The logarithmic method and the solution to the TP2-completion problem

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The Logarithmic Method and the Solution to the TP₂-Completion Problem

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A matrix is called TP$_2$ if all 1-by-1 and 2-by-2 minors are positive. A partial matrix is one with some of its entries specified, while the remaining, unspecified, entries are free to be chosen. A TP$_2$-completion, of a partial matrix $T$, is a choice of values for the unspecified entries of $T$ so that the resulting matrix is TP$_2$. The TP$_2$-completion problem asks which partial matrices have a TP$_2$-completion. A complete solution is given here. It is shown that the Bruhat partial order on permutations is the inverse of a certain natural partial order induced by TP$_2$ matrices and that a positive matrix is TP$_2$ if and only if it satisfies certain inequalities induced by the Bruhat order. The Bruhat order on permutations is generalized to a partial order, GBr, on nonnegative matrices, and the concept of majorization is generalized to a partial order, DM, on nonnegative matrices. It is shown that these two partial orders are inverses of each other on the set of nonnegative matrices. Using this relationship and the Hadamard exponential transform on nonnegative matrices, explicit conditions for TP$_2$-completablety of a given partial matrix are given. It is shown that an $m$-by-$n$ partial TP$_2$ matrix $T$ is TP$_2$-completable if and only if $\prod_{t_{ij}\text{ specified}} t_{ij}^{a_{ij}} \geq 1$ for every matrix $A = (a_{ij}) \in M_{m,n}$ having (1) $a_{ij} = 0$ if $t_{ij}$ is unspecified; (2) each row sum and each column sum of $A$ is zero; and (3) $\sum_{1 \leq i \leq p \atop 1 \leq j \leq q} a_{ij} \geq 0$, for all $(p, q) \in \{1, 2, \ldots, m\} \times \{1, 2, \ldots, n\}$. However, there may be infinitely many such conditions, and some of them may be obtainable from others. In order to find a set of minimal conditions, the theory of cones and generators, and the logarithmic method are used. It is shown that the set of matrices used in the exponents of the inequalities forms a finitely generated cone with integral generators. This gives finitely many polynomial inequalities on the specified entries of a partial matrix of given pattern as conditions for TP$_2$-completablety. A computational scheme for explicitly finding the generators is given and the combinatorial structure of TP$_2$-completable pattern is investigated.
## Contents

<table>
<thead>
<tr>
<th>Contents</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acknowledgements</td>
<td>v</td>
</tr>
<tr>
<td>1 Introduction</td>
<td>1</td>
</tr>
<tr>
<td>2 TP$_2$ Matrices</td>
<td>5</td>
</tr>
<tr>
<td>2.1 Background on TP$_2$ Matrices</td>
<td>5</td>
</tr>
<tr>
<td>2.2 The TP$_2$-completion Problem and its Motivation</td>
<td>14</td>
</tr>
<tr>
<td>3 Partial orders</td>
<td>18</td>
</tr>
<tr>
<td>3.1 Partial Orders on Permutations</td>
<td>18</td>
</tr>
<tr>
<td>3.1.1 The Inverse Relationship between Bruhat and TP$_2$</td>
<td>20</td>
</tr>
<tr>
<td>3.2 Partial Orders on Matrices</td>
<td>24</td>
</tr>
<tr>
<td>3.2.1 The Inverse Relationship between GBr and DM</td>
<td>27</td>
</tr>
<tr>
<td>4 General Conditions for a TP$_2$-completion</td>
<td>33</td>
</tr>
<tr>
<td>5 Minimal Conditions for a TP$_2$-completion</td>
<td>42</td>
</tr>
<tr>
<td>5.1 Cones and Generators</td>
<td>43</td>
</tr>
</tbody>
</table>
5.2 Main Result .................................................. 48

6 Algorithm .................................................. 50

7 TP₂-completable Patterns .................................. 79

Bibliography .................................................. 90
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Chapter 1

Introduction

An $m$-by-$n$ real matrix is called \textit{totally positive} (TP) if the determinant of every square submatrix is positive. The study of TP matrices began in the early 1900’s; the first major book was [20] and a modern reference is [15], among others. Totally positive matrices arise in many ways, such as differential equations, representation theory of the infinite symmetric group and the Edrei-Thoma theorem, spline functions, probability, mathematical biology, statistics, computer aided geometric design, stochastic processes and approximation theory; see [11, 17, 21, 24]. An $m$-by-$n$ entry-wise positive matrix $A$ is called \textit{totally positive 2-by-2 (TP$_2$)} if the determinant of every square submatrix of size 2-by-2 is positive. It is known that TP$_2$ matrices are eventually TP under Hadamard powers [14]. This fact, together with the relative simplicity of recognition, indicate the importance of TP$_2$ matrices in the study of TP matrices.

A \textit{partial matrix} is a matrix in which some of the entries are specified and the remaining, unspecified, entries are free to be chosen. For a partial matrix $Q$, a \textit{completion} of $Q$ is a choice of values for the unspecified entries of $Q$ that results in a
conventional matrix $Q'$. The pattern of a partial matrix is its arrangement of specified entries. Given a class $\mathcal{C}$ of matrices, the $\mathcal{C}$-completion problem asks which partial matrices have a completion in $\mathcal{C}$. Matrix completion problems for several classes of matrices have been well studied, such as positive semidefinite matrices, completely positive matrices, M-matrices and Euclidean distance matrices, etc. [24]. The only prior class for which the matrix completion problem is completely solved is the class of M-matrices (square matrices with nonpositive off-diagonal entries and entry-wise positive inverse), [28], and this is due only to a very simple observation. The main goal of this work is to solve the TP$_2$-completion problem, i.e. for every pattern of specified entries to determine which data has a TP$_2$-completion. In order to have a TP$_2$-completion, the specified entries of a partial matrix must be consistent with a TP$_2$-completion; every specified entry and every 2-by-2 fully specified minor must be positive. However, this condition of being "partial TP$_2$" is not generally sufficient for TP$_2$-completable. The patterns for which it is, the TP$_2$-completable patterns, are also considered.

A subset of a real vector space defined by a finite list of polynomial inequalities is called a semi-algebraic set. According to a result from [25], if a class $\mathcal{C}$ of matrices is semi-algebraic set, then there are finitely many polynomial conditions on the specified entries of a partial matrix with a given pattern for compleatability in $\mathcal{C}$. This uses the Tarski-Seidenberg principle of real algebraic geometry [6]. Unfortunately, it is notoriously difficult (essentially impossible) to find these conditions in general via Tarski-Seidenberg. The only case in which such a finite list of polynomial conditions has been found is M-matrices [28].

Note that by definition, a matrix $A = (a_{ij})\in M_{m,n}$ is TP$_2$ if and only if it satisfies
the following finitely many polynomial inequalities

\[ a_{ij} > 0, \text{ and } a_{pk}a_{q\ell} - a_{pf}a_{qk} > 0 \]

for all \( p, q, k, \ell \) with \( 1 \leq p < q \leq m \) and \( 1 \leq k < \ell \leq n \). Thus, the set of \( m \times n \) TP\(_2\) matrices can be described by a finite list of polynomial inequalities, and therefore, is a semi-algebraic set. Hence, there is a finite list of polynomial conditions on the specified entries of a partial TP\(_2\) matrix \( T \) that are sufficient for \( T \) to be TP\(_2\)-completable.

Here, the TP\(_2\)-completion problem is completely solved by giving an explicit description of the finitely many polynomial inequalities on the specified entries of a given pattern for TP\(_2\)-completability. This is accomplished through a sequence of steps given in Chapters 3-6.

Chapter 2 provides the background and basic facts about TP\(_2\) matrices.

It turns out that there is a very nice relationship between the Bruhat order on permutations and TP\(_2\) matrices. Chapter 3 describes this relationship by giving a partial order induced by TP\(_2\) matrices. It is shown that there is an inverse relationship between the Bruhat order on permutations and this TP\(_2\) partial order. Moreover, by extending techniques from the Bruhat order on permutations, two partial orders on nonnegative matrices are introduced, namely, the Generalized Bruhat order (GBr) and the Double Majorization order (DM). It is shown that the GBr and DM partial orders are inverses of each other on the set of nonnegative matrices.

Chapter 4 provides a solution to the TP\(_2\)-completion problem by giving infinitely many exponential inequalities on the specified entries of a given partial TP\(_2\) matrix. This uses the inverse relationship of the GBr and DM partial orders on the set of
nonnegative matrices.

Since the conditions obtained in Chapter 4 are infinitely many, the goal in Chapter 5 is to reduce this number to finitely many. For this, it is shown that there is a remarkable relationship between the solution to the TP₂-completion problem and the theory of cones and generators. That is, the set of matrices used in the exponents of the inequalities obtained in Chapter 4 forms a polyhedral cone and, therefore, has finitely many generators. This fact, together with what we refer to as the logarithmic method (transforming a nonlinear problem to a linear one in exponent space) is used to improve the conditions obtained in Chapter 4 to a set of finitely many polynomial inequalities on the specified entries of a given partial TP₂ matrix. The main result in Chapter 5 explicitly gives minimal conditions (polynomial inequalities on the data) for a partial TP₂ matrix to be TP₂-completable.

Chapter 6 describes how these conditions can be obtained computationally by using a computer program, cdd+ [12], for any given pattern. The algorithm uses linear programming to convert a half-space description of a cone to a generator description, and is highly accurate. Converting the generators obtained from cdd+ to the generators for our purpose gives the minimal conditions obtained in our main result. To elaborate the process of finding conditions for a pattern, several examples are presented.

In Chapter 7, the TP₂-completion problem is considered combinatorially. Conditions for TP₂-completability of patterns with small size or with a small number of unspecified entries is given. Moreover, some general results about TP₂-completable patterns are given.
Chapter 2

TP$_2$ Matrices

This chapter is about the basic definitions and facts that are useful to understand TP$_2$ matrices.

2.1 Background on TP$_2$ Matrices

In this section, we present some background on TP$_2$ matrices. Most facts here are easily proven but they are very useful in the study of TP$_2$ matrices.

