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Regularity of 1-, 2-, and 3-Sums of Matroids

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Chapter 1

Preliminaries

1.1 Total Unimodularity

Definition 1. Matrix is a function that takes a row index and returns a vector, which is a function that takes a column index and returns a value. The former aforementioned identity is definitional, the latter is syntactical. By abuse of notation $\left(R^Y\right)^X \equiv R^{X \times Y}$ we do not curry functions in this text. When a matrix happens to be finite (that is, both X and Y are finite) and its entries are numeric, we like to represent it by a table of numbers.

Definition 2. Matrix Let A be a square matrix over a commutative ring. Determinant of A is the sum over all permutations, sign of the permutation times the product of ... . (Todo: complete definition).

Definition 3. Matrix.det Let R be a commutative ring. We say that a matrix $A \in R^{X \times Y}$ is totally unimodular, or TU for short, if for every $k \in \mathbb{N}$, every (not necessarily contiguous) $k \times k$ submatrix T of A has $\det T \in \{0, \pm 1\}$.

Lemma 4. Matrix.IsTotallyUnimodular Let A be a TU matrix. Suppose rows of A are multiplied by $\{0, \pm 1\}$ factors. Then the resulting matrix A' is also TU.

Proof. Matrix.IsTotallyUnimodular We prove that A' is TU by Definition **??**. To this end, let T' be a square submatrix of A'. Our goal is to show that $\det T' \in \{0, \pm 1\}$. Let T be the submatrix of A that represents T' before pivoting. If some of the rows of T were multiplied by zeros, then T' contains zero rows, and hence $\det T' = 0$. Otherwise, T' was obtained from T by multiplying certain rows by -1. Since T' has finitely many rows, the number of such multiplications is also finite. Since multiplying a row by -1 results in the determinant getting multiplied by -1, we get $\det T' = \pm \det T \in \{0, \pm 1\}$ as desired. $\square$

Lemma 5. Matrix.IsTotallyUnimodular Let A be a TU matrix. Suppose columns of A are multiplied by $\{0, \pm 1\}$ factors. Then the resulting matrix A' is also TU.

Proof. Matrix.IsTotallyUnimodular,Matrix.IsTotallyUnimodular.mul$_rowsApplyLemma$ **??**toA$^\top$. ☐

Definition 6. Matrix.det Given $k \in \mathbb{N}$, we say that a matrix A is k-partially unimodular, or k-PU for short, if every (not necessarily contiguous, not necessarily injective) $k \times k$ submatrix T of A has $\det T \in \{0, \pm 1\}$.

Lemma 7. Matrix.IsTotallyUnimodular,Matrix.IsPartiallyUnimodular A matrix A is TU if and only if A is k-PU for every $k \in \mathbb{N}$.

Proof. Matrix.IsTotallyUnimodular,Matrix.IsPartiallyUnimodular This follows from Definitions **??** and **??**. ☐

Definition 8. Matrix Matrix made of 4 blocks (2x2).

1.2 Pivoting

Definition 9. Matrix Let $A \in R^{X \times Y}$ be a matrix and let $(x, y) \in X \times Y$ be such that $A(x, y) \neq 0$. A long tableau pivot in A on (x, y) is the operation that maps A to the matrix A' where

$$\forall i \in X,\ \forall j \in Y,\ A'(i,j) = \begin{cases} \frac{A(i,j)}{A(x,y)}, & \text{if } i = x, \\ A(i,j) - \frac{A(i,y) \cdot A(x,j)}{A(x,y)}, & \text{if } i \neq x. \end{cases}$$

Lemma 10. Matrix.IsTotallyUnimodular,Matrix.longTableauPivot Let $A \in \mathbb{Q}^{X \times Y}$ be a TU matrix and let $(x, y) \in X \times Y$ be such that $A(x, y) \neq 0$. Then performing the long tableau pivot in A on (x, y) yields a TU matrix.

Proof. See implementation in Lean. ☐

Definition 11. Matrix.longTableauPivot Let $A \in R^{X \times Y}$ be a matrix and let $(x, y) \in X \times Y$ be such that $A(x, y) \neq 0$. Perform the following sequence of operations.

1. Adjoin the identity matrix $1 \in R^{X \times X}$ to A, resulting in the matrix $B = \begin{bmatrix} 1 & A \end{bmatrix} \in R^{X \times (X \oplus Y)}$.
2. Perform a long tableau pivot in B on (x, y), and let C denote the result.
3. Swap columns x and y in C, and let D be the resulting matrix.
4. Finally, remove columns indexed by X from D, and let A' be the resulting matrix.

A short tableau pivot in A on (x, y) is the operation that maps A to the matrix A' defined above.

Lemma 12. Matrix.shortTableauPivot Let $A \in R^{X \times Y}$ be a matrix and let $(x, y) \in X \times Y$ be such that $A(x, y) \neq 0$. Then the short tableau pivot in A on (x, y) maps A to A' with

$$\forall i \in X,\ \forall j \in Y,\ A'(i,j) = \begin{cases} \frac{1}{A(x,y)}, & \text{if } i = x \text{ and } j = y, \\ \frac{A(x,j)}{A(x,y)}, & \text{if } i = x \text{ and } j \neq y, \\ -\frac{A(i,j)}{A(x,y)}, & \text{if } i \neq x \text{ and } j = y, \\ A(i,j) - \frac{A(i,y) \cdot A(x,j)}{A(x,y)}, & \text{if } i \neq x \text{ and } j \neq y. \end{cases}$$

Proof. Follows by direct calculation. □

Lemma 13. Matrix.shortTableauPivot Let $B = \begin{bmatrix} B_{11} & 0 \\ B_{21} & B_{22} \end{bmatrix} \in \mathbb{Q}^{\{X_1 \cup X_2\} \times \{Y_1 \times Y_2\}}$. Let $B' = \begin{bmatrix} B'_{11} & B'_{12} \\ B'_{21} & B'_{22} \end{bmatrix}$ be the result of performing a short tableau pivot on $(x, y) \in X_1 \times Y_1$ in B. Then $B'_{12} = 0$, $B'_{22} = B_{22}$, and $\begin{bmatrix} B'_{11} \\ B'_{21} \end{bmatrix}$ is the matrix resulting from performing a short tableau pivot on (x, y) in $\begin{bmatrix} B_{11} \\ B_{21} \end{bmatrix}$.

Proof. This follows by a direct calculation. Indeed, because of the 0 block in B, B_{12} and B_{22} remain unchanged, and since $\begin{bmatrix} B_{11} \\ B_{21} \end{bmatrix}$ is a submatrix of B containing the pivot element, performing a short tableau pivot in it is equivalent to performing a short tableau pivot in B and then taking the corresponding submatrix. □

Lemma 14. Matrix.shortTableauPivot Let $k \in \mathbb{N}$, let $A \in \mathbb{Q}^{k \times k}$, and let A' be the result of performing a short tableau pivot in A on (x, y) with $x, y \in \{1, \dots, k\}$ such that $A(x, y) \neq 0$. Then A' contains a submatrix A'' of size $(k-1) \times (k-1)$ with $|\det A''| = |\det A| / |A(x, y)|$.

Proof. Let $X = \{1, \dots, k\} \backslash \{x\}$ and $Y = \{1, \dots, k\} \backslash \{y\}$, and let $A'' = A'(X, Y)$. Since A'' does not contain the pivot row or the pivot column, $\forall (i, j) \in X \times Y$ we have $A''(i, j) = A(i, j) - \frac{A(i,y) \cdot A(x,j)}{A(x,y)}$. For $\forall j \in Y$, let B_j be the matrix obtained from A by removing row x and column j, and let B''_j be the matrix obtained from A'' by replacing column j with $A(X, y)$ (i.e., the pivot column without the pivot element). The cofactor expansion along row x in A yields

$$\det A = \sum_{j=1}^{k} (-1)^{y+j} \cdot A(x, j) \cdot \det B_j.$$

By reordering columns of every B_j to match their order in B''_j, we get

$$\det A = (-1)^{x+y} \cdot \left(A(x, y) \cdot \det A' - \sum_{j \in Y} A(x, j) \cdot \det B''_j \right).$$

By linearity of the determinant applied to $\det A''$, we have

$$\det A'' = \det A' - \sum_{j \in Y} \frac{A(x,j)}{A(x,y)} \cdot \det B''_j$$

Therefore, $|\det A''| = |\det A|/|A(x,y)|$. ☐

Lemma 15. Matrix.IsTotallyUnimodular,Matrix.shortTableauPivot Let $A \in \mathbb{Q}^{X \times Y}$ be a TU matrix and let $(x,y) \in X \times Y$ be such that $A(x,y) \neq 0$. Then performing the short tableau pivot in A on (x,y) yields a TU matrix.

