\sigma$ is a bijection. Condition (a) clearly holds. To see that $\phi_2 \circ \sigma \circ \phi_1^{-1}$ satisfies condition (b), set $Y_0 = \emptyset$. If $\sigma(C) = C$, then $|\phi_1(X)| = |\phi_2(X)|$ and $r_1(\phi_1(X)) = r_2(\phi_2(X))$ for all $X \in \{Y_{h-1}, Y_h\}$ with $h \in [t]$, which gives condition (b) in this case. If $\sigma(C) = \alpha_j(C)$, then $|\phi_1(X)| = |\phi_2(\alpha_j(X))|$ and $r_1(\phi_1(X)) = r_2(\phi_2(\alpha_j(X)))$ for all $X \in \{Y_{h-1}, Y_h\}$ with $h \in [t]$, which gives condition (b) in this case.

Now $\text{ch}(L_1^0) - \text{ch}(L_2^0) = \{\{Y_1 \subseteq Y_2 \subseteq \cdots \subseteq Y_t\} : Y_t \in H_i_1 - H_i_2\}$ for $(i_1, i_2)$ in $\{(1, 2), (2, 1)\}$. For each $C = \{Y_1 \subseteq Y_2 \subseteq \cdots \subseteq Y_t\} \in \text{ch}(L_1^0) - \text{ch}(L_2^0)$, there is a unique $j \in [p]$ with $Y_t \in A_j$, and Corollary 3.3 applies to the chains $\phi_1(C)$ of $M_1$ and $\phi_2(\alpha_j(C))$ of $M_2$. Properties (a)–(c) hold as in the previous paragraph.

We now treat the nonempty chains in $\text{ch}(L_1^0) \cap \text{ch}(L_2^0)$. For any chain $C$ that contains a set in $H_1 \cap H_2$, Corollary 3.3 applies to the chains $\phi_1(C)$ in $M_1$ and $\phi_2(C)$ in $M_2$. To treat the remaining chains, we define a graph $G$ whose vertices are the nonempty chains in $\text{ch}(L_1^0) \cap \text{ch}(L_2^0)$ that contain no hyperplane. Two such chains $C = \{Y_1 \subseteq Y_2 \subseteq \cdots \subseteq Y_t\}$
and \( C' = \{ Y'_1 \subseteq Y'_2 \subseteq \cdots \subseteq Y'_t \} \) are adjacent in \( G \) if \( t = t' \) and there is a \( j \in [p] \) and an \( X \in A_j \) such that either (i) \( Y'_t \subseteq X \) and \( C' = \alpha_j(C) \) or (ii) \( Y'_t' \subseteq X \) and \( C = \alpha_j(C') \). Thus, if \( C \) and \( C' \) are adjacent, then, setting \( Y_0 = Y'_0 = \emptyset \), there is a bijection \( \beta_h : [Y_{h-1}, Y_h] \to [Y'_{h-1}, Y'_h] \) for each \( h \in [t] \) such that for each \( X \in [Y_{h-1}, Y_h] \),

- \( |\phi_2(X)| = |\phi_1(X)| = |\phi_1(\beta_h(X))| = |\phi_2(\beta_h(X))| \), and
- \( r_2(\phi_2(X)) = r_1(\phi_1(X)) = r_1(\phi_1(\beta_h(X))) = r_2(\phi_2(\beta_h(X))) \).

(The bijection \( \beta_h \) is a restriction of \( \alpha_j \) if \( Y_t \subseteq X \) and \( C' = \alpha_j(C) \), otherwise \( \beta_h \) is a restriction of \( \alpha_j^{-1} \)). So the following minors of \( M_1 \) and \( M_2 \) have the same configuration:

- the restrictions \( M_2|\phi_2(Y_1), M_1|\phi_1(Y_1), M_1|\phi_1(Y'_1), \) and \( M_2|\phi_2(Y'_1) \),
- the minors \( M_2|\phi_2(Y'_h)/\phi_2(Y_{h-1}), M_1|\phi_1(Y_h)/\phi_1(Y_{h-1}), M_1|\phi_1(Y'_h)/\phi_1(Y'_{h-1}), \) and \( M_2|\phi_2(Y'_h)/\phi_2(Y'_{h-1}) \) for each \( h \) with \( 2 \leq h \leq t \).