An $m$-by-$n$ real matrix $A$ is called totally positive (totally nonnegative), $k$-by-$k$, if the determinant of every square submatrix of size at most $k$ is positive (nonnegative); it is denoted by TP$_k$ (TN$_k$). If $A$ is TP$_k$ (TN$_k$), with $k=\min\{m,n\}$, then $A$ is called totally positive, TP, (totally nonnegative, TN).

The set of matrices of size $m$-by-$n$ with entries from the field $\mathbb{F}$ is denoted by $M_{m,n}(\mathbb{F})$, if $m = n$, it is abbreviated to $M_n(\mathbb{F})$. For $\mathbb{F} = \mathbb{R}$, it is simply denoted by $M_{m,n}$ (or $M_n$ for the case $m = n$). The set of TP$_k$ (resp. TP) matrices of size $m$-by-$n$ is denoted by TP$_k(m,n)$ (resp. TP($m,n$)). If the size of the matrix is clear from the
context, we use the same notation $TP_k$ (resp. TP) for the set of $TP_k$ (resp. TP) matrices as well.

**Lemma 2.1.1** Every submatrix of a $TP_2$ matrix $T$ is also $TP_2$.

**Proof.** It is clear since in a $TP_2$ matrix every entry and every 2-by-2 minor, in particular the ones in a given submatrix, are positive. 

Another way to express the above lemma is that if a matrix $T$ is not $TP_2$, then every matrix, containing $T$ as a submatrix, is also not $TP_2$. This will be used later in the $TP_2$-completable patterns; see Lemma 7.0.7.

For a positive integer $n$, let $[n] = \{1, 2, \ldots, n\}$. The submatrix of $A \in M_{m,n}$ lying in rows $\alpha$ and columns $\beta$, with $\alpha \subseteq [m]$ and $\beta \subseteq [n]$, is denoted by $A[\alpha, \beta]$. The following example shows that there exists a $TP_2$ matrix of size $n$, for all $n \geq 1$.

**Example 2.1.2** The symmetric matrix $T = (t_{ij}) \in M_n$, $n \geq 1$ of the following form is $TP_2$

$$T = \begin{pmatrix}
1 & 1 & 1 & \ldots & 1 & 1 \\
1 & 2 & 3 & \ldots & n-1 & n \\
1 & 3 & 5 & \ldots & 2n-3 & 2n-1 \\
\vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\
1 & n-1 & 2n-3 & \ldots & n^2-4n+5 & n^2-3n+3 \\
1 & n & 2n-1 & \ldots & n^2-3n+3 & n^2-2n+2
\end{pmatrix}.$$ 

The entry $t_{ij}$ is obtained from the following equation

$$t_{ij} = j + (i-2)(j-1) \quad (2.1)$$
Proof. Consider the 2-by-2 submatrix of $T$ lying in rows $p, q$ and columns $k, \ell$ with $1 \leq p < q \leq n$ and $1 \leq k < \ell \leq n$. Using the equation (2.1), we have

$$
\det A[p, q, \{k, \ell\}] = \begin{vmatrix}
    a_{pk} & a_{pl} \\
    a_{qk} & a_{ql}
\end{vmatrix} = [k + (p-2)(k-1)][\ell + (q-2)(\ell-1)] - [k + (p-2)(k-1)][\ell + (q-2)(\ell-1)] = (q-p)(\ell-k).
$$

By the choice of $p, q, k, \ell$, we have $\det A[p, q, \{k, \ell\}] = (q-p)(\ell-k) > 0$. Since $T$ is entry wise positive and $p, q, k, \ell$ were arbitrary, $T$ is TP$_2$. $
$
Notice that, the above example together with Lemma 2.1.1 imply that there is a TP$_2$ matrix of size $m$-by-$n$ for all $m, n \geq 1$.

One of the simple cases to check whether a matrix is TP$_2$ or not is when the matrix has only two rows (or two columns).

Lemma 2.1.3 If $T$ is a TP$_1$ matrix, then $T$ is TP$_2$ if and only if

$$
\frac{t_{11}}{t_{21}} > \frac{t_{12}}{t_{22}} > \ldots > \frac{t_{1n}}{t_{2n}}.
$$

(2.2)

Proof. Clearly if $T$ is TP$_2$, then $\det T[\{1, 2\}, \{j, j+1\}] > 0$, for every $j = 1, 2, \ldots, n-1$, so the inequalities in (2.2) hold. For the converse, suppose (2.2) holds and consider a $2 \times 2$ minor obtained from columns $\ell, j$ with $\ell > j$. Then

$$
\frac{t_{1j}}{t_{2j}} > \frac{t_{1(j+1)}}{t_{2(j+1)}} > \ldots > \frac{t_{1(\ell-1)}}{t_{2(\ell-1)}} > \frac{t_{1\ell}}{t_{2\ell}}.
$$
Hence, \( \frac{t_{1\ell}}{t_{2j}} > \frac{t_{1\ell}}{t_{2\ell}} \) which implies the minor lying in columns \( \ell, j \) is positive. Since \( j \) and \( \ell \) were arbitrary, the matrix \( T \) is TP2. 

Note that, the number of minors of all possible sizes in an \( n \times n \) matrix is \( \binom{n}{1}^2 + \binom{n}{2}^2 + \ldots + \binom{n}{n}^2 = \binom{2n}{n} \).

Thus, it is not easy to check for TP just by using the definition. However, the following result in [15] shows that checking for TP is not hard. A matrix \( T \in M_{m,n} \) is called TP\(_k\) contiguous if 
\[
\det T[\{i,i+1,\ldots,i+k-1\},\{j,j+1,\ldots,j+k-1\}] > 0,
\]
for every \( i \in [m-k+1] \) and \( j \in [n-k+1] \).

**Lemma 2.1.4** Let \( T \) be an \( m \times n \) matrix and suppose \( 1 \leq k \leq \min\{m,n\} \). Then \( T \) is TP\(_k\) if and only if it is TP\(_k\) contiguous.

The number of \( k \times k \) contiguous minors in an \( m \times n \) matrix is \( (m-k+1)(n-k+1) \). Therefore, the total number of contiguous minors is 
\[
\sum_{k=1}^{\min\{m,n\}} (m-k+1)(n-k+1).
\]

An initial minor of a matrix is a minor lying in consecutive rows and columns with at least one of them using the first row or the first column. The number of initial minors of an \( n \times n \) matrix is \( n^2 \), since every entry corresponds to an initial minor and vice versa. The minimal set of minors to check for TP is the set of initial minors by the following result; see [22].

**Lemma 2.1.5** An \( m \times n \) matrix \( T \) is TP if and only if all of all its initial minors are positive.

The following lemma is a direct result of Lemma 2.1.4. But, in the case of \( k = 2 \), the proof can be given in a simple way, which is explained here.
Lemma 2.1.6 An $m$-by-$n$ matrix $T$ is $TP_2$ if and only if it is $TP_2$ contiguous.

Proof. If the matrix $T$ is $TP_2$, then all of the 2-by-2 minors in particular the contiguous ones are positive, hence $T$ is $TP_2$ contiguous. For the converse, suppose $T$ is $TP_2$ contiguous, consider a $2 \times 2$ minor lying in the rows $p, q$ and columns $k, \ell$ with $1 \leq p < q \leq m$ and $1 \leq k < \ell \leq n$. We have

\begin{align*}
\frac{t_{pk}}{t_{(p+1)k}} > \frac{t_{p(k+1)}}{t_{(p+1)(k+1)}} &> \ldots > \frac{t_{p\ell}}{t_{(p+1)\ell}} \quad (2.3) \\
\frac{t_{(p+1)k}}{t_{(p+2)k}} > \frac{t_{(p+1)(k+1)}}{t_{(p+2)(k+1)}} &> \ldots > \frac{t_{(p+1)\ell}}{t_{(p+2)\ell}}. \quad (2.4)
\end{align*}

Multiplying the corresponding terms in the inequalities (2.3) and (2.4), implies the following

\begin{align*}
\frac{t_{pk}}{t_{(p+2)k}} &> \frac{t_{p(k+1)}}{t_{(p+2)(k+1)}} > \ldots > \frac{t_{p\ell}}{t_{(p+2)\ell}}.
\end{align*}

Continuing this process $q - p - 1$ times, we have

\begin{align*}
\frac{t_{pk}}{t_{qk}} > \frac{t_{p(k+1)}}{t_{q(k+1)}} > \ldots > \frac{t_{p\ell}}{t_{q\ell}}
\end{align*}

which implies

\begin{align*}
\frac{t_{pk}}{t_{qk}} > \frac{t_{p\ell}}{t_{q\ell}}.
\end{align*}

Since $p, q, k, \ell$ were arbitrarily, this implies that $T$ is $TP_2$. \qed

The following proposition is easy to prove.

Proposition 2.1.7 If a matrix $T$ is $TP_2$, then its transpose $T^t$ is also $TP_2$.

For $n \geq 1$, the $n$-by-$n$ backward identity matrix, $R_n = (r_{ij})$, is of the following
form

\[ R_n = \begin{pmatrix} 0 & 0 & \ldots & 0 & 1 \\ 0 & \ldots & 1 & 0 \\ \vdots & \vdots & \vdots \\ 0 & 1 & \ldots & 0 & 0 \\ 1 & 0 & \ldots & 0 \end{pmatrix}, \]

that is,

\[ \tau_{ij} = \begin{cases} 1, & \text{if } j = n - i + 1 \\ 0, & \text{otherwise.} \end{cases} \]

**Lemma 2.1.8** If \( T = (t_{ij}) \in TP_2(m,n) \), then \( M = R_mTR_n \in TP_2(m,n) \).

**Proof.** Let \( M = (m_{ij}) \). Then \( m_{ij} = t_{(m-i+1)(n-j+1)} \). Consider a \( 2 \times 2 \) minor lying in the rows \( p, q \) and columns \( k, \ell \) of \( M \), with \( 1 \leq p < q \leq m \) and \( 1 \leq k < \ell \leq n \). We have

\[ \det M[p, q, k, \ell] = t_{(m-p+1)(n-k+1)}t_{(m-q+1)(n-\ell+1)} - t_{(m-p+1)(n-\ell+1)}t_{(m-q+1)(n-k+1)} \]

which is positive by the choice of \( p, q, k, \ell \). Therefore, \( M \) is TP_2.