Proof. Matrix.IsTotallyUnimodular.longTableauPivot See implementation in Lean. ☐

1.3 Vector Matroids

Definition 16. (Todo: Add definition of matroids)

Definition 17. Matrix, Matroid Let R be a division ring, let X and Y be sets, and let $A \in R^{X \times Y}$ be a matrix. The vector matroid of A is the matroid $M = (Y, \mathcal{I})$ where a set $I \subset Y$ is independent in M if and only if the columns of A indexed by I are linearly independent.

Definition 18. VectorMatroid Let R be a division ring, let X and Y be disjoint sets, and let $S \in R^{X \times Y}$ be a matrix. Let $A = \begin{bmatrix} 1 & S \end{bmatrix} \in R^{X \times (X \cup Y)}$ be the matrix obtained from S by adjoining the identity matrix as columns, and let M be the vector matroid of A. Then S is called the standard representation of M.

Lemma 19. StandardRepr Let $S \in R^{X \times Y}$ be a standard representation of a vector matroid M. Then X is a base in M.

Proof. See implementation in Lean. ☐

Lemma 20. VectorMatroid Adding extra zero rows to a full representation matrix of a vector matroid does not change the matroid.

Proof. See implementation in Lean. ☐

Lemma 21. Matrix.IsTotallyUnimodular,VectorMatroid,StandardRepr Let $A \in \mathbb{Q}^{X \times Y}$ be a TU matrix, let M be the vector matroid of A, and let B be a base of M. Then there exists a matrix $S \in \mathbb{Q}^{B \times (Y \setminus B)}$ such that S is TU and S is a standard representation of M.

Proof. Matrix.IsTotallyUnimodular.longTableauPivot,Matrix.fromRows$_{z}ero_{r}eindex_{t}oMatroidSeeimplementa$

Definition 22. Matrix Let R be a magma containing zero. The support of matrix $A \in R^{X \times Y}$ is $A^{\#} \in \{0,1\}^{X \times Y}$ given by

$$\forall i \in X,\ \forall j \in Y,\ A^{\#}(i,j) = \begin{cases} 0, & \text{if } A(i,j) = 0, \\ 1, & \text{if } A(i,j) \neq 0. \end{cases}$$

Lemma 23. Matrix.support Transpose of a support matrix is equal to a support of the transposed matrix.

Proof. Definitional equality. □

Lemma 24. Matrix.support Submatrix of a support matrix is equal to a support matrix of the submatrix.

Proof. Definitional equality. □

Lemma 25. Matrix.support If A is a matrix over $\mathbb{Z}_2$, then $A^{\#} = A$.

Proof. Check elementwise equality. □

Lemma 26. Matrix.support,StandardRepr If two standard representation matrices of the same matroid have the same base, then they have the same support.

Proof. See implementation in Lean. □

Lemma 27. Matrix.det A square matrix is invertible iff its determinant is invertible.

Proof. This result is proved in Mathlib. □

Lemma 28. Matrix.IsTotallyUnimodular,Matrix.support Let A be a rational TU matrix with finite number of rows and finite number of columns. Its rows are linearly independent iff the rows of its support matrix are linearly independent.

Proof. Matrix.support$_{s}ubmatrix, Matrix.isUnit_{i}ff_{i}sUnit_{d}etSeeimplementationinLean.$ □

Lemma 29. Matrix.IsTotallyUnimodular,Matrix.support Let A be a rational TU matrix with finite number of rows. Its rows are linearly independent iff the rows of its support matrix are linearly independent.

Proof. Matrix.IsTotallyUnimodular.linearIndependent$_{i}ff_{s}upport_{l}inearIndependent_{o}f_{f}inite_{o}f_{f}initeSeeimple$

Lemma 30. Matrix.IsTotallyUnimodular,Matrix.support Let A be a rational TU matrix. Its rows are linearly independent iff the rows of its support matrix are linearly independent.

Proof. Matrix.IsTotallyUnimodular.linearIndependent$_{i}ff_{s}upport_{l}inearIndependent_{o}f_{f}initeSeeimplementati$

Lemma 31. Matrix.IsTotallyUnimodular,Matrix.support,StandardRepr Let A be a TU matrix.

1. If a matroid is represented by A, then it is also represented by $A^{\#}$.
2. If a matroid is represented by $A^{\#}$, then it is also represented by A.

Proof. Matrix.support$_{t}ranspose, Matrix.support_{s}ubmatrix, Matrix.IsTotallyUnimodular.linearIndependen$

1.4 Regular Matroids

Definition 32. Matroid,VectorMatroid,Matrix.IsTotallyUnimodular A matroid M is regular if there exists a TU matrix $A \in \mathbb{Q}^{X \times Y}$ such that M is a vector matroid of A.

Definition 33. Matrix.IsTotallyUnimodular We say that $A' \in \mathbb{Q}^{X \times Y}$ is a TU signing of $A \in \mathbb{Z}_2^{X \times Y}$ if A' is TU and

$$\forall i \in X,\ \forall j \in Y,\ |A'(i,j)| = A(i,j).$$

Lemma 34. StandardRepr,Matroid.IsRegular,Matrix.IsTuSigningOf Let $B \in \mathbb{Z}_2^{X \times Y}$ be a standard representation matrix of a matroid M. Then M is regular if and only if B has a TU signing.

Proof. Matroid.IsRegular,Matrix.IsTuSigningOf,StandardRepr.toMatroid$_{isBase_X}, VectorMatroid.exists_s tan$ $\in \mathbb{Q}^{X \times Y}$ such that M is a vector matroid of A. By Lemma **??**, X (the row set of B) is a base of M. By Lemma **??**, A can be converted into a standard representation matrix $B' \in \mathbb{Q}^{X \times Y}$ of M such that B' is also TU. Since B' and B are both standard representations of M, by Lemma **??** the support matrices $(B')^{\#}$ and $B^{\#}$ are the same. Lemma **??** gives $B^{\#} = B$. Thus, B' is TU and $(B')^{\#} = B$, so B' is a TU signing of B.

Suppose that B has a TU signing $B' \in \mathbb{Q}^{X \times Y}$. Then $A = [1 \mid B']$ is TU, as it is obtained from B' by adjoining the identity matrix. Moreover, by Lemma **??**, A represents the same matroid as $A^{\#} = [1 \mid B]$, which is M. Thus, A is a TU matrix representing M, so M is regular. □

Chapter 2

Regularity of 1-Sum

Definition 35. StandardRepr,Matrix.fromBlocks Let R be a magma containing zero (we will use $R = \mathbb{Z}_2$ and $R = \mathbb{Q}$). Let $B_\ell \in R^{X_\ell \times Y_\ell}$ and $B_r \in R^{X_r \times Y_r}$ be matrices where X_ℓ, Y_ℓ, X_r, Y_r are pairwise disjoint sets. The 1-sum $B = B_\ell \oplus_1 B_r$ of B_ℓ and B_r is

$$B = \begin{bmatrix} B_\ell & 0 \\ 0 & B_r \end{bmatrix} \in R^{(X_\ell \cup X_r) \times (Y_\ell \cup Y_r)}.$$

Definition 36. Matroid,StandardRepr,standardRepr1sumComposition A matroid M is a 1-sum of matroids M_ℓ and M_r if there exist standard $\mathbb{Z}_2$ representation matrices B_ℓ, B_r, and B (for M_ℓ, M_r, and M, respectively) of the form given in Definition **??**.

Lemma 37. Matrix.det Let A be a square matrix of the form $A = \begin{bmatrix} A_{11} & A_{12} \\ 0 & A_{22} \end{bmatrix}$. Then $\det A = \det A_{11} \cdot \det A_{22}$.