It follows that the same conclusions hold for any two chains in the same component of \( G \). Let \( C_1, C_2, \ldots, C_s \) be the vertices in a connected component of \( G \). We complete the proof by showing that Lemma 3.6 applies to \( \phi_1(C_1), \phi_1(C_2), \ldots, \phi_1(C_s) \) in \( M_1 \) and \( \phi_2(C_1), \phi_2(C_2), \ldots, \phi_2(C_s) \) in \( M_2 \). Property (a) in that lemma follows from what we just deduced. For \( k \in [s] \), let \( Z_k \) be the largest set in the chain \( C_k \). The sets \( Z_1, Z_2, \ldots, Z_s \) need not be distinct. Consider the map

\[
\Phi : \bigcup_{k \in [s]} \left( \text{ch}((Z_k, E)_{L_1}) \times \{ C_k \} \right) \to \bigcup_{k \in [s]} \left( \text{ch}((Z_k, E)_{L_2}) \times \{ C_k \} \right)
\]

given as follows: for \( D = \{ W_1 \subseteq W_2 \subseteq \cdots \subseteq W_s \} \) in the interval \( (Z_k, E)_{L_1} \),

\[
\Phi((D, C_k)) = \begin{cases} 
(\alpha_j(D), \alpha_j(C_k)), & \text{if } W_s \in A_j, \\
(D, C_k), & \text{otherwise.}
\end{cases}
\]

It is easy to see that \( \Phi \) is a bijection. When we apply \( \phi_1 \) and \( \phi_2 \), property (b) in Lemma 3.6 follows by the same type of argument as in the second paragraph.

When two paving matroids \( N_1 \) and \( N_2 \) on \( E \) have the same configuration, partitions \( \{ A_1, A_2, \ldots, A_p \} \) and \( \{ B_1, B_2, \ldots, B_p \} \) and bijections \( \alpha_j : E \to E \), for \( j \in [p] \), that satisfy the hypothesis of Theorem 5.1 exist since the blocks can be singletons and the multiset of cardinalities of the hyperplanes will be the same for \( N_1 \) as for \( N_2 \). However, poorly-chosen partitions and bijections can restrict the size-rank data in \( M_1 \) and \( M_2 \) more than necessary. We illustrate two efficient choices of partitions and bijections, as well as how the matroids \( M_1 \) and \( M_2 \) can be constructed.

**Example 3.** Fix integers \( m \geq 2 \) and \( n \geq 2 \). Let \( N_1 \) and \( N_2 \) be the rank-3 paving matroids on the set \( \{ a, b, x_1, x_2, \ldots, x_m, y_1, y_2, \ldots, y_n \} \) where

- the dependent hyperplanes of \( N_1 \) are \( \{ a, x_1, x_2, \ldots, x_m \} \) and \( \{ b, y_1, y_2, \ldots, y_n \} \), and
- the dependent hyperplanes of \( N_2' \) are \( \{ a, x_1, x_2, \ldots, x_m \} \) and \( \{ a, y_1, y_2, \ldots, y_n \} \).

These paving matroids are shown in Figure 2. Now

- \( H_1 - H_2 = \{ \{ b, y_1, y_2, \ldots, y_n \}, \{ a, y_1 \}, \{ a, y_2 \}, \ldots, \{ a, y_n \} \} \), and
- \( H_2 - H_1 = \{ \{ a, y_1, y_2, \ldots, y_n \}, \{ b, y_1 \}, \{ b, y_2 \}, \ldots, \{ b, y_n \} \} \).