Throughout, a row or a column of a matrix is referred to as a line of that matrix.

Using Lemma 2.1.6, a TP_2 matrix can be extended to a TP_2 matrix of larger size by inserting a row or column. We call this process line insertion.

**Lemma 2.1.9** If \( T \in TP_2 \), then \( T \) may be extended to a larger TP_2 matrix by inserting a new line between any two consecutive lines of \( T \) or outside any of the 4 boundary lines, to produce a matrix \( W \) that is also TP_2.

**Proof.** The statement is shown for column insertion, the proof for row insertion is similar or Lemma 2.1.7 can be used together with this proof. For interior line
insertion, consider two columns $j$ and $j + 1$ of the TP$_2$ matrix $T$ for some $j \in [n - 1]$. Let the columns $j + 1, j + 2, \ldots, n$ of $T$ be renamed to $j + 2, j + 3, \ldots, n + 1$, respectively. To insert a column $j + 1$ between the columns $j$ and $j + 2$ in $T$, let the entry $t_{1(j+1)}$ be an arbitrary positive number. To find a value for the entry $t_{2(j+1)}$, note that by Lemma 2.1.6, if each of the minors lying in the entries $t_{1j}, t_{1(j+1)}, t_{2j}, t_{2(j+1)}$ and $t_{1(j+1)}, t_{1(j+2)}, t_{2(j+1)}, t_{2(j+2)}$ is positive, then every minor containing the entry $t_{2(j+1)}$ is positive. Thus, it is sufficient to find a value for $t_{2(j+1)}$ such that

$$\frac{t_{1(j+1)}t_{2j}}{t_{1j}} < t_{2(j+1)} < \frac{t_{1(j+1)}t_{2(j+2)}}{t_{1(j+2)}}.$$  

(2.5)

Since $T$ is TP$_2$, $\frac{t_{1(j+1)}t_{2j}}{t_{1j}} < \frac{t_{1(j+1)}t_{2(j+2)}}{t_{1(j+2)}}$, hence, the real interval in (2.5) is nonempty. This implies that there is a value for the $(2, j+1)$ position, $t_{2(j+1)}$, such that the matrix resulting from replacement of $t_{2(j+1)}$ by the unspecified entry in the $(2, j+1)$ position satisfies the TP$_2$ conditions. By a similar method, the entry $t_{i(j+1)}$ for $i = 3, \ldots, n$ can be chosen so that the matrix stays TP$_2$. Since $j$ was arbitrary, this implies that an interior column may be inserted to a TP$_2$ matrix such that the resulting matrix is also TP$_2$. The proof for exterior column insertion is similar, except that there is only one minor (and thus a ray) to check each time.

Note that, the above statement is not true for partial TP$_2$ matrices which will be defined later on page 14.

The following is the well-known Cauchy-Binet Theorem; for details see [23].

**Theorem 2.1.10** Let $A \in M_{m,p}(\mathbb{F})$ and $B \in M_{p,n}(\mathbb{F})$, $1 \leq r \leq \min\{m, p, n\}$, $\alpha \subseteq [m]$ and $\beta \subseteq [n]$ with $|\alpha| = |\beta| = r$, then

$$detAB[\alpha, \beta] = \sum_{\gamma} detA[\alpha, \gamma]detB[\gamma, \beta].$$

11
For a set $S$, the cardinality of $S$ is denoted by $|S|$. Using compound matrices and the Cauchy-Binet formula, one can show that $\text{TP}_2$ (and in fact $\text{TP}_k$) matrices are closed under the conventional matrix multiplication. Consider a matrix $A \in M_{m,n}$, and let $1 \leq k \leq \min\{m, n\}$. For $\alpha \subseteq [m]$ and $\beta \subseteq [n]$ with $|\alpha| = |\beta| = k$, let $c_{\alpha, \beta} = \det A[\alpha, \beta]$. The \(\binom{m}{k}\)-by-\(\binom{n}{k}\) matrix with entries $c_{\alpha, \beta}$, with index sets ordered lexicographically, is called the $k$-th compound matrix of $A$ and is denoted by $C_k(A)$. It is known that compound matrices are multiplicative, i.e., $C_k(AB) = C_k(A)C_k(B)$, when $AB$ is defined. Using this, a minor of size $k$ in a product of two matrices is the sum of the product of some of the minors of the same size from each matrix, so that if $A \in M_{m,p}$ and $B \in M_{p,n}$ had all positive $k$-by-$k$ minors, then $AB \in M_{m,n}$ will also have positive $k$-by-$k$ minors. This all follows from the Cauchy-Binet formula. Therefore, we have the following lemma.

**Lemma 2.1.11** For any $k$ with $1 \leq k \leq \min\{m, n, p\}$, if $T \in \text{TP}_k(m, p)$ and $W \in \text{TP}_k(p, n)$, then their conventional product is also $\text{TP}_k$, i.e. $TW \in \text{TP}_k(m, n)$.

For given two matrices of the same size, the Hadamard product is defined as follows:

**Definition 2.1.12** Suppose $A = (a_{ij}) \in M_{m,n}$ and $B = (b_{ij}) \in M_{m,n}$. Then the Hadamard product of $A$ and $B$ is the matrix $A \circ B = (a_{ij}b_{ij}) \in M_{m,n}$.

The $r$-th Hadamard power of the matrix $A = (a_{ij}) \in M_{m,n}$ is the matrix $A^{(r)} = (a_{ij}^r) \in M_{m,n}$.

**Lemma 2.1.13** The set of $m$-by-$n$ $\text{TP}_2$ matrices is closed under Hadamard products.
Proof. Suppose $T = (t_{ij}), W = (w_{ij}) \in TP_2(m, n)$. Consider the $2 \times 2$ submatrix of the Hadamard product $T \circ W = (t_{ij}w_{ij})$ lying in the rows $p, q$ and columns $k, \ell$, for some $p, q, k, \ell$ with $1 \leq p < q \leq m$ and $1 \leq k < \ell \leq n$. Since $T$ and $W$ are both TP$_2$ matrices, we have $t_{pk}w_{pk}t_{q\ell}w_{q\ell} > t_{p\ell}w_{p\ell}t_{qk}w_{qk}$. Therefore, $T \circ W \in TP_2(m, n)$.

A consequence of the above lemma is the following.

Corollary 2.1.14 If $T, W \in TP_2(m, n)$, then $T^{(r)} \circ W^{(s)} \in TP_2(m, n)$ for all $r, s > 0$.

Proof. Consider the $2 \times 2$ submatrix of $T$ lying in the rows $p, q$ and columns $k, \ell$, for some $p, q, k, \ell$ with $1 \leq p < q \leq m$ and $1 \leq k < \ell \leq n$. Since $T$ is TP$_2$, we have $t_{pk}t_{q\ell} > t_{p\ell}t_{qk}$. Thus, $(t_{pk}t_{q\ell})^r > (t_{p\ell}t_{qk})^r$, this is true for every $2 \times 2$ submatrix of $T^{(r)}$, which implies that $T^{(r)}$ is TP$_2$. Similarly, $W^{(s)}$ is TP$_2$. Using Lemma 2.1.13, the proof is complete.

Note that, in general TP$_k$ matrices with $k \geq 3$ are not closed under the Hadamard product, [15].

As mentioned before, TP$_2$ matrices play an important role in the study of TP matrices, since checking for TP$_2$ is easier. On the other hand, note that every TP matrix is also TP$_2$. In fact, we have

$$TP \subset TP_{k-1} \subset \ldots \subset TP_3 \subset TP_2 \subset TP_1.$$ 

Moreover, there is a very nice relationship between TP$_2$ matrices and TP matrices; it is shown that every TP$_2$ matrix is eventually TP under Hadamard powers; see [14].

Theorem 2.1.15 For any $T \in TP_2$, there is a constant $\kappa_0 > 0$ such that $T^{(\kappa)}$ is TP for all $\kappa \geq \kappa_0$. 

13
The above result indicates the importance of TP$_2$ matrices in the theory of total positivity.

2.2 The TP$_2$-completion Problem and its Motivation

In this section, the TP$_2$-completion problem is defined, and then the importance of this problem in the study of TP matrices is presented.

A partial matrix is called partial TP$_2$ if every specified entry is positive and every fully specified 2-by-2 submatrix has a positive determinant. Similarly, a partial TP$_2$ matrix is a partial matrix in which every fully specified square submatrix has a positive determinant.

Note that, not every partial TP$_2$ matrix has a TP$_2$-completion. For instance see Proposition 7.0.5 in Chapter 7.

A partial TP$_2$ matrix does not necessarily satisfy every statement about TP$_2$ matrices. For instance, by Lemma 2.1.9, a TP$_2$ matrix can be enlarged to another TP$_2$ matrix by a line insertion. However, by the following example, line insertion in partial TP$_2$ matrices is not necessarily always possible. Consider the partial TP$_2$ matrix $T$ and let $W$ be a partial matrix obtained from $T$ by inserting a column of specified entries between the first and the second columns of $T$.

$$T = \begin{pmatrix} 1 & ? & 1 \\ ? & 2 & 1 \\ 1 & 1 & 3 \end{pmatrix}, \quad W = \begin{pmatrix} 1 & w_{12} & ? & 1 \\ ? & w_{22} & 2 & 1 \\ 1 & w_{32} & 1 & 3 \end{pmatrix}$$

14
In order for \( \mathcal{W} \) to be partial \( TP_2 \), we have

\[
\text{det}A[\{1, 3\}, \{1, 2\}] > 0, \text{det}A[\{1, 2\}, \{2, 4\}] > 0, \text{det}A[\{2, 3\}, \{2, 3\}] > 0
\]

these inequalities imply

\[
w_{32} > w_{12} > w_{22} > 2w_{32}
\]

which is impossible.

Notice that, the above discussion also implies that there is no \( TP_2 \)-completion for the partial \( TP_2 \) matrix \( \mathcal{T} \). Since otherwise, suppose \( \mathcal{T}_c \) is a \( TP_2 \)-completion for \( \mathcal{T} \). By Lemma 2.1.9, a new column can be inserted between the first and second columns of \( \mathcal{T}_c \). This column can also be used in \( \mathcal{W} \) to make a partial \( TP_2 \) matrix, which as explained above, it is impossible.