Proof. This result is proved in Mathlib. □

Lemma 38. standardRepr1sumComposition,Matrix.IsTotallyUnimodular Let B_ℓ and B_r from Definition **??** be TU matrices (over $\mathbb{Q}$). Then $B = B_\ell \oplus_1 B_r$ is TU.

Proof. standardRepr1sumComposition,Matrix.IsTotallyUnimodular,Matrix.det$_{f}romBlocks_{z}eroWeprovethat$
$\{0, \pm 1\}$.

Let T_ℓ and T_r denote the submatrices in the intersection of T with B_ℓ and B_r, respectively. Then T has the form

$$T = \begin{bmatrix} T_\ell & 0 \\ 0 & T_r \end{bmatrix}.$$

First, suppose that T_ℓ and T_r are square. Then $\det T = \det T_\ell \cdot \det T_r$ by Lemma **??**. Moreover, $\det T_\ell, \det T_r \in \{0, \pm 1\}$, since T_ℓ and T_r are square submatrices of TU matrices B_ℓ and B_r, respectively. Thus, $\det T \in \{0, \pm 1\}$, as desired.

Without loss of generality we may assume that T_ℓ has fewer rows than columns. Otherwise we can transpose all matrices and use the same proof, since TUness and determinants are preserved under transposition. Thus, T can be represented in the form

$$T = \begin{bmatrix} T_{11} & T_{12} \\ 0 & T_{22} \end{bmatrix},$$

where T_{11} contains T_ℓ and some zero rows, T_{22} is a submatrix of T_r, and T_{12} contains the rest of the rows of T_r (not contained in T_{22}) and some zero rows. By Lemma **??**, we have $\det T = \det T_{11} \cdot \det T_{22}$. Since T_{11} contains at least one zero row, $\det T_{11} = 0$. Thus, $\det T = 0 \in \{0, \pm 1\}$, as desired. ☐

Theorem 39. *Matroid.Is1sumOf,Matroid.IsRegular Let M be a* 1*-sum of regular matroids M_ℓ and M_r. Then M is also regular.*

Proof. StandardRepr,Matroid.Is1sumOf,Matroid.IsRegular,StandardRepr.toMatroid$_{i}sRegular_{i}ff_{h}asTuSigni$
B_r, and B be standard $\mathbb{Z}_2$ representation matrices from Definition **??**. Since M_ℓ and M_r are regular, by Lemma **??**, B_ℓ and B_r have TU signings B'_ℓ and B'_r, respectively. Then $B' = B'_\ell \oplus_1 B'_r$ is a TU signing of B. Indeed, B' is TU by Lemma **??**, and a direct calculation shows that B' is a signing of B. Thus, M is regular by Lemma **??**. ☐

Chapter 3

Regularity of 2-Sum

Definition 40. StandardRepr,Matrix.fromBlocks Let R be a semiring (we will use $R = \mathbb{Z}_2$ and $R = \mathbb{Q}$). Let $B_\ell \in R^{(X_\ell \cup \{x\}) \times Y_\ell}$ and $B_r \in R^{X_r \times (Y_r \cup \{y\})}$ be matrices of the form

$$B_\ell = \begin{bmatrix} A_\ell \\ r \end{bmatrix}, \quad B_r = \begin{bmatrix} c & A_r \end{bmatrix}.$$

The 2-sum $B = B_\ell \oplus_{2,x,y} B_r$ of B_ℓ and B_r is defined as

$$B = \begin{bmatrix} A_\ell & 0 \\ D & A_r \end{bmatrix} \quad \text{where} \quad D = c \otimes r.$$

Here $A_\ell \in R^{X_\ell \times Y_\ell}$, $A_r \in R^{X_r \times Y_r}$, $r \in R^{Y_\ell}$, $c \in R^{X_r}$, $D \in R^{X_r \times Y_\ell}$, and the indexing is consistent everywhere.

Definition 41. Matroid,StandardRepr,matrix2sumComposition A matroid M is a 2-sum of matroids M_ℓ and M_r if there exist standard $\mathbb{Z}_2$ representation matrices B_ℓ, B_r, and B (for M_ℓ, M_r, and M, respectively) of the form given in Definition **??**.

Lemma 42. matrix2sumComposition,Matrix.IsTotallyUnimodular Let B_ℓ and B_r from Definition **??** be TU matrices (over $\mathbb{Q}$). Then $C = \begin{bmatrix} D & A_r \end{bmatrix}$ is TU.

Proof. matrix2sumComposition,Matrix.IsTotallyUnimodular,Matrix.IsTotallyUnimodular.mul$_{c}olsSince$B$_\ell$ is TU, all its entries are in $\{0, \pm 1\}$. In particular, r is a $\{0, \pm 1\}$ vector. Therefore, every column of D is a copy of y, $-y$, or the zero column. Thus, C can be obtained from B_r by adjoining zero columns, duplicating the y column, and multiplying some columns by -1. Since all these operations preserve TUess and since B_r is TU, C is also TU. □

Lemma 43. matrix2sumComposition,Matrix.shortTableauPivot Let B_ℓ and B_r be matrices from Definition **??**. Let B'_ℓ and B' be the matrices obtained by performing a short tableau pivot on $(x_\ell, y_\ell) \in X_\ell \times Y_\ell$ in B_ℓ and B, respectively. Then $B' = B'_\ell \oplus_{2,x,y} B_r$.

Proof. matrix2sumComposition,Matrix.shortTableauPivot,Matrix.shortTableauPivot$_zero, Matrix.shortTable$
$\begin{bmatrix} A'_\ell \\ r' \end{bmatrix}$, $\quad B' = \begin{bmatrix} B'_{11} & B'_{12} \\ B'_{21} & B'_{22} \end{bmatrix}$ where the blocks have the same dimensions as in B_ℓ and B, respectively. By Lemma **??**, $B'_{11} = A'_\ell$, $B'_{12} = 0$, and $B'_{22} = A_r$. Equality $B'_{21} = c \otimes r'$ can be verified via a direct calculation. Thus, $B' = B'_\ell \oplus_{2,x,y} B_r$. ☐

Lemma 44. matrix2sumComposition,Matrix.IsTotallyUnimodular Let B_ℓ and B_r from Definition **??** be TU matrices (over $\mathbb{Q}$). Then $B_\ell \oplus_{2,x,y} B_r$ is TU.

Proof. Matrix.isTotallyUnimodular$_iff_forall_isPartiallyUnimodular, matrix2sumComposition, Matrix.IsTo$
B_r is k-PU for every $k \in \mathbb{N}$. We prove this claim by induction on k. The base case with $k = 1$ holds, since all entries of $B_\ell \oplus_{2,x,y} B_r$ are in $\{0, \pm 1\}$ by construction.

Suppose that for some $k \in \mathbb{N}$ we know that for any TU matrices B'_ℓ and B'_r (from Definition **??**) their 2-sum $B'_\ell \oplus_{2,x,y} B'_r$ is k-PU. Now, given TU matrices B_ℓ and B_r (from Definition **??**), our goal is to show that $B = B_\ell \oplus_{2,x,y} B_r$ is $(k+1)$-PU, i.e., that every $(k+1) \times (k+1)$ submatrix T of B has $\det T \in \{0, \pm 1\}$.

First, suppose that T has no rows in X_ℓ. Then T is a submatrix of $\begin{bmatrix} D & A_r \end{bmatrix}$, which is TU by Lemma **??**, so $\det T \in \{0, \pm 1\}$. Thus, we may assume that T contains a row $x_\ell \in X_\ell$.

Next, note that without loss of generality we may assume that there exists $y_\ell \in Y_\ell$ such that $T(x_\ell, y_\ell) \neq 0$. Indeed, if $T(x_\ell, y) = 0$ for all y, then $\det T = 0$ and we are done, and $T(x_\ell, y) = 0$ holds whenever $y \in Y_r$.