We partition each of these into a single block. A bijection \( \alpha \) that has the properties in Theorem 5.1 is the 2-cycle \((a, b)\).

With this pair of rank-3 paving matroids \( N_1 \) and \( N_2 \), we illustrate how straight-forward it is to construct matroids \( M_1 \) and \( M_2 \) that satisfy the hypotheses of Theorem 5.1 and so have different configurations and the same \( G \)-invariant. It is well known that a matroid \( M \)
Figure 2. The rank-3 paving matroids in Example 3.

is determined by the set \( \{(X, r(X)) : X \in \mathcal{Z}(M)\} \). We construct \( M_1 \) and \( M_2 \) by giving their cyclic flats and the ranks of these sets; this approach is justified by the following result [4, Theorem 3.2].

**Lemma 5.2.** For a set \( \mathcal{Z} \) of subsets of a set \( E \) and a function \( r : \mathcal{Z} \to \mathbb{Z} \), there is a matroid \( M \) on \( E \) with \( \mathcal{Z}(M) = \mathcal{Z} \) and \( r_M(X) = r(X) \) for all \( X \in \mathcal{Z} \) if and only if

\[
\text{(Z0)} \quad (\mathcal{Z}, \subseteq) \text{ is a lattice,}
\]

\[
\text{(Z1)} \quad r(0) = 0, \text{ where } 0 \in \mathcal{Z} \text{ is the least set in } \mathcal{Z},
\]

\[
\text{(Z2)} \quad 0 < r(Y) - r(X) < |Y - X| \text{ for all } X, Y \in \mathcal{Z} \text{ with } X \subset Y, \text{ and}
\]

\[
\text{(Z3)} \quad r(X \cup Y) + r(X \cap Y) + (|X \cap Y| - (X \cap Y)| \leq r(X) + r(Y) \text{ for } X, Y \in \mathcal{Z}.
\]

Let \( S = \{A, B, X_1, X_2, \ldots, X_m, Y_1, Y_2, \ldots, Y_n\} \) be a set of pairwise disjoint sets, each with at least seven elements, and with \( |A| = |B| \). Let \( a \in E(N_1) \) correspond to \( A \in S \), and likewise for the other elements and sets. Let \( E \) be the union of the sets in \( S \). Let \( Z_1 \) be the set of unions of sets in \( S \) that correspond to flats of \( N_1 \), and let \( Z_2 \) be the set of unions of sets in \( S \) that correspond to flats of \( N_2 \). Thus, \( Z_1 \) and \( Z_2 \) are lattices. Define \( r_1 : Z_1 \to \mathbb{Z} \) and \( r_2 : Z_2 \to \mathbb{Z} \) as follows.

- Set \( r_1(\emptyset) = r_2(\emptyset) = 0 \).
- Set \( r_1(E) = r_2(E) = 10 \).
- For each set \( Z \in S \), pick an \( i \in \{5, 6\} \) and set \( r_1(Z) = r_2(Z) = i \), where, in addition, \( r_1(A) = r_2(A) = r_1(B) = r_2(B) \).
- Pick an \( i \in \{8, 9\} \) and set \( r_1(A \cup B) = r_2(A \cup B) = i \).
- For each \( j \in \{m\} \), pick an \( i \in \{8, 9\} \) and set \( r_1(B \cup X_j) = r_2(B \cup X_j) = i \).
- For each \( j \in \{n\} \), pick an \( i \in \{8, 9\} \) and set \( r_1(A \cup Y_k) = r_2(A \cup Y_k) = i \).
- For each \( j \in \{m\} \) and \( k \in \{n\} \), pick an \( i \in \{8, 9\} \) and set \( r_1(X_j \cup Y_k) = r_2(X_j \cup Y_k) = i \).
- Pick an \( i \in \{8, 9\} \) and set \( r_1(A \cup X_1 \cup \cdots \cup X_m) = r_2(A \cup X_1 \cup \cdots \cup X_m) = i \).
- Pick an \( i \in \{8, 9\} \) and set \( r_1(B \cup Y_1 \cup \cdots \cup Y_n) = r_2(B \cup Y_1 \cup \cdots \cup Y_n) = i \).