A partial \( TP_2 \) (TP) matrix \( \mathcal{T} \) is said to have a \( TP_2 \)-completion (TP-completion), if there exist values for the unspecified entries of \( \mathcal{T} \) such that replacing these values with the corresponding unspecified entries results in a conventional \( TP_2 \) (TP) matrix. A pattern \( \mathcal{P} \) of the specified entries is called \( TP_2 \)-completable (TP-completable), if every partial \( TP_2 \) (TP) matrix with pattern \( \mathcal{P} \) has a \( TP_2 \)-completion (TP-completion).

A Hadamard power for a partial matrix can be defined in a similar way to the Hadamard power of a conventional matrix; if \( \mathcal{T} = (t_{ij}) \) is a partial matrix, then \( \mathcal{T}^{(s)} = (t_{ij}) \) is a partial matrix defined as follows,

\[
t_{ij} = \begin{cases} 
\hat{t}_{ij}, & \text{if } t_{ij} \text{ is specified} \\
\text{unspecified}, & \text{otherwise}.
\end{cases}
\]

Using Theorem 2.1.15, we have the following result.

**Corollary 2.2.1** If \( \mathcal{T} \) is a partial \( TP_2 \) matrix, then there is a constant \( \kappa_0 > 0 \), such that \( \mathcal{T}^{(s)} \) is partial TP, for all \( \kappa \geq \kappa_0 \).
Proof. Using Lemma 2.1.1 and Theorem 2.1.15, for every fully specified square submatrix $T_i$ of $T$, there exists a constant $\kappa_i$ such that $T_i^{(\kappa_i)}$ is TP for all $\kappa \geq \kappa_i$. Let $\kappa_0$ be the maximum of all such $\kappa_i$, with the maximum taken over all fully specified square submatrices of $T$. Then, for all $\kappa \geq \kappa_0$, every fully specified square submatrix of $T^{(\kappa)}$ has a positive determinant, thus $T^{(\kappa)}$ is partial TP for all $\kappa \geq \kappa_0$. }

The following lemma gives a motivation to study the TP$_2$-completable patterns.

**Lemma 2.2.2** Every TP-completable pattern is also a TP$_2$-completable pattern.

**Proof.** Suppose the pattern $P$ is TP-completable. In order to show that $P$ is TP$_2$-completable, consider a partial TP$_2$ matrix $T$ with pattern $P$. By Corollary 2.2.1, a Hadamard power of $T$, say $T^{(s)}$ for some $s > 0$, is partial TP. Since $T^{(s)}$ is a partial TP matrix with pattern $P$, by assumption it is TP-completable. Suppose $T_c^{(s)}$ is a TP-completion of $T^{(s)}$. Note that, every TP matrix is also TP$_2$, thus $T_c^{(s)}$ is TP$_2$. Therefore, by Corollary 2.1.14, $A = (T_c^{(s)})^{(1)}$ is TP$_2$, and the matrix $A$ is a TP$_2$-completion for $T$. Since $T$ was arbitrary, it implies that every partial TP$_2$ matrix with pattern $P$ is TP$_2$-completable. Therefore, $P$ is TP$_2$-completable. }

Therefore, all of the conditions necessary for TP$_2$-completability of a given pattern are also necessary for the TP-completability of the same pattern.

Notice that, the converse of Lemma 2.2.2 is not true. There exists a TP$_2$-completable pattern that is not TP-completable. For example, in [16] it is shown that there is no TP-completion for the following partial TP matrix $T$ with pattern $P$. However, by a result in Chapter 7, the pattern $P$ is TP$_2$-completable.
\[ P = \begin{pmatrix} 
\times & \times & \times & \times \\
\times & \times & \times & \times \\
\times & \times & \times & \times \\
\times & \times & \times & \times 
\end{pmatrix}, \quad T = \begin{pmatrix}
100 & 100 & 40 & x \\
40 & 100 & 100 & 40 \\
20 & 80 & 100 & 100 \\
3 & 20 & 40 & 100 
\end{pmatrix} \]
Chapter 3

Partial orders

The aim of this chapter is to show the close relationship between TP$_2$ matrices and the Bruhat order on permutations. This plays a key role in solving the TP$_2$-completion problem.

3.1 Partial Orders on Permutations

This section focuses on partial orders on permutations related to TP$_2$ matrices. The Bruhat order on permutations is introduced, then a partial order on permutations induced by TP$_2$ matrices, TP$_2$ partial order, is defined.

The Bruhat partial order on permutations (defined below) arises in a variety of ways (e.g. Coxeter groups [4] and transitivity of simple majority voting [2]) and is much studied. For most of the following results about the Bruhat order on permutations, we have adapted some of the notation and proofs from [4]; see also [3] for more on permutations.

Recall that for a set $S = \{1, 2, \ldots, n\}$, a bijection $\pi : S \rightarrow S$ is called a per-
mutation of $S$. The set of all permutations of $S$ is called the symmetric group and is denoted by $S_n$. A permutation $\pi \in S_n$, is denoted by listing the values of $\pi(i)$ from left to right for $i = 1, 2, \ldots, n$. For instance, 3241 denotes the permutation, say $\pi \in S_4$, with $\pi(1) = 3, \pi(2) = 2, \pi(3) = 4, \pi(4) = 1$.

For a permutation $\pi \in S_n$, a transposition of $i$ and $j$, with $i < j$ and $\pi(i) < \pi(j)$, is called an upward transposition of $\pi$. The result is a new permutation $\pi'$, in which $\pi(i)$ lies in the position $j$ and $\pi(j)$ lies in the position $i$ of $\pi$. If $\pi$ is obtained from $\sigma \in S_n$ by a sequence of upward transpositions, then $\sigma$ is said to be less than or equal to $\pi$ in the Bruhat partial order ($\sigma \leq_{Br} \pi$); see [4].

**Example 3.1.1** Let $\pi, \sigma \in S_5$ with $\pi = 45132$ and $\sigma = 31524$. Then $\sigma \leq_{Br} \pi$.

The permutation $\pi$ can be obtained from $\sigma$ by a sequence of upward transpositions as follows. The underlined entries at each permutation are the ones considered for upward transposition.

\[
\sigma = 31524 \rightarrow \underline{35124} \rightarrow 45123 \rightarrow 45132 = \pi.
\]

Let $M_\pi = (m_{ij})$ denote the $n$-by-$n$ permutation matrix of the permutation $\pi \in S_n$, that is,

\[
m_{ij} = \begin{cases} 
1, & \text{if } j = \pi(i) \\
0, & \text{otherwise.}
\end{cases}
\]

For $A = (a_{ij}) \in M_{m,n}$, and $(p, q) \in [m] \times [n]$, the sum of the entries of $A$ lying in rows $1, 2, \ldots, p$ and columns $1, 2, \ldots, q$ is denoted by $A(p,q)$; that is, $A(p,q) = \sum_{(i,j) \in [p] \times [q]} a_{ij}$. If $A = M_\pi$, the permutation matrix associated with $\pi \in S_n$, then $M_\pi(p,q)$ is equal to the number of ones in the northwest corner of $M_\pi$ bounded by the row $p$ and column $q$. 

19
The following theorem gives a method to test for Bruhat order on permutations; see [4].

**Theorem 3.1.2** For two permutations \( \sigma \neq \pi \in S_n \), \( \sigma <_{Br} \pi \) if and only if \( M_\sigma(i,j) \geq M_\pi(i,j) \), for all \( i, j \in [n] \).

**Example 3.1.3** Consider \( M_\sigma, M_\pi \) with permutations \( \sigma, \pi \) in Example 3.1.1.

Note that, \( M_\sigma(i,j) \geq M_\pi(i,j) \) for all \( i, j \in [n] \). Moreover, the following process shows the sequence of upward transpositions on the corresponding permutation matrices.

\[
M_\sigma = \begin{pmatrix}
0 & 0 & 1 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 \\
0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 \\
\end{pmatrix} \quad \Rightarrow \quad \begin{pmatrix}
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1 \\
0 & 1 & 0 & 0 \\
0 & 0 & 0 & 1 \\
0 & 1 & 0 & 0 \\
\end{pmatrix} = M_\pi.
\]

### 3.1.1 The Inverse Relationship between Bruhat and TP\(_2\)

In this section, a partial order on permutations induced by TP\(_2\) matrices is introduced. It is shown that the TP\(_2\) partial order is the inverse of the Bruhat partial order on permutations.
Given a matrix \( A \in M_n \) and a permutation \( \pi \in S_n \), let \( A_\pi = \prod_{i \in [n]} a_{i \pi(i)} \).

**Definition 3.1.4** If \( \pi, \sigma \in S_n \) are such that
\[
T_\pi < T_\sigma
\]
for all \( n \)-by-\( n \) TP\(_2\) matrices \( T \), then \( \pi \) is less than \( \sigma \) in the TP\(_2\) partial order. We denote this as \( \pi <_{TP_2} \sigma \).

The matrix \( D_{pq} = (d_{ij}) \in M_n \) with
\[
d_{ij} = \begin{cases} 
2, & \text{if } (i, j) \in [p] \times [q] \\
1, & \text{otherwise}
\end{cases}
\]
is an example of a TN\(_2\) matrix, since every minor of size at most 2 is in the set \{0, 1, 2\}.

**Theorem 3.1.5** For \( \pi, \sigma \in S_n, \pi \neq \sigma \), we have \( \sigma <_{Br} \pi \) if and only if \( \pi <_{TP_2} \sigma \).

**Proof.** For the forward implication, it suffices to consider the effect upon \( T_\sigma \) of a single upward transposition applied to \( \sigma \). Thus, suppose \( \pi \) is obtained from \( \sigma \) by doing only one upward transposition of \( i \) and \( j \) with \( i < j \) and \( \sigma(i) < \sigma(j) \) which implies \( \sigma <_{Br} \pi \). Consider a matrix \( T \in TP_2 \). Since the minor lying in the rows \( i, j \) and columns \( \sigma(i), \sigma(j) \) is positive, \( t_{\sigma(i)j}t_{\sigma(j)i} > t_{\sigma(j)i}t_{\sigma(j)i} \), this implies that \( T_\sigma > T_\pi \).