Since B is 1-PU, all entries of T are in $\{0, \pm 1\}$, and hence $T(x_\ell, y_\ell) \in \{\pm 1\}$. Thus, by Lemma **??**, performing a short tableau pivot in T on (x_ℓ, y_ℓ) yields a matrix that contains a $k \times k$ submatrix T'' such that $|\det T| = |\det T''|$. Since T is a submatrix of B, matrix T'' is a submatrix of the matrix B' resulting from performing a short tableau pivot in B on the same entry (x_ℓ, y_ℓ). By Lemma **??**, we have $B' = B'_\ell \oplus_{2,x,y} B_r$ where B'_ℓ is the result of performing a short tableau pivot in B_ℓ on (x_ℓ, y_ℓ). Since B_ℓ is TU, by Lemma **??**, B'_ℓ is also TU. Thus, by the inductive hypothesis applied to T'' and $B'_\ell \oplus_{2,x,y} B_r$, we have $\det T'' \in \{0, \pm 1\}$. Since $|\det T| = |\det T''|$, we conclude that $\det T \in \{0, \pm 1\}$. ☐

Theorem 45. *Matroid.IsRegular,Matroid.Is2sumOf Let M be a 2-sum of regular matroids M_ℓ and M_r. Then M is also regular.*

Proof. StandardRepr,Matroid.Is2sumOf,StandardRepr.toMatroid$_isRegular_iff_hasTuSigning, matrix2sumCo$
B_r, and B be standard $\mathbb{Z}_2$ representation matrices from Definition **??**. Since M_ℓ and M_r are regular, by Lemma **??**, B_ℓ and B_r have TU signings B'_ℓ and B'_r, respectively. Then $B' = B'_\ell \oplus_{2,x,y} B'_r$ is a TU signing of B. Indeed, B' is TU by Lemma **??**, and a direct calculation verifies that B' is a signing of B. Thus, M is regular by Lemma **??**. ☐

Chapter 4

Regularity of 3-Sum

4.1 Definition

Definition 46. StandardRepr,Matrix.fromBlocks Let $B_\ell \in \mathbb{Z}_2^{(X_\ell \cup \{x_0,x_1\}) \times (Y_\ell \cup \{y_2\})}$, $B_r \in \mathbb{Z}_2^{(X_r \cup \{x_2\}) \times (Y_r \cup \{y_0,y_1\})}$ be matrices of the form

$$B_\ell = \begin{array}{|c|cc|c|} \hline \multicolumn{3}{|c|}{A_\ell} & 0 \\ \cline{2-4} & 1 & 1 & 0 \\ \hline D_\ell & \multicolumn{2}{c|}{D_0} & 1 \\ & & & 1 \\ \hline \end{array} \quad \text{and} \quad B_r = \begin{array}{|cc|c|c|} \hline 1 & 1 & 0 & 0 \\ \hline \multicolumn{2}{|c|}{D_0} & 1 & \\ & & 1 & A_r \\ \cline{1-2} \multicolumn{2}{|c|}{D_r} & & \\ \hline \end{array} \quad \text{where } D_0 = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \text{ or } D_0 = \begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix}.$$

The 3-sum $B = B_\ell \oplus_3 B_r \in \mathbb{Z}_2^{(X_\ell \cup X_r) \times (Y_\ell \cup Y_r)}$ of B_ℓ and B_r is defined as

$$B = \begin{array}{|c|cc|c|c|} \hline \multicolumn{3}{|c|}{A_\ell} & \multicolumn{2}{c|}{0} \\ \cline{2-4} & 1 & 1 & 0 & \\ \hline D_\ell & \multicolumn{2}{c|}{D_0} & 1 & \\ & & & 1 & A_r \\ \cline{1-4} D_{\ell r} & \multicolumn{2}{c|}{D_r} & & \\ \hline \end{array} \quad \text{where } D_{\ell r} = D_r \cdot (D_0)^{-1} \cdot D_\ell.$$

Here $x_2 \in X_\ell$, $x_0, x_1 \in X_r$, $y_0, y_1 \in Y_\ell$, $y_2 \in Y_r$, $A_\ell \in \mathbb{Z}_2^{X_\ell \times Y_\ell}$, $A_r \in \mathbb{Z}_2^{X_r \times Y_r}$, $D_\ell \in \mathbb{Z}_2^{\{x_0,x_1\} \times (Y_\ell \setminus \{y_0,y_1\})}$, $D_r \in \mathbb{Z}_2^{(X_r \setminus \{x_0,x_1\}) \times \{y_0,y_1\}}$, $D_{\ell r} \in \mathbb{Z}_2^{(X_r \setminus \{x_0,x_1\}) \times (Y_\ell \setminus \{y_0,y_1\})}$, $D_0 \in \mathbb{Z}_2^{\{x_0,x_1\} \times \{y_0,y_1\}}$. The indexing is consistent everywhere.

Note that D_0 is non-singular by construction, so $D_{\ell r}$ and B are well-defined. Moreover, a non-singular $\mathbb{Z}_2^{2\times 2}$ matrix is either $\begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix}$ or $\begin{bmatrix}1 & 1\\ 0 & 1\end{bmatrix}$ up to re-indexing. Thus, Definition **??** can be equivalently restated with D_0 required to be non-singular and B_ℓ, B_r, and B re-indexed appropriately.

Definition 47. Matroid,StandardRepr,MatrixSum3.matrix A matroid M is a 3-sum of matroids M_ℓ and M_r if there exist standard $\mathbb{Z}_2$ representation matrices B_ℓ, B_r, and B (for M_ℓ, M_r, and M, respectively) of the form given in Definition **??**.

4.2 Canonical Signing

Definition 48. Matrix.fromBlocks We call $D_0' \in \mathbb{Q}^{\{x_0,x_1\}\times\{y_0,y_1\}}$ the canonical signing of $D_0 \in \mathbb{Z}_2^{\{x_0,x_1\}\times\{y_0,y_1\}}$ if

$$D_0 = \begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix} \quad \text{and} \quad D_0' = \begin{bmatrix}1 & 0\\ 0 & -1\end{bmatrix}, \quad \text{or} \quad D_0 = \begin{bmatrix}1 & 1\\ 0 & 1\end{bmatrix} \quad \text{and} \quad D_0' = \begin{bmatrix}1 & 1\\ 0 & 1\end{bmatrix}.$$

Similarly, we call $S' \in \mathbb{Q}^{\{x_0,x_1,x_2\}\times\{y_0,y_1,y_2\}}$ the canonical signing of $S \in \mathbb{Z}_2^{\{x_0,x_1,x_2\}\times\{y_0,y_1,y_2\}}$ if

$$S = \begin{array}{|c|c|c|}\hline 1 & 1 & 0 \\ \hline \multicolumn{2}{|c|}{\multirow{2}{*}{D_0}} & 1 \\ \cline{3-3} \multicolumn{2}{|c|}{} & 1 \\ \hline\end{array} \quad \text{and} \quad S' = \begin{array}{|c|c|c|}\hline 1 & 1 & 0 \\ \hline \multicolumn{2}{|c|}{\multirow{2}{*}{D_0'}} & 1 \\ \cline{3-3} \multicolumn{2}{|c|}{} & 1 \\ \hline\end{array}$$

To simplify notation, going forward we use D_0, D_0', S, and S' to refer to the matrices of the form above. BTW, the canonical signing S' of S (from Definition **??**) is TU.

Lemma 49. Matrix.IsTuSigningOf,matrix3x3signed Let Q be a TU signing of S (from Definition **??**). Let $u \in \{0,\pm 1\}^{\{x_0,x_1,x_2\}}$, $v \in \{0,\pm 1\}^{\{y_0,y_1,y_2\}}$, and Q' be defined as follows:

$$u(i) = \begin{cases} Q(x_2,y_0)\cdot Q(x_0,y_0), & i = x_0,\\ Q(x_2,y_0)\cdot Q(x_0,y_0)\cdot Q(x_0,y_2)\cdot Q(x_1,y_2), & i = x_1,\\ 1, & i = x_2,\end{cases}$$

$$v(j) = \begin{cases} Q(x_2,y_0), & j = y_0,\\ Q(x_2,y_1), & j = y_1,\\ Q(x_2,y_0)\cdot Q(x_0,y_0)\cdot Q(x_0,y_2), & j = y_2,\end{cases}$$

$$Q'(i,j) = Q(i,j)\cdot u(i)\cdot v(j) \quad \forall i \in \{x_0,x_1,x_2\},\ \forall j \in \{y_0,y_1,y_2\}.$$

Then $Q' = S'$ (from Definition **??**).