It is easy to see that properties (Z0)–(Z3) hold for the pairs \( (Z_1, r_1) \) and \( (Z_2, r_2) \), so this yields matroids \( M_1 \) and \( M_2 \) to which Theorem 5.1 applies.

Even within the narrow numerical range in this example, there can be more flexibility than presented above. For instance,

- if a set in \( S \) has rank five, it might have only six elements;
- a set in \( S \) can have rank seven (in which case it must have at least eight elements) provided that it is not the intersection of two cyclic flats that each have rank eight;
- sets in \( S \) could have rank four provided that, for any two such sets, sets that contain their union and correspond to lines of \( N_1 \) or \( N_2 \) have rank eight;
- if proper care is taken when assigning ranks (so that condition (Z3) will hold), the sets in \( S \) do not have to be pairwise disjoint (for a smaller example of this type, compare \( N_1 \) and \( N_2 \));
• while we considered just certain unions of the sets in $S$, we could allow certain supersets of these unions.

Combining these factors with allowing other ranks yields an abundance of matroid $M_1$ and $M_2$ to which Theorem 5.1 applies, and the same can be done for any paving matroid $N_1$ and $N_2$.

In the concluding example, we focus exclusively on an efficient choice of the partitions $\{A_1, A_2, \ldots, A_p\}$ and $\{B_1, B_2, \ldots, B_p\}$ and the bijections $\alpha_j : E \rightarrow E$, for $j \in \mathbb{Z}_p$.

**Example 4.** Let $N_1$ and $N_2$ be the rank-4 paving matroids on $\{a, b, c, d, e, f, q, p, r, s, t, u\}$ where

- the dependent hyperplanes of $N_1$ are $\{a, b, c, d\}$, $\{a, b, e, f\}$, and $\{c, d, e, f\}$, and
- the dependent hyperplanes of $N_2$ are $\{a, b, p, q\}$, $\{c, d, r, s\}$, and $\{e, f, t, u\}$.

These paving matroids are shown in Figure 3. We partition $H_1 - H_2$ into

- $A_1 = \{\{a, b, e, f\}, \{a, b, p\}, \{a, b, q\}, \{a, p, q\}, \{b, p, q\}\}$,
- $A_2 = \{\{a, b, c, d\}, \{c, d, r\}, \{c, d, s\}, \{c, r, s\}, \{d, r, s\}\}$,
- $A_3 = \{\{c, d, e, f\}, \{e, f, t\}, \{e, f, u\}, \{e, t, u\}, \{f, t, u\}\}$,

and $H_1 - H_2$ into

- $B_1 = \{\{a, b, p, q\}, \{a, b, e\}, \{a, b, f\}, \{a, e, f\}, \{b, e, f\}\}$,
- $B_2 = \{\{c, d, r, s\}, \{c, d, a\}, \{c, d, b\}, \{c, a, b\}, \{d, a, b\}\}$,
- $B_3 = \{\{e, f, t, u\}, \{e, f, c\}, \{e, f, d\}, \{e, c, d\}, \{f, c, d\}\}$.

Three bijections that have the properties in Theorem 5.1, given as products of cycles, are $\alpha_1 = (e, p)(q, f)$, $\alpha_2 = (a, r)(b, s)$, and $\alpha_3 = (c, t)(d, u)$.

The lattices of flats, $L_1$ and $L_2$, of $N_1$ and $N_2$ have 288 elements, and the isomorphisms $\phi_1 : L_1 \rightarrow Z(M_1)$ and $\phi_2 : L_2 \rightarrow Z(M_2)$ must, for instance, assign to $\{e\}$ and $\{p\}$ cyclic flats of the same size and rank, and likewise for $\{a, e\}$ and $\{a, p\}$.

**References**


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