For the converse, suppose \( \sigma \not<_{Br} \pi \). Using Theorem 3.1.2, there exist \( p, q \in [n] \) such that \( M_\sigma(p, q) < M_\pi(p, q) \). This means that in the matrix \( D_{pq} \) we have \( 2^{M_\sigma(p, q)} = \prod_{i=1}^{n} d_{i\sigma(i)} < \prod_{i=1}^{n} d_{i\pi(i)} = 2^{M_\pi(p, q)} \). Given \( \epsilon > 0 \), we may choose \( \epsilon_{ij} < \epsilon \), \( 1 \leq i, j \leq n - 1 \), and \( \epsilon_{ij} = 0 \) for \( i \) or \( j = n \), so that for \( E = (\epsilon_{ij}) \), \( D_{pq} + E \) is TP\(_2\). (Choose \( \epsilon_{ij} \), starting
with \(i = n - 1, j = n - 1\) and proceeding right to left and bottom to top, sufficiently small to make each contiguous 2-by-2 minor positive.)

Since \(\epsilon\) was arbitrary, it implies that there exists a TP\(_2\) matrix \(B\) such that \(\prod_{l=1}^{n} b_{\sigma(l)} < \prod_{l=1}^{n} b_{\pi(l)}\). Therefore, \(\pi \not\sim_{TP_2} \sigma\).

The following result gives a necessary and sufficient condition for a positive matrix to be TP\(_2\). It also shows how closely the TP\(_2\) and Bruhat partial orders are related.

**Theorem 3.1.6** An entry-wise positive matrix \(T\) is TP\(_2\) if and only if \(\tau < \sigma\) whenever \(\sigma <_{Br} \pi\).

**Proof.** Suppose \(T\) is TP\(_2\) and \(\sigma <_{Br} \pi\). By Theorem 3.1.5, \(\pi <_{TP_2} \sigma\) which implies \(\tau < \sigma\). For the converse, consider a positive matrix \(T = (t_{ij})\) satisfying the assumption. Using Lemma 2.1.6, it is enough to show that every 2-by-2 contiguous minor is positive. Consider the contiguous minor composed of the entries \((i, j), (i, j + 1), (i + 1, j), \) and \((i + 1, j + 1)\) for \((i, j) \in [n - 1] \times [n - 1]\). Let \(\sigma \in S_n\) with \(\sigma(i) = j\) and \(\sigma(i + 1) = j + 1\) and let \(\pi \in S_n\) with \(\pi(i) = j + 1\) and \(\pi(i + 1) = j\) and \(\sigma(\ell) = \pi(\ell)\) for \(\ell \neq i, i + 1\). Then, \(\sigma <_{Br} \pi\) which by assumption, implies that \(\tau < \sigma\), or, equivalently, that \(t_{ij}t_{i+1,j+1} > t_{i,j+1}t_{i+1,j}\). Since this is true for every 2-by-2 contiguous minor of \(T\), the matrix \(T\) is TP\(_2\).

**Proposition 3.1.7** The identity permutation \(id = 12\ldots(n - 1)n \in S_n\), for \(n \geq 3\) is less than every other permutation in \(S_n\) in the Bruhat partial order.

**Proof.** Consider a permutation \(\pi \in S_n\) with \(\pi \neq id\). Let \(\pi(i) = 1\), for some \(i \in [n]\). By doing a sequence of upward transpositions on \(id\) of the form \(1\ell \mapsto \ell 1\) for \(\ell \leq i\) we have the following (the underlined entries are considered to be transposed)
\[ id = 123 \ldots (i-1)i \ldots (n-1)n \mapsto 213 \ldots (i-1)i \ldots (n-1)n \mapsto 2314 \ldots (i-1)i \ldots (n-1)n \mapsto 234 \ldots (i-1)i \ldots (n-1)n = \sigma_1. \]

In the permutation \( \sigma_1 \), we have \( \sigma_1(i) = 1 \). Note that, the order of the elements in the permutation \( \sigma_1 \), except for \( \sigma_1(i) = 1 \), is the same as of \( id \). Let \( id_1 \) and \( \pi_1 \) be permutations obtained from \( \sigma_1 \) and \( \pi \) by omitting \( \sigma_1(i) \) and \( \pi(i) \), respectively. By a similar process on \( id_1 \) and \( \pi_1 \), the entry 2 in \( id_1 \) can be moved to the position of \( \pi_1(2) \). The proof is complete by reduction. 

Similarly, the backward identity permutation \( id' = n(n-1) \ldots 21 \in S_n \), for \( n \geq 3 \), is greater than every other permutation in \( S_n \), in the Bruhat partial order. Therefore, using Theorem 3.1.6, for every \( n \)-by-\( n \) TP2 matrix \( T \), the product of the diagonal entries of \( T \) dominates the product of every \( n \) entries in distinct rows and distinct columns, and the product of every \( n \) entries in distinct rows and distinct columns, dominates the product of the backwards diagonal entries. Therefore, we have the following remarks.

**Remark 3.1.8** For every \( T \in TP_2(n,n) \), and every permutation \( \pi \neq id \) in \( S_n \),

\[ \prod_{i \in [n]} t_{ii} > \prod_{i \in [n]} t_{i\pi(i)}. \]

**Remark 3.1.9** For every \( T \in TP_2(n,n) \), and every permutation \( \pi \neq id' \) in \( S_n \),

\[ \prod_{i \in [n]} t_{i(n-i)} < \prod_{i \in [n]} t_{i\pi(i)}. \]
3.2 Partial Orders on Matrices

Here the concept of Bruhat order on permutation matrices is extended to a partial order on nonnegative matrices, the "generalized Bruhat order". And then, the notion of majorization is generalized to a partial order on nonnegative matrices, "double majorization".

Let $e$ be the vector with all entries equal to one; the size of $e$ is clear from the context. For two matrices $A, B \in M_{m,n}$, if $Ae = Be$ and $e'A = e'B$ for appropriate sizes of $e$, then $A$ and $B$ have the same row sum vectors and the same column sum vectors. Matrices $A$ and $B$ are said to have equal line sums, and it is denoted by $A \sim_{ELS} B$. In the future discussion (Bruhat inequalities), sometimes it is necessary to emphasize a set of indices that are allowed to have nonzero entries in $A$ and $B$, say the set $K$, and the remaining entries must be zero. Then the ELS relationship between $A$ and $B$ is denoted by $A \sim_{ELS(K)} B$.

For $\delta > 0$ and $p, q, k, \ell$ integers with $1 \leq p < q \leq m$ and $1 \leq k < \ell \leq n$, the matrix $K_{p,q,k,\ell}(\delta) = (k_{ij}) \in M_{m,n}$ is defined as follows:

$$k_{ij} = \begin{cases} -\delta, & \text{if } (i,j) = (p,k) \text{ or } (q,\ell) \\ \delta, & \text{if } (i,j) = (p,\ell) \text{ or } (q,k) \\ 0, & \text{otherwise}. \end{cases}$$

**Definition 3.2.1** Let $A$ be an $m$-by-$n$ nonnegative matrix. For indices $p,q,k,\ell$ with $1 \leq p < q \leq m$ and $1 \leq k < \ell \leq n$, and $\delta$ with $0 < \delta \leq \min\{a_{pk},a_{q\ell}\}$, the mapping $A \mapsto A + K_{p,q,k,\ell}(\delta)$ is called a $\delta$-exchange on the entries of $A$ with subscripts from the set $\{p,q\} \times \{k,\ell\}$.

Note that, by the choice of $\delta$, the matrix $A + K_{p,q,k,\ell}(\delta)$ is also nonnegative.
Proposition 3.2.2 Let $A, B$ be $m$-by-$n$ matrices and $r \in \mathbb{R}$. If $B$ is obtained from $A$ by a sequence of $\delta$-exchanges, with possibly different values of $\delta > 0$, then $A \sim_{ELS} B$.

Proof. It is enough to show that $A, B$ have the same row sum vectors and the same column sum vectors, when $B = A + K_{p,q,k,\ell}(\delta)$, for some $p, q, k, \ell$ with $1 \leq p < q \leq m$ and $1 \leq k < \ell \leq n$ and $\delta > 0$, but this is clear because in each line there is either no change or there is a net addition of $\delta - \delta = 0$.

Definition 3.2.3 Suppose $A, B$ are $m$-by-$n$ nonnegative matrices. Matrix $A$ is said to be less than $B$ in generalized Bruhat partial order if there are finite sequences of nonnegative matrices $A = E_1, E_2, \ldots, E_k = B$ and parameters $\delta_1 > 0, \delta_2 > 0, \ldots, \delta_{k-1} > 0$ such that $E_{i+1}$ is obtained from $E_i$ by a $\delta_i$-exchange on some entries of $E_i$. This is denoted by $A <_{GBr} B$.

A special case in Definitions 3.2.1 and 3.2.3 is when $A = M_\pi$ is a permutation matrix of the permutation $\pi \in S_n$, and $\delta = 1$, then the 1-exchange on the entries of $A$ with indices from the set $\{p, q\} \times \{\pi(p), \pi(q)\}$ results in a new permutation matrix $M_\sigma$ with

$$
\sigma(i) = \begin{cases} 
\pi(i), & \text{if } i \neq p, q \\
\pi(q), & \text{if } i = p \\
\pi(p), & \text{if } i = q 
\end{cases}
$$

If $p < q$ and $\pi(p) < \pi(q)$, then this is exactly doing an upward transposition on the permutation $\pi$ to obtain the permutation $\sigma$. Therefore, if in Definition 3.2.3, $A = M_\pi$ and $B = M_\sigma$, for some permutations $\pi, \sigma \in S_n$, and $\delta_i = 1$, for $i \in [k - 1]$, then the generalized Bruhat order $M_\pi <_{GBr} M_\sigma$ is exactly the Bruhat order $M_\pi <_{Br} M_\sigma$.

The following is a corollary to Theorem 3.1.2.
**Corollary 3.2.4** For two permutations \( \sigma \neq \pi \in S_n \), the permutation matrix \( M_\sigma \) can be obtained from \( M_\pi \) by a sequence of 1-exchanges if and only if \( M_\sigma(i,j) \geq M_\pi(i,j) \) for all \( i, j \in [n] \).