Proof. Matrix.IsTuSigningOf,Matrix.IsTotallyUnimodular.mul$_rows, Matrix.IsTotallyUnimodular.mul_cols, M$
factors, Q' is also a TU signing of S. By construction, we have

$$
\begin{aligned}
&Q'(x_2, y_0) = Q(x_2, y_0) \cdot 1 \cdot Q(x_2, y_0) = 1,\\
&Q'(x_2, y_1) = Q(x_2, y_1) \cdot 1 \cdot Q(x_2, y_1) = 1,\\
&Q'(x_2, y_2) = 0,\\
&Q'(x_0, y_0) = Q(x_0, y_0) \cdot (Q(x_2, y_0) \cdot Q(x_0, y_0)) \cdot Q(x_2, y_0) = 1,\\
&Q'(x_0, y_1) = Q(x_0, y_1) \cdot (Q(x_2, y_0) \cdot Q(x_0, y_0)) \cdot Q(x_2, y_1),\\
&Q'(x_0, y_2) = Q(x_0, y_2) \cdot (Q(x_2, y_0) \cdot Q(x_0, y_0)) \cdot (Q(x_2, y_0) \cdot Q(x_0, y_0) \cdot Q(x_0, y_2)) = 1,\\
&Q'(x_1, y_0) = 0,\\
&Q'(x_1, y_1) = Q(x_1, y_1) \cdot (Q(x_2, y_0) \cdot Q(x_0, y_0) \cdot Q(x_0, y_2) \cdot Q(x_1, y_2)) \cdot (Q(x_2, y_1)),\\
&Q'(x_1, y_2) = Q(x_1, y_2) \cdot (Q(x_2, y_0) \cdot Q(x_0, y_0) \cdot Q(x_0, y_2) \cdot Q(x_1, y_2)) \cdot (Q(x_2, y_0) \cdot Q(x_0, y_0) \cdot Q(x_0, y_2)) = 1.
\end{aligned}
$$

Thus, it remains to show that $Q'(x_0, y_1) = S'(x_0, y_1)$ and $Q'(x_1, y_1) = S'(x_1, y_1)$.

Consider the entry $Q'(x_0, y_1)$. If $D_0(x_0, y_1) = 0$, then $Q'(x_0, y_1) = 0 = S'(x_0, y_1)$. Otherwise, we have $D_0(x_0, y_1) = 1$, and so $Q'(x_0, y_1) \in \{\pm 1\}$, as Q' is a signing of S. If $Q'(x_0, y_1) = -1$, then

$$\det Q'(\{x_0, x_2\}, \{y_0, y_1\}) = \det \begin{bmatrix} 1 & -1 \\ 1 & 1 \end{bmatrix} = 2 \notin \{0, \pm 1\},$$

which contradicts TUness of Q'. Thus, $Q'(x_0, y_1) = 1 = S'(x_0, y_1)$.

Consider the entry $Q'(x_1, y_1)$. Since Q' is a signing of S, we have $Q'(x_1, y_1) \in \{\pm 1\}$. Consider two cases.

1. Suppose that $D_0 = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$. If $Q'(x_1, y_1) = 1$, then $\det Q = \det \begin{bmatrix} 1 & 1 & 0 \\ 1 & 0 & 1 \\ 0 & 1 & 1 \end{bmatrix} = -2 \notin \{0, \pm 1\}$, which contradicts TUness of Q'. Thus, $Q'(x_1, y_1) = -1 = S'(x_1, y_1)$.

2. Suppose that $D_0 = \begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix}$. If $Q'(x_1, y_1) = -1$, then $\det Q(\{x_0, x_1\}, \{y_1, y_2\}) = \det \begin{bmatrix} 1 & 1 \\ -1 & 1 \end{bmatrix} = 2 \notin \{0, \pm 1\}$, which contradicts TUness of Q'. Thus, $Q'(x_1, y_1) = 1 = S'(x_1, y_1)$.

□

Definition 50. Matrix.IsTotallyUnimodular Let X and Y be sets with $\{x_0, x_1, x_2\} \subseteq X$ and $\{y_0, y_1, y_2\} \subseteq Y$. Let $Q \in \mathbb{Q}^{X \times Y}$ be a TU matrix. Define $u \in \{0, \pm 1\}^X$,

$v \in \{0, \pm 1\}^Y$, and Q' as follows:

$$u(i) = \begin{cases} Q(x_2, y_0) \cdot Q(x_0, y_0), & i = x_0, \\ Q(x_2, y_0) \cdot Q(x_0, y_0) \cdot Q(x_0, y_2) \cdot Q(x_1, y_2), & i = x_1, \\ 1, & i = x_2, \\ 1, & i \in X \setminus \{x_0, x_1, x_2\}, \end{cases}$$

$$v(j) = \begin{cases} Q(x_2, y_0), & j = y_0, \\ Q(x_2, y_1), & j = y_1, \\ Q(x_2, y_0) \cdot Q(x_0, y_0) \cdot Q(x_0, y_2), & j = y_2, \\ 1, & j \in Y \setminus \{y_0, y_1, y_2\}, \end{cases}$$

$$Q'(i, j) = Q(i, j) \cdot u(i) \cdot v(j) \quad \forall i \in X,\ \forall j \in Y.$$

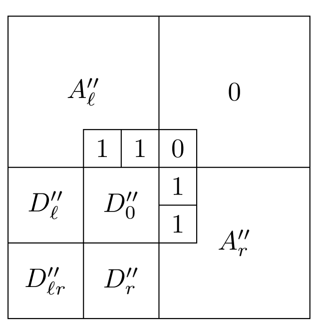
We call Q' the canonical re-signing of Q.

Lemma 51. Matrix.IsTuSigningOf,matrix3x3signed,Matrix.toCanonicalSigning Let X and Y be sets with $\{x_0, x_1, x_2\} \subseteq X$ and $\{y_0, y_1, y_2\} \subseteq Y$. Let $Q \in \mathbb{Q}^{X \times Y}$ be a TU signing of $Q_0 \in \mathbb{Z}_2^{X \times Y}$ such that $Q_0(\{x_0, x_1, x_2\}, \{y_0, y_1, y_2\}) = S$ (from Definition **??**). Then the canonical re-signing Q' of Q (from Definition **??**) is a TU signing of Q_0 and $Q'(\{x_0, x_1, x_2\}, \{y_0, y_1, y_2\}) = S'$ (from Definition **??**).

Proof. Matrix.IsTuSigningOf,Matrix.IsTotallyUnimodular.mul$_{r}ows, Matrix.IsTotallyUnimodular.mul_{c}ols, M$ and Q' is obtained from Q by multiplying some rows and columns by ± 1 factors, Q' is also a TU signing of Q_0. Equality $Q'(\{x_0, x_1, x_2\}, \{y_0, y_1, y_2\}) = S'$ follows from Lemma **??**. □

Definition 52. MatrixSum3.matrix,Matrix.IsTuSigningOf,Matrix.toCanonicalSigning Suppose that B_ℓ and B_r from Definition **??** have TU signings B'_ℓ and B'_r, respectively. Let B''_ℓ and B''_r be the canonical re-signings (from Definition **??**) of B'_ℓ and B'_r, respectively. Let A''_ℓ, A''_r, D''_ℓ, D''_r, and D''_0 be blocks of B''_ℓ and B''_r analogous to blocks A_ℓ, A_r, D_ℓ, D_r, and D_0 of B_ℓ and B_r. The canonical signing B'' of B is defined as

$B'' =$



where $D''_{\ell r} = D''_r \cdot (D''_0)^{-1} \cdot D''_\ell$.

Note that D''_0 is non-singular by construction, so $D''_{\ell r}$ and hence B'' are well-defined.

4.3 Properties of Canonical Signing

Lemma 53. MatrixSum3.toCanonicalSigning B'' from Definition **??** is a signing of B.

Proof. Matrix.HasTuCanonicalSigning.toCanonicalSigning,Matrix.IsTuSigningOf By Lemma **??**, B''_ℓ and B''_r are TU signings of B_ℓ and B_r, respectively. As a result, blocks A''_ℓ, A''_r, D''_ℓ, D''_r, and D''_0 in B'' are signings of the corresponding blocks in B. Thus, it remains to show that $D''_{\ell r}$ is a signing of $D_{\ell r}$. This can be verified via a direct calculation. (Todo: Need details?) $\square$

Lemma 54. MatrixSum3.matrix,Matrix.IsTuSigningOf,Matrix.toCanonicalSigning Suppose that B_r from Definition **??** has a TU signing B'_r. Let B''_r be the canonical re-signing (from Definition **??**) of B'_r. Let $c''_0 = B''_r(X_r, y_0)$, $c''_1 = B''_r(X_r, y_1)$, and $c''_2 = c''_0 - c''_1$. Then the following statements hold.

1. For every $i \in X_r$, $\begin{bmatrix} c''_0(i) & c''_1(i) \end{bmatrix} \in \{0, \pm 1\}^{\{y_0, y_1\}} \setminus \left\{ \begin{bmatrix} 1 & -1 \end{bmatrix}, \begin{bmatrix} -1 & 1 \end{bmatrix} \right\}$.
2. For every $i \in X_r$, $c''_2(i) \in \{0, \pm 1\}$.
3. $\begin{bmatrix} c''_0 & c''_2 & A''_r \end{bmatrix}$ is TU.
4. $\begin{bmatrix} c''_1 & c''_2 & A''_r \end{bmatrix}$ is TU.
5. $\begin{bmatrix} c''_0 & c''_1 & c''_2 & A''_r \end{bmatrix}$ is TU.

Proof. Matrix.HasTuCanonicalSigning.toCanonicalSigning,Matrix.IsTotallyUnimodular,Matrix.shortTableauP is TU, which holds by Lemma **??**.

1. Since B''_r is TU, all its entries are in $\{0, \pm 1\}$, and in particular $\begin{bmatrix} c''_0(i) & c''_1(i) \end{bmatrix} \in \{0, \pm 1\}^{\{y_0, y_1\}}$. If $\begin{bmatrix} c'_0(i) & c''_1(i) \end{bmatrix} = \begin{bmatrix} 1 & -1 \end{bmatrix}$, then
$$\det B''_r(\{x_2, i\}, \{y_0, y_1\}) = \det \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} = -2 \notin \{0, \pm 1\},$$
which contradicts TUness of B''_r. Similarly, if $\begin{bmatrix} c''_0(i) & c''_1(i) \end{bmatrix} = \begin{bmatrix} -1 & 1 \end{bmatrix}$, then
$$\det B''_r(\{x_2, i\}, \{y_0, y_1\}) = \det \begin{bmatrix} 1 & 1 \\ -1 & 1 \end{bmatrix} = 2 \notin \{0, \pm 1\},$$
which contradicts TUness of B''_r. Thus, the desired statement holds.
2. Follows from item **??** and a direct calculation.
3. Performing a short tableau pivot in B''_r on (x_2, y_0) yields:
$$B''_r = \begin{bmatrix} \boxed{1} & 1 & 0 \\ c_0 & c_1 & A_r \end{bmatrix} \quad \to \quad \begin{bmatrix} 1 & 1 & 0 \\ -c_0 & c''_1 - c_0 & A_r \end{bmatrix}$$
The resulting matrix can be transformed into $\begin{bmatrix} c''_0 & c''_2 & A''_r \end{bmatrix}$ by removing row x_2 and multiplying columns y_0 and y_1 by -1. Since B''_r is TU and since TUness is preserved under pivoting, taking submatrices, multiplying columns by ± 1 factors, we conclude that $\begin{bmatrix} c''_0 & c''_2 & A''_r \end{bmatrix}$ is TU.

4. Similar to item **??**, performing a short tableau pivot in B_r'' on (x_2, y_1) yields:

$$B_r'' = \begin{bmatrix} 1 & \boxed{1} & 0 \\ c_0 & c_1 & A_r \end{bmatrix} \quad \to \quad \begin{bmatrix} 1 & 1 & 0 \\ c_0'' - c_1 & -c_1 & A_r \end{bmatrix}$$

The resulting matrix can be transformed into $\begin{bmatrix} c_1'' & c_2'' & A_r'' \end{bmatrix}$ by removing row x_2, multiplying column y_1 by -1, and swapping the order of columns y_0 and y_1. Since B_r'' is TU and since TUness is preserved under pivoting, taking submatrices, multiplying columns by ± 1 factors, and re-ordering columns, we conclude that $\begin{bmatrix} c_1'' & c_2'' & A_r'' \end{bmatrix}$ is TU.

5. Let V be a square submatrix of $\begin{bmatrix} c_0'' & c_1'' & c_2'' & A_r'' \end{bmatrix}$. Our goal is to show that $\det V \in \{0, \pm 1\}$.

   Suppose that column c_2'' is not in V. Then V is a submatrix of B_r'', which is TU. Thus, $\det V \in \{0, \pm 1\}$. Going forward we assume that column z is in V.

   Suppose that columns c_0'' and c_1'' are both in V. Then V contains columns c_0'', c_1'', and $c_2'' = c_0'' - c_1''$, which are linearly. Thus, $\det V = 0$. Going forward we assume that at least one of the columns c_0'' and c_1'' is not in V.

   Suppose that column c_1'' is not in V. Then V is a submatrix of $\begin{bmatrix} c_0'' & c_2'' & A_r'' \end{bmatrix}$, which is TU by item **??**. Thus, $\det V \in \{0, \pm 1\}$. Similarly, if column c_0'' is not in V, then V is a submatrix of $\begin{bmatrix} c_1'' & c_2'' & A_r'' \end{bmatrix}$, which is TU by item **??**. Thus, $\det V \in \{0, \pm 1\}$.

□

Lemma 55. MatrixSum3.matrix,Matrix.IsTuSigningOf,Matrix.toCanonicalSigning Suppose that B_ℓ from Definition **??** has a TU signing B_ℓ'. Let B_ℓ'' be the canonical re-signing (from Definition **??**) of B_ℓ'. Let $d_0'' = B_\ell''(x_0, Y_\ell)$, $d_1'' = B_\ell''(x_1, Y_\ell)$, and $d_2'' = d_0'' - d_1''$. Then the following statements hold.

1. For every $j \in Y_\ell$, $\begin{bmatrix} d_0''(i) \\ d_1''(j) \end{bmatrix} \in \{0, \pm 1\}^{\{x_0, x_1\}} \setminus \left\{ \begin{bmatrix} 1 \\ -1 \end{bmatrix}, \begin{bmatrix} -1 \\ 1 \end{bmatrix} \right\}$.
2. For every $j \in Y_\ell$, $d_2''(j) \in \{0, \pm 1\}$.
3. $\begin{bmatrix} A_\ell'' \\ d_0'' \\ d_2'' \end{bmatrix}$ is TU.
4. $\begin{bmatrix} A_\ell'' \\ d_1'' \\ d_2'' \end{bmatrix}$ is TU.
5. $\begin{bmatrix} A_\ell'' \\ d_0'' \\ d_1'' \\ d_2'' \end{bmatrix}$ is TU.

Proof. MatrixSum3.HasTuBr.cccAr$_i$*sTotallyUnimodularApplyLemma* **??***to*B$_\ell^\top$, or repeat the same arguments up to transposition. □

Lemma 56. MatrixSum3.toCanonicalSigning,Matrix.IsTotallyUnimodular Let B'' be from Definition **??**. Let $c''_0 = B''(X_r, y_0)$, $c''_1 = B''(X_r, y_1)$, and $c''_2 = c''_0 - c''_1$. Similarly, let $d''_0 = B''(x_0, Y_\ell)$, $d''_1 = B''(x_1, Y_\ell)$, and $d''_2 = d''_0 - d''_1$. Then the following statements hold.