**Definition 3.2.5** Suppose \( A, B \) are \( m \times n \) nonnegative matrices, with \( A \sim_{ELS} B \). Then \( A \) is said to be greater than or equal to \( B \) in the double majorization partial order, if \( A(i,j) \geq B(i,j) \), for all \( (i,j) \in [m-1] \times [n-1] \). This is denoted by \( A \geq_{DM} B \). If \( A \) and \( B \) are not equal, the notation \( A >_{DM} B \) will be used.

In context, when we write \( A \geq_{DM} B \), we implicitly assume that \( A \sim_{ELS} B \) without mentioning it. The following results are used in the proof of Theorem 3.2.9.

**Lemma 3.2.6** For \( m \times n \) matrices \( A, B \) with \( A \sim_{ELS} B \)

i) \( A(i,n) = B(i,n) \), for \( i = 1, 2, \ldots, m \).

ii) \( A(m,j) = B(m,j) \), for \( j = 1, 2, \ldots, n \).

**Proof.** For the matrix \( A \), \( A(i,n) \) is sum of the entries of \( A \) lying in the first \( i \) rows. Since sum of the entries in row \( \ell \) of \( A \) is the same as sum of the entries in row \( \ell \) of \( B \), for all \( \ell \in [m] \), we have \( A(i,n) = B(i,n) \), for \( i = 1, 2, \ldots, m \). The proof for part (ii) is similar. 

For a submatrix \( C \) of \( A \), the sum of the entries lying in \( C \) is denoted by \( A(C) \).

**Lemma 3.2.7** Let \( A \) be an \( m \times n \) nonnegative matrix and \( C \) be a contiguous submatrix of \( A \) with upper left corner with indices \((r_1,c_1)\) and lower right corner with indices \((r_2,c_2)\). Then

\[
A(C) = A(r_2,c_2) - A(r_1 - 1,c_2) - A(r_2,c_1 - 1) + A(r_1 - 1,c_1 - 1).
\]
Proof. In order to calculate \(A(C)\), we subtract \(A(r_1 - 1, c_2) + A(r_2, c_1 - 1)\) from \(A(r_2, c_2)\), but then \(A(r_1 - 1, c_1 - 1)\) is subtracted twice, so adding it once to the above subtract will result in \(A(C)\).

**Lemma 3.2.8** Suppose \(A \geq_{DM} B\) for \(m\)-by-\(n\) nonegative matrices \(A, B\). Let \(c \in [n - 1]\). If \(A(1, j) = B(1, j)\) for \(j = 1, \ldots, c - 1\), \(A(1, c) > B(1, c)\), \(A(1, c + 1) = B(1, c + 1)\) and \(A(2, c) = B(2, c)\), then \(a_{2,c+1} \geq A(1,c) - B(1,c)\).

**Proof.** Since \(A(1,c+1) = B(1,c+1)\), it implies that \(b_{1,c+1} = A(1,c+1) - B(1,c) = A(1,c) - B(1,c) + a_{1,c+1} > 0\). On the other hand, \(A(2,c) = B(2,c)\) implies that \(a_{1,c+1} + a_{2,c+1} \geq b_{1,c+1} + b_{2,c+1} = A(1,c) - B(1,c) + a_{1,c+1} + b_{2,c+1}\). Therefore, \(a_{2,c+1} \geq A(1,c) - B(1,c) + b_{2,c+1}\), since \(b_{2,c+1} \geq 0\), we have \(a_{2,c+1} \geq A(1,c) - B(1,c)\).

### 3.2.1 The Inverse Relationship between GBr and DM

In this section, it is shown that the partial orders GBr and DM are inverse of each other on the set of nonnegative matrices. This will be particularly useful in studying the TP2-completion problem in the next chapter.

**Theorem 3.2.9** If \(A\) and \(B\) are \(m\)-by-\(n\) nonnegative matrices, then

\[A \preceq_{GBr} B \iff A \succeq_{DM} B.\]

**Proof.** Suppose \(A <_{GBr} B\), then \(B\) is obtained from \(A\) by a sequence of \(\delta_i\)-exchanges with \(\delta_i > 0\), for \(i = 1, 2, \ldots, r\). For a \(\delta_i > 0\), by doing a \(\delta_i\)-exchange on a matrix, the sum of the entries in the corresponding upper left corner decreases by \(\delta_i\), and it does

27
not increase at any of the other upper left corners. Since this happens at each of the \( \delta_i \)-exchanges, we have \( A >_{DM} B \). For the converse, let \( A >_{DM} B \) and suppose the first \( t \) rows of \( A \) and \( B \) are equal, for some \( t \in [m] \). Let \( A', B' \) be obtained from \( A, B \) by deleting the rows 1, 2, \ldots, \( t \), respectively, then \( A' >_{DM} B' \) and the following proof applies to \( A' \) and \( B' \) (therefore to \( A \) and \( B \)). So without loss of generality, suppose the first rows of \( A \) and \( B \) are not equal and let the column \( c_1 \) be the first column from left that the entries of the first rows of \( A \) and \( B \) are not equal. That is, \( a_{1c_1} > b_{1c_1} \) and \( a_{1j} = b_{1j} \), for \( j = 1, 2, \ldots, c_1 - 1 \). Hence, \( A(1, c_1) > B(1, c_1) \) and \( A(1, j) = B(1, j) \) for \( j = 1, 2, \ldots, c_1 - 1 \). Let \( c_2 \) be the column in which \( A(1, j) - B(1, j) > 0 \) for \( j \) with \( c_1 \leq j \leq c_2 \) and \( A(1, c_2 + 1) = B(1, c_2 + 1) \). Let \( D_A \) be the maximal contiguous submatrix of \( A \) with upper left corner \((1, c_1)\) and upper right corner \((1, c_2)\) in which \( A(i, j) > B(i, j) \), for all \((i, j) \in D_A\); see Figure 3.1.

\[
A = \begin{pmatrix}
\begin{array}{ccc}
D_A & & C_A \\
a_{1c_1} & \ldots & a_{1c_2} \\
& a_{2c_1} & \ldots & a_{2c_2+1} \\
& \vdots & \ddots & \vdots \\
& a_{rc_1} & \ldots & a_{rc_2} \\
a_r & \ldots & a_{r+1c_2+1}
\end{array}
\end{pmatrix}
\]

Figure 3.1: \( D_A \) and \( C_A \)
There exists such a submatrix since $A(1, c_1) > B(1, c_1)$. Moreover, $D_A$ is unique since the entries $(1, c_1)$ and $(1, c_2)$ are chosen uniquely. Let $(r, c_2)$ be the lower right corner of $D_A$. By Lemma 3.2.6, we have $r < m, c_2 < n$. Since $D_A$ is maximal, there must be a column $\ell$, with $c_1 \leq \ell \leq c_2$ such that $A(r+1, \ell) = B(r+1, \ell)$. Let $C_A$ (respectively $C_B$) be the submatrix of $A$ (respectively $B$) with upper left corner $(2, \ell+1)$ and lower right corner $(r+1, c_2+1)$. By our notation used in Lemma 3.2.7, $A(C_A) - B(C_B)$ denotes the sum of the entries of $C_A$ minus the sum of the entries of $C_B$. By Lemma 3.2.7,

$$A(C_A) - B(C_B) = [A(r+1, c_2+1) - B(r+1, c_2+1)] - [A(1, c_2 + 1) - B(1, c_2 + 1)] - [A(r+1, \ell) - B(r+1, \ell)] + [A(1, \ell) - B(1, \ell)].$$

Since $A(r+1, c_2+1) - B(r+1, c_2+1)$ is nonnegative and $A(1, \ell) - B(1, \ell)$ is positive, we have $A(C_A) - B(C_B) > 0$. This implies that there exists $(u_1, v_1)$ with $2 \leq u_1 \leq r+1$ and $\ell + 1 \leq v_1 \leq c_2 + 1$ such that $a_{u_1v_1} > b_{u_1v_1}$. Let

$$f(u_1, v_1) = \begin{cases} 
\min_{(i,j)\in[\ell]\times[v_1]}\{A(i,j) - B(i,j)\}, & \text{if } u_1 = r+1 \\
\min_{(i,j)\in[u_1]\times[\ell]}\{A(i,j) - B(i,j)\}, & \text{if } v_1 = c_2 + 1 \\
\min_{(i,j)\in[u_1]\times[v_1]}\{A(i,j) - B(i,j)\}, & \text{otherwise.}
\end{cases}$$

Hence, $f(u_1, v_1) > 0$. Suppose

$$\delta_1 = \min\{a_{1c_1} - b_{1c_1}, a_{u_1v_1}, f(u_1, v_1)\}. \quad (3.1)$$

Let $E_1 = A + K_{1,u_1,c_1,v_1}(\delta_1)$. Then, $E_1 \geq 0$ and $A \succ_{DM} E_1 \geq_{DM} B$. If $e_{1c_1} = b_{1c_1}$, then the proof is complete by reduction on the entries of $A$ and $B$ that are not equal. Otherwise, we want to show that by repeating this process on $E_1$, at some step, say
We have $e_{k1c_1} = b_{1c_1}$, since one can repeat a similar process on the next entry of $A$ that is not equal to its corresponding entry in $B$, the proof is complete by reduction.

Now, let $E_i$ be the matrix obtained at step $i$ from the matrix $E_{i-1}$ by repeating the above process, i.e. $A >_{DM} E_1 >_{DM} \ldots >_{DM} E_{i-1} >_{DM} E_i >_{DM} \ldots \geq_{DM} B$. In order to show that there exists $k \in \mathbb{N}$ such that $e_{k1c_1} = b_{1c_1}$, we use reduction on the size of $D_A$, that is, we show that at some step the size of $D_A$ will decrease. Since there are finitely many entries in $D_A$, repeating the above process will lead to either $e_{k1c_1} = b_{1c_1}$ at some step $k$, or $D_{E_k} = (e_{k1c_1})$. In the former case, the proof is complete.