1. For every $i \in X_r$, $c''_2(i) \in \{0, \pm 1\}$.
2. If $D''_0 = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$, then $D'' = c''_0 \otimes d''_0 - c''_1 \otimes d''_1$. If $D''_0 = \begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix}$, then $D'' = c''_0 \otimes d''_0 - c''_0 \otimes d''_1 + c''_1 \otimes d''_1$.
3. For every $j \in Y_\ell$, $D''(X_r, j) \in \{0, \pm c''_0, \pm c''_1, \pm c''_2\}$.
4. For every $i \in X_r$, $D''(i, Y_\ell) \in \{0, \pm d''_0, \pm d''_1, \pm d''_2\}$.
5. $\begin{bmatrix} A''_\ell \\ D'' \end{bmatrix}$ is TU.

Proof. MatrixSum3.HasTuBr.cccAr$_i sTotallyUnimodular, lem : three_s um_s igning_{Blp} rops, Matrix.IsTotallyU$

Holds by Lemma **??**.**??**.

Note that

$$\begin{bmatrix} D''_\ell \\ D''_{\ell r} \end{bmatrix} = \begin{bmatrix} D''_0 \\ D''_r \end{bmatrix} \cdot (D''_0)^{-1} \cdot D''_\ell, \quad \begin{bmatrix} D''_0 \\ D''_r \end{bmatrix} = \begin{bmatrix} D''_0 \\ D''_r \end{bmatrix} \cdot (D''_0)^{-1} \cdot D''_0, \quad \begin{bmatrix} D''_0 \\ D''_r \end{bmatrix} = \begin{bmatrix} c''_0 & c''_1 \end{bmatrix}, \quad \begin{bmatrix} D''_\ell & D''_0 \end{bmatrix} = \begin{bmatrix} d''_0 \\ d''_1 \end{bmatrix}.$$

Thus,

$$D'' = \begin{bmatrix} D''_\ell & D''_0 \\ D''_{\ell r} & D''_r \end{bmatrix} = \begin{bmatrix} D''_0 \\ D''_r \end{bmatrix} \cdot (D''_0)^{-1} \cdot \begin{bmatrix} D''_\ell & D''_0 \end{bmatrix} = \begin{bmatrix} c''_0 & c''_1 \end{bmatrix} \cdot (D''_0)^{-1} \cdot \begin{bmatrix} d''_0 \\ d''_1 \end{bmatrix}.$$

Considering the two cases for D''_0 and performing the calculations yields the desired results.

Let $j \in Y_\ell$. By Lemma **??**.**??**, $\begin{bmatrix} d''_0(i) \\ d''_1(j) \end{bmatrix} \in \{0, \pm 1\}^{\{x_0, x_1\}} \setminus \left\{ \begin{bmatrix} 1 \\ -1 \end{bmatrix}, \begin{bmatrix} -1 \\ 1 \end{bmatrix} \right\}$. Consider two cases.

1. If $D''_0 = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$, then by item **??** we have $D''(X_r, j) = d''_0(j) \cdot c''_0 + (-d''_1(j)) \cdot c''_1$. By considering all possible cases for $d''_0(j)$ and $d''_1(j)$, we conclude that $D''(X_r, j) \in \{0, \pm c''_0, \pm c''_1, \pm(c''_0 - c''_1)\}$.
2. If $D''_0 = \begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix}$, then by item **??** we have $D''(X_r, j) = (d''_0(j) - d''_1(j)) \cdot c''_0 + d''_1(j) \cdot c''_1$. By considering all possible cases for $d''_0(j)$ and $d''_1(j)$, we conclude that $D''(X_r, j) \in \{0, \pm c''_0, \pm c''_1, \pm(c''_0 - c''_1)\}$.

Let $i \in X_r$. By Lemma **??**.**??**, $\begin{bmatrix} c''_0(i) & c''_1(i) \end{bmatrix} \in \{0, \pm 1\}^{\{y_0, y_1\}} \setminus \{ \begin{bmatrix} 1 & -1 \end{bmatrix}, \begin{bmatrix} -1 & 1 \end{bmatrix} \}$. Consider two cases.

1. If $D''_0 = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$, then by item **??** we have $D''(i, Y_\ell) = c''_0(i) \cdot d''_0 + (-c''_1(i)) \cdot d''_1$. By considering all possible cases for $c''_0(i)$ and $c''_1(i)$, we conclude that $D''(i, Y_\ell) \in \{0, \pm d''_0, \pm d''_1, \pm d''_2\}$.
2. If $D''_0 = \begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix}$, then by item **??** we have $D''(i, Y_\ell) = c''_0(i) \cdot d''_0 + (c''_1(i) - c''_0(i)) \cdot d''_1$. By considering all possible cases for $c''_0(i)$ and $c''_1(i)$, we conclude that $D''(i, Y_\ell) \in \{0, \pm d''_0, \pm d''_1, \pm d''_2\}$.

By Lemma **??**.**??**, $\begin{bmatrix} A''_\ell \\ d''_0 \\ d''_1 \\ d''_2 \end{bmatrix}$ is TU. Since TUness is preserved under adjoining zero rows, copies of existing rows, and multiplying rows by ± 1 factors, $\begin{bmatrix} A''_\ell \\ 0 \\ \pm d''_0 \\ \pm d''_1 \\ \pm d''_2 \end{bmatrix}$ is also TU. By item **??**, $\begin{bmatrix} A''_\ell \\ D'' \end{bmatrix}$ is a submatrix of the latter matrix, hence it is also TU.

□

4.4 Proof of Regularity

Definition 57. Matrix.IsTotallyUnimodular Let X_ℓ, Y_ℓ, X_r, Y_r be sets and let $c_0, c_1 \in \mathbb{Q}^{X_r}$ be column vectors such that for every $i \in X_r$ we have $c_0(i),\ c_1(i),\ c_0(i) - c_1(i) \in \{0, \pm 1\}$. Define $\mathcal{C}(X_\ell, Y_\ell, X_r, Y_r; c_0, c_1)$ to be the family of matrices of the form $\begin{bmatrix} A_\ell & 0 \\ D & A_r \end{bmatrix}$ where $A_\ell \in \mathbb{Q}^{X_\ell \times Y_\ell}$, $A_r \in \mathbb{Q}^{X_r \times Y_r}$, and $D \in \mathbb{Q}^{X_r \times Y_\ell}$ are such that:

1. for every $j \in Y_\ell$, $D(X_r, j) \in \{0, \pm c_0, \pm c_1, \pm(c_0 - c_1)\}$,
2. $\begin{bmatrix} c_0 & c_1 & c_0 - c_1 & A_r \end{bmatrix}$ is TU,
3. $\begin{bmatrix} A_\ell \\ D \end{bmatrix}$ is TU.

Lemma 58. MatrixSum3.toCanonicalSigning,MatrixLikeSum3 Let B'' be from Definition **??**. Then $B'' \in \mathcal{C}(X_\ell, Y_\ell, X_r, Y_r; c''_0, c''_1)$ where $c''_0 = B''(X_r, y_0)$ and $c''_1 = B''(X_r, y_1)$.

Proof. lem:three$_sum_signing_{Bp}rops, MatrixLikeSum3Recallthat$c$''_0 - c''_1 \in \{0, \pm 1\}^{X_r}$ by Lemma **??**.**??**, so $\mathcal{C}(X_\ell, Y_\ell, X_r, Y_r; c''_0, c''_1)$ is well-defined. To see that $B'' \in \mathcal{C}(X_\ell, Y_\ell, X_r, Y_r; c''_0, c''_1)$, note that all properties from Definition **??** are satisfied: property **??** holds by Lemma **??**.**??**, property **??** holds by Lemma **??**.**??**, and property **??** holds by Lemma **??**.**??**. □

Lemma 59. MatrixLikeSum3,Matrix.shortTableauPivot Let $C \in \mathcal{C}(X_\ell, Y_\ell, X_r, Y_r; c_0, c_1)$ from Definition **??**. Let $x \in X_\ell$ and $y \in Y_\ell$ be such that $A_\ell(x, y) \neq 0$, and let C' be the result of performing a short tableau pivot in C on (x, y). Then $C' \in \mathcal{C}(X_\ell, Y_\ell, X_r, Y_r; c_0, c_1)$.