In the latter case, using Lemma 3.2.8, the $(e_{k1c_1} - b_{1c_1})$-exchange on the entries with subscripts from $\{1, 2\} \times \{c_1, c_1 + 1\}$ will result in $e_{k+11c_1} = b_{1c_1}$ and again the proof is complete by reduction. Now suppose the size of $D_{E_k}$ does not decrease at any of the steps. It follows that at each step one entry in the submatrix $C_A$ becomes zero but still $D_{E_k}$ has the same upper left and lower right corners as of $D_A$. But note that, $C_{E_k}$ must have an entry $e_{uk,vk}$ with $e_{uk,vk} > b_{uk,vk} \geq 0$, thus $C_{E_k}$ cannot be a zero submatrix. Since there are finitely many entries, this implies that at some step $k$, $\delta_k$ should be equal to either $e_{k1c_1} - b_{1c_1}$ or $f(u_k, v_k)$ for some $(u_k, v_k)$. In the former case, the proof is complete. In the latter case, the size of $D_A$ decreases, and again the proof is complete since there are finitely many entries.

Theorem 3.2.9 is a very useful tool in solving the TP$_2$-completion problem, as is explained in the next chapter. The requirement of nonnegativity for the matrices is necessary for consideration of the TP$_2$-completion problem. However, by eliminating the conditions of nonnegativity of matrices in Definitions 3.2.3 and 3.2.5, and the condition of $0 < \delta < \min\{a_{pk}, a_{ql}\}$ in Definition 3.2.1, the partial orders GBr and DM
can also be defined on the set of real matrices. It is not hard to see that these partial orders have the inverse relationship on the set of real matrices as well. In order to show this, note that, by the first part of the proof of Theorem 3.2.9, the GBR partial order implies the inverse of the DM partial order on the set of real matrices as well, since nonnegativity does not play a role in this part. For the converse, let $A >_{DM} B$ (and $A \sim_{ELS} B$) for $m$-by-$n$ nonnegative real matrices $A, B$. Since we don’t have to worry about being nonnegative at each step, using the notations in the proof of Theorem 3.2.9, we can simply subtract $\delta = a_{1c_1} - b_{1c_1}$ from the entries $a_{1c_1}, a_{2(c_1+1)}$ and add it to the entries $a_{1(c_1+1)}, a_{2c_1}$. This transformation will result in a matrix $E_1 = (e_{k,l})$ with $A \succeq_{GBr} E_1 \succeq_{GBr} B$ and $b_{1c_1} = e_{1c_1}$. Since there are finitely many entries, the proof is complete by reduction on the entries of $A$ and $B$ that are not equal. Thus, in set of real matrices we have

$$A \preceq_{GBr} B \iff A \succeq_{DM} B.$$  

Moreover, it is also easy to see that if $A, B$ are nonnegative integer matrices, then $\delta_i$ can be chosen an integer at each step so that the resulting matrix is an integer matrix. Therefore, the partial orders GBr and DM are also inverses of each other on the set of nonnegative integer matrices.

Another interesting case is the set of $0,1$ matrices. Theorem 3.2.9, in particular in the case of integer matrices, answers the question raised by the paper [7]. The authors give an example of $0,1$ matrix that cannot be obtained from another $0,1$ matrix by a sequence of 1-exchanges such the resulting matrix at each step is a $0,1$ matrix. However, by Theorem 3.2.9 it is clear that if $A \succeq_{DM} B$ with $A, B$ 0,1 matrices, one can get from $A$ to $B$ by a sequence of 1-exchanges, although the matrices obtained
during the process may not to be 0,1 matrices anymore.

**Remark 3.2.10** If $A, B$ are 0,1 matrices with $A \geq_{DM} B$, then $B$ can be obtained from $A$ by a sequence of 1-exchanges.
Chapter 4

General Conditions for a TP₂-completion

In this chapter, a characterization for an m-by-n TP₂-completable partial TP₂ matrix with a given pattern is given. All of the patterns or partial TP₂ matrices in this chapter, have at least two specified entries in at least one line. The case of patterns with at most one specified entry in each line is considered separately in Chapter 7.

Consider an m-by-n partial positive matrix $T$. Let $P_T$ denote the set of m-by-n nonnegative matrices with zero entries in the positions of the unspecified entries of $T$. Let $H_T : P_T \rightarrow \mathbb{R}^+$ be the transformation defined by $H_T(A) = \prod_{t_{ij} \text{ specified}} t_{ij}^{a_{ij}}$, for $A \in P_T$. We call $H_T$, a Hadamard exponential transformation with base $T$, or for simplicity, a Hadamard transform. Note that, by the assumption on $T$ in this chapter, $H_T(A)$ is defined and positive, for all $A \in P_T$.

Observe that the Hadamard exponential transformation can also be defined when $T$ is a conventional matrix. For instance, the notation $A_\pi$ for a positive matrix
A ∈ Mₙ and a permutation π ∈ Sₙ, introduced on page 21, is the same as \( H_A(M_n) = \prod_{i \in [n]} a_{\pi(i)} \).

**Lemma 4.0.11** If the nonnegative matrix \( B \) is obtained from a nonnegative matrix \( A \in M_{m,n} \) by (only) one \( b \)-exchange, for some \( b > 0 \), then \( H_T(A) > H_T(B) \) for all \( T \in TP_2(m,n) \).

**Proof.** Let \( B = A + K_{p,q,k,\ell}(\delta) \) for some \( p, q, k, \ell \) with \( 1 \leq p < q \leq m \) and \( 1 \leq k < \ell \leq n \). Thus, \( a_{ij} = b_{ij} \) for all \( (i, j) \in [m] \times [n] \), except for the entries with subscripts from the set \( \{p, q\} \times \{k, \ell\} \). Therefore, there exists a constant \( P \) such that

\[
H_T(A) = \prod_{(i,j) \in [m] \times [n]} t_{ij}^{a_{ij}} = P t_{pk}^{a_{pk}} t_{qk}^{a_{qk}} t_{p\ell}^{a_{p\ell}} t_{q\ell}^{a_{q\ell}}
\]

and

\[
H_T(B) = \prod_{(i,j) \in [m] \times [n]} t_{ij}^{b_{ij}} = P t_{pk}^{b_{pk}} t_{qk}^{b_{qk}} t_{p\ell}^{b_{p\ell}} t_{q\ell}^{b_{q\ell}}.
\]

Thus, it is enough to show that

\[
t_{pk}^{a_{pk}} t_{qk}^{a_{qk}} t_{p\ell}^{a_{p\ell}} t_{q\ell}^{a_{q\ell}} > t_{pk}^{b_{pk}} t_{qk}^{b_{qk}} t_{p\ell}^{b_{p\ell}} t_{q\ell}^{b_{q\ell}}.
\]

The matrix \( T \) is \( TP_2 \), so every 2×2 minor is positive, in particular the one lying on the rows \( \{p, q\} \) and columns \( \{k, \ell\} \), hence

\[
t_{pk} t_{q\ell} > t_{qk} t_{p\ell}
\]

Thus, it is enough to show that

\[
t_{pk} t_{q\ell} > t_{qk} t_{p\ell},
\]

and

\[
t_{pk}^{-1} t_{qk} t_{p\ell} t_{q\ell}^{-1} > 1,
\]

and

\[
t_{pk}^{-\delta} t_{qk} t_{p\ell} t_{q\ell}^{-\delta} > 1,
\]

and

\[
t_{pk}^{a_{pk}} t_{qk}^{a_{qk}} t_{p\ell}^{a_{p\ell}} t_{q\ell}^{a_{q\ell}} > t_{pk}^{a_{pk} - \delta} t_{qk}^{a_{qk} + \delta} t_{p\ell}^{a_{p\ell} + \delta} t_{q\ell}^{a_{q\ell} - \delta}.
\]

34
Using the above Lemma and the inverse relationship between GBr and DM partial orders, we have the following very important fact.

**Theorem 4.0.12** If the nonnegative m-by-n matrices $A, B$ satisfy $A \geq_{DM} B$, then $H_T(A) \geq H_T(B)$, for all $T \in TP_2(m,n)$.

**Proof.** By Theorem 3.2.9, $A \geq_{DM} B$ implies that there are finite sequences of non-negative matrices $A = E_1, E_2, \ldots, E_k = B$ and parameters $\delta_1 > 0, \delta_2 > 0, \ldots, \delta_{k-1} > 0$ such that $E_{i+1}$ is obtained from $E_i$ by a $\delta_i$-exchange on some entries of $E_i$. By Lemma 4.0.11, $H_T(A) \geq H_T(E_2) \geq \ldots H_T(E_{k-1}) \geq H_T(B)$ for any given partial TP$_2$ matrix $T$. Thus, $H_T(A) \geq H_T(B)$, for all $T \in TP_2(m,n)$.

**Definition 4.0.13** For an m-by-n partial positive matrix $T$ and nonnegative matrices $A, B \in P_T$ with $A >_{DM} B$, an inequality of the form $H_T(A) > H_T(B)$ is called a Bruhat inequality for $T$.

**Definition 4.0.14** Let $T$ be a partial positive matrix. If for every pair of nonnegative matrices $A, B \in P_T$, satisfying $A >_{DM} B$, we have $H_T(A) > H_T(B)$, then $T$ is said to satisfy the Bruhat inequalities.