Proof. Matrix.shortTableauPivot$_zero, Matrix.IsTotallyUnimodular, Matrix.IsTotallyUnimodular.shortTal$
$= \begin{bmatrix} C'_{11} & C'_{12} \\ C'_{21} & C'_{22} \end{bmatrix}, andlet \begin{bmatrix} A'_\ell \\ D' \end{bmatrix} betheresultofperformingashorttableaupivoton(x, y)in \begin{bmatrix} A_\ell \\ D \end{bmatrix}.Observethefollowing.$

- By Lemma **??**, $C'_{11} = A'_\ell$, $C'_{12} = 0$, $C'_{21} = D'$, and $C'_{22} = A_r$.
- Since $\begin{bmatrix} A_\ell \\ D \end{bmatrix}$ is TU by property **??** for C, all entries of A_ℓ are in $\{0, \pm 1\}$.
- $A_\ell(x, y) \in \{\pm 1\}$, as $A_\ell(x, y) \in \{0, \pm 1\}$ by the above observation and $A_\ell(x, y) \neq 0$ by the assumption.
- Since $\begin{bmatrix} A_\ell \\ D \end{bmatrix}$ is TU by property **??** for C, and since pivoting preserves TUness, $\begin{bmatrix} A'_\ell \\ D' \end{bmatrix}$ is also TU.

These observations immediately imply properties **??** and **??** for C'. Indeed, property **??** holds for C', since $C'_{22} = A_r$ and $\begin{bmatrix} c_0 & c_1 & c_0 - c_1 & A_r \end{bmatrix}$ is TU by property **??** for C. On the other hand, property **??** follows from $C'_{11} = A'_\ell$, $C'_{21} = D'$, and $\begin{bmatrix} A'_\ell \\ D' \end{bmatrix}$ being TU. Thus, it only remains to show that C' satisfies property **??**. Let $j \in Y_r$. Our goal is to prove that $D'(X_r, j) \in \{0, \pm c_0, \pm c_1, \pm(c_0 - c_1)\}$.

Suppose $j = y$. By the pivot formula, $D'(X_r, y) = -\frac{D(X_r, y)}{A_\ell(x, y)}$. Since $D(X_r, y) \in \{0, \pm c_0, \pm c_1, \pm(c_0 - c_1)\}$ by property **??** for C and since $A_\ell(x, y) \in \{\pm 1\}$, we get $D'(X_r, y) \in \{0, \pm c_0, \pm c_1, \pm(c_0 - c_1)\}$.

Now suppose $j \in Y_\ell \setminus \{y\}$. By the pivot formula, $D'(X_r, j) = D(X_r, j) - \frac{A_\ell(x, j)}{A_\ell(x, y)} \cdot D(X_r, y)$. Here $D(X_r, j)$, $D(X_r, y) \in \{0, \pm c_0, \pm c_1, \pm(c_0 - c_1)\}$ by property **??** for C, and $A_\ell(x, j) \in \{0, \pm 1\}$ and $A_\ell(x, y) \in \{\pm 1\}$ by the prior observations. Perform an exhaustive case distinction on $D(X_r, j)$, $D(X_r, y)$, $A_\ell(x, j)$, and $A_\ell(x, y)$. In every case, we can show that either $\begin{bmatrix} A_\ell(x, y) & A_\ell(x, j) \\ D(X_r, y) & D(X_r, j) \end{bmatrix}$ contains a submatrix with determinant not in $\{0, \pm 1\}$, which contradicts TUness of $\begin{bmatrix} A_\ell \\ D \end{bmatrix}$, or that $D'(X_r, j) \in \{0, \pm c_0, \pm c_1, \pm(c_0 - c_1)\}$, as desired. (Todo: need details?) $\square$

Lemma 60. MatrixLikeSum3,Matrix.IsTotallyUnimodular Let $C \in \mathcal{C}(X_\ell, Y_\ell, X_r, Y_r; c_0, c_1)$ from Definition **??**. Then C is TU.

Proof. MatrixLikeSum3,Matrix.isTotallyUnimodular$_iff_forall_isPartiallyUnimodular, shortTableauPivot_sub$
$three_sum_like_pivotByLemma$ **??**, $itsufficestoshowthat$Cisk$-PUforevery$k $\in$

$\mathbb{N}$. We prove this claim by induction on k. The base case with $k = 1$ holds, since properties **??** and **??** in Definition **??** imply that A_ℓ, A_r, and D are TU, so all their entries of $C = \begin{bmatrix} A_\ell & 0 \\ D & A_r \end{bmatrix}$ are in $\{0, \pm 1\}$, as desired.

Suppose that for some $k \in \mathbb{N}$ we know that every $C' \in \mathcal{C}(X_\ell, Y_\ell, X_r, Y_r; c_0, c_1)$ is k-PU. Our goal is to show that C is $(k+1)$-PU, i.e., that every $(k+1) \times (k+1)$ submatrix S of C has $\det V \in \{0, \pm 1\}$.

First, suppose that V has no rows in X_ℓ. Then V is a submatrix of $\begin{bmatrix} D & A_r \end{bmatrix}$, which is TU by property **??** in Definition **??**, so $\det V \in \{0, \pm 1\}$. Thus, we may assume that S contains a row $x_\ell \in X_\ell$.

Next, note that without loss of generality we may assume that there exists $y_\ell \in Y_\ell$ such that $V(x_\ell, y_\ell) \neq 0$. Indeed, if $V(x_\ell, y) = 0$ for all y, then $\det V = 0$ and we are done, and $V(x_\ell, y) = 0$ holds whenever $y \in Y_r$.

Since C is 1-PU, all entries of V are in $\{0, \pm 1\}$, and hence $V(x_\ell, y_\ell) \in \{\pm 1\}$. Thus, by Lemma **??**, performing a short tableau pivot in V on (x_ℓ, y_ℓ) yields a matrix that contains a $k \times k$ submatrix S'' such that $|\det V| = |\det V''|$. Since V is a submatrix of C, matrix V'' is a submatrix of the matrix C' resulting from performing a short tableau pivot in C on the same entry (x_ℓ, y_ℓ). By Lemma **??**, we have $C' \in \mathcal{C}(X_\ell, Y_\ell, X_r, Y_r; c_0, c_1)$. Thus, by the inductive hypothesis applied to V'' and C', we have $\det V'' \in \{0, \pm 1\}$. Since $|\det V| = |\det V''|$, we conclude that $\det V \in \{0, \pm 1\}$. ☐

Lemma 61. MatrixSum3.toCanonicalSigning,Matrix.IsTotallyUnimodular B'' from Definition **??** is TU.

Proof. lem:three$_s um_l ike_s igning_B, lem : three_s um_l ike_t uCombinetheresultsofLemmas$ **??**and **??**. ☐

Theorem 62. *Matroid.Is3sumOf,Matroid.IsRegular Let M be a 3-sum of regular matroids M_ℓ and M_r. Then M is also regular.*

Proof. StandardRepr,Matroid.Is3sumOf,StandardRepr.toMatroid$_i sRegular_i ff_h asTuSigning, MatrixSum3.t$
$three_s um_s igning_B v alid, lem : three_s um_s igning_B t uLet$B$_\ell$, B_r, and B be standard $\mathbb{Z}_2$ representation matrices from Definition **??**. Since M_ℓ and M_r are regular, by Lemma **??**, B_ℓ and B_r have TU signings. Then the canonical signing B'' from Definition **??** is a TU signing of B. Indeed, B'' is a signing of B by Lemma **??**, and B'' is TU by Lemma **??**. Thus, M is regular by Lemma **??**. ☐

Chapter 5

Conclusion

Definition 63. Matroid.IsRegular,Matroid.Is1sumOf,Matroid.Is2sumOf,Matroid.Is3sumOf Regular matroid is good. Any 1-sum of good matroids is a good matroid. Any 2-sum of good matroids is a good matroid. Any 3-sum of good matroids is a good matroid.

Corollary 64. Matroid.IsGood,Matroid.IsRegular Any good matroid is regular. This is the easy direction of the Seymour theorem.

Proof. Matroid.Is1sumOf.isRegular,Matroid.Is2sumOf.isRegular,Matroid.Is3sumOf.isRegular Structural induction. □