The Bruhat inequality $H_T(A) > H_T(B)$ for a partial matrix $T$ is considered when $A$ and $B$ have zeros in the positions of the unspecified entries of $T$. If we substitute a value in an unspecified entry of $T$, say $t_{k\ell}$ in the $(k, \ell)$ unspecified position, we obtain a new partial matrix $W$, and the Bruhat inequalities for $W$, $H_W(A') > H_W(B')$, will be considered for matrices $A', B'$ with zero entries in the positions of the unspecified
entries of $W$. These are the unspecified entries of $T$, together with possibly the $(k, \ell)$ position. Thus, one question is; if a partial $TP_2$ matrix $T$ satisfies all the Bruhat inequalities and the $(k, \ell)$ entry is an unspecified entry, does there exist a value for the $(k, \ell)$ position, say $t_{k\ell}$, such that the matrix obtained from $T$ by substituting $t_{k\ell}$ for the $(k, \ell)$ position also satisfies the Bruhat inequalities? In order to answer this question, consider an $m$-by-$n$ partial positive matrix $T$ with an unspecified entry in the $(k, \ell)$ position. Let $S_T(k, \ell)$ be the set of ordered pairs of $m$-by-$n$ nonnegative matrices $(A, B)$, with $A >_{DM} B$, and with 0 entries in the positions of the unspecified entries of $T$, except the $(k, \ell)$ position. For $(A, B) \in S_T(k, \ell)$ with $A = (a_{ij}), B = (b_{ij})$ identify three possibilities for $a_{k\ell}$ and $b_{k\ell}$:

(i) $a_{k\ell} > b_{k\ell}$. In this case, in order for $W$ to satisfy the Bruhat inequality $H_W(A) > H_W(B)$, we have

\[
\prod_{t_{ij} \text{ specified}} t_{ij}^{a_{ij}} t_{k\ell}^{a_{k\ell}} > \prod_{t_{ij} \text{ specified}} t_{ij}^{b_{ij}} t_{k\ell}^{b_{k\ell}} \iff \prod_{t_{ij} \text{ specified}} t_{ij}^{a_{ij} - b_{ij}} t_{k\ell}^{a_{k\ell} - b_{k\ell}} \iff \prod_{t_{ij} \text{ specified}} t_{ij}^{b_{ij} - a_{ij}} t_{k\ell}^{b_{k\ell} - a_{k\ell}}.
\]

Since the product on the right hand side of the inequality (4.1) is on the specified entries of $T$, the inequality (4.1) gives a lower bound for the $(k, \ell)$ unspecified entry. The maximum of all such lower bounds for $t_{k\ell}$, when the maximum is taken over all of the elements of $S_T(k, \ell)$, is called the lower bound for $t_{k\ell}$ obtained from the Bruhat inequalities.

(ii) $a_{k\ell} < b_{k\ell}$. In this case, in order for $W$ to satisfy the Bruhat inequality $H_W(A) > H_W(B)$ we have

\[
\prod_{t_{ij} \text{ specified}} t_{ij}^{a_{ij}} t_{k\ell}^{a_{k\ell}} > \prod_{t_{ij} \text{ specified}} t_{ij}^{b_{ij}} t_{k\ell}^{b_{k\ell}} \iff \prod_{t_{ij} \text{ specified}} t_{ij}^{a_{ij} - b_{ij}} t_{k\ell}^{a_{k\ell} - b_{k\ell}} \iff \prod_{t_{ij} \text{ specified}} t_{ij}^{b_{ij} - a_{ij}} t_{k\ell}^{b_{k\ell} - a_{k\ell}}.
\]

36
which gives an upper bound for the \((k, \ell)\) unspecified entry. The minimum of all such upper bounds for \(t_{k\ell}\), when the minimum is taken over all elements of \(S_T(k, \ell)\), is called an upper bound for \(t_{k\ell}\) obtained from the Bruhat inequalities.

(iii) \(a_{k\ell} = b_{k\ell}\). In this case, canceling \(t_{k\ell}\) from both sides of the inequality \(H_W(A) > H_W(B)\), gives an inequality only on the specified entries of \(T\) occurring on both sides, thus there is no upper or lower bound for \(t_{k\ell}\) in this case.

Notice that, since the specified entries in a partial TP2 matrix are always positive, for every unspecified entry the lower bound obtained from the Bruhat inequalities is always greater than 0 and the upper bound obtained from the Bruhat inequalities can be any positive number depending on the specified entries.

Define \(E_{k\ell} = (e_{ij}) \in M_{m,n}\), with \(k \in [m]\), \(\ell \in [n]\) as follows;

\[
e_{ij} = \begin{cases} 1, & \text{if } (i,j) = (k, \ell) \\ 0, & \text{otherwise}. \end{cases}
\]

The matrix \(E_{k\ell}\) is used in the proof of the following lemma.

**Lemma 4.0.15** Let \(T\) be an \(m\)-by-\(n\) partial positive matrix satisfying the Bruhat inequalities and suppose that \(T\) has an unspecified entry in the \((k, \ell)\) position. Consider \((A, B), (C, D) \in S_T(k, \ell)\), with \(A \sim_{ELS(I_1)} B\) and \(C \sim_{ELS(I_2)} D\), for some \(I_1, I_2 \subseteq [m] \times [n]\). If \(a_{k\ell} > b_{k\ell}\) and \(c_{k\ell} < d_{k\ell}\), then

\[
\prod_{I_1 \cup I_2 / (k, \ell)}^{\frac{a_{ij} - d_{ij}}{t_{ij}^{a_{i\ell} - c_{i\ell}}}} > \prod_{I_1 \cup I_2 / (k, \ell)}^{\frac{b_{ij} - a_{ij}}{t_{ij}^{b_{i\ell} - d_{i\ell}}}}.
\]

**Proof.** Consider \(A, B, C, D\) as given. Let \(A_1 = A - b_{k\ell}E_{k\ell}, B_1 = B - b_{k\ell}E_{k\ell}, C_1 = C - c_{k\ell}E_{k\ell}, D_1 = D - c_{k\ell}E_{k\ell}\). Thus, \(A_1, B_1, C_1\) and \(D_1\) are nonnegative matrices.
with \( A_1 >_{DM} B_1 \) and \( C_1 >_{DM} D_1 \). Let \( s = \frac{a_{kl} - b_{kl}}{d_{kl} - c_{kl}} \), since \( s > 0 \), it follows that
\[
sC_1 >_{DM} sD_1.
\]
Therefore, \( A_1 + sC_1 >_{DM} B_1 + sD_1 \) and hence \( A_2 = A_1 + sC_1 - (a_{kl} - b_{kl})E_{kl} >_{DM} B_2 = B_1 + sD_1 - (a_{kl} - b_{kl})E_{kl} \). Note that, in \( A_2 \) and \( B_2 \), the \((k, l)\) entry and all other entries corresponding to the unspecified entries of \( T \) are zero. So we have \( A_2, B_2 \in P_T \). Thus, from the assumption it follows that \( H_T(A_2) > H_T(B_2) \).

Therefore,
\[
\prod_{I_1 \cup I_2 / (k, \ell)} t_{ij}^{a_{ij} + sc_{ij}} > \prod_{I_1 \cup I_2 / (k, \ell)} t_{ij}^{b_{ij} + s d_{ij}},
\]
so
\[
\prod_{I_1 \cup I_2 / (k, \ell)} t_{ij}^{\frac{a_{ij} - b_{ij}}{d_{ij} - c_{ij}}} > \prod_{I_1 \cup I_2 / (k, \ell)} t_{ij}^{\frac{b_{ij} - a_{ij}}{d_{ij} - c_{ij}}}.
\]

This is equivalent to the following
\[
\prod_{I_1 \cup I_2 / (k, \ell)} t_{ij}^{\frac{c_{ij} - d_{ij}}{d_{ij} - c_{ij}}} > \prod_{I_1 \cup I_2 / (k, \ell)} t_{ij}^{\frac{b_{ij} - a_{ij}}{d_{ij} - c_{ij}}},
\]

Considering the fact that \( S_T(k, \ell) \) has infinitely many elements, there are infinitely many lower bounds and infinitely many upper bounds obtained from the Bruhat inequalities for each of the unspecified entries. Therefore, for \( W \) to satisfy all of the Bruhat inequalities, for every unspecified entry, the supremum of lower bounds obtained from the Bruhat inequalities must be less than or equal to the infimum of upper bounds obtained from the Bruhat inequalities. The following Lemma shows that this is true if the partial TP2 matrix \( T \) satisfies all the Bruhat inequalities.

**Lemma 4.0.16** If a partial positive matrix \( T \) satisfies the Bruhat inequalities, then for an unspecified entry in the \((k, \ell)\) position, every lower bound obtained from the
Bruhat inequalities is less than or equal to every upper bound obtained from the Bruhat inequalities, if there are any.

**Proof.** Suppose $T$ is an unspecified entry in the $(k,\ell)$ position. Consider matrices $A \sim_{ELS(I_1)} B$ and $C \sim_{ELS(I_2)} D$ with $(A, B), (C, D) \in S_T(k,\ell)$. Suppose $a_{kl} > b_{kl}$ and $d_{kl} > c_{kl}$, that is, $A >_{DM} B$ implies a lower bound for $t_{kl}$ obtained from the Bruhat inequalities and $C >_{DM} D$ implies an upper bound for $t_{kl}$ obtained from the Bruhat inequalities. Therefore, we have

$$t_{kl}^{a_{kl} - b_{kl}} > \prod_{I_1/\{(k,\ell)\}} t_{ij}^{b_{ij}} \quad \text{and} \quad \prod_{I_2/\{(k,\ell)\}} t_{ij}^{c_{ij}} > t_{kl}^{d_{kl} - c_{kl}}.$$

So

$$\left( \prod_{I_2/\{(k,\ell)\}} t_{ij}^{c_{ij}} \right)^{1/(d_{kl} - c_{kl})} \left( \prod_{I_1/\{(k,\ell)\}} t_{ij}^{a_{ij}} \right)^{1/(b_{kl} - a_{kl})} > t_{kl}^{b_{ij}} \quad \text{and} \quad t_{kl}^{a_{ij}} \left( \prod_{I_1/\{(k,\ell)\}} t_{ij}^{a_{ij}} \right)^{1/(b_{ij} - a_{kl})}. $$

We want to show that

$$\left( \prod_{I_2/\{(k,\ell)\}} t_{ij}^{c_{ij}} \right)^{1/(d_{kl} - c_{kl})} \left( \prod_{I_1/\{(k,\ell)\}} t_{ij}^{a_{ij}} \right)^{1/(b_{kl} - a_{kl})} \quad \left( \prod_{I_1/\{(k,\ell)\}} t_{ij}^{b_{ij}} \right)^{1/(a_{ij} - b_{kl})} \quad \left( \prod_{I_2/\{(k,\ell)\}} t_{ij}^{d_{ij}} \right)^{1/(c_{ij} - d_{kl})},$$

which is equivalent to

$$\prod_{I_1 \cup I_2/\{(k,\ell)\}} t_{ij}^{a_{ij} - b_{ij}} t_{ij}^{c_{ij} - d_{ij}} > \prod_{I_1 \cup I_2/\{(k,\ell)\}} t_{ij}^{b_{ij} - a_{ij}} t_{ij}^{d_{ij} - c_{ij}}.$$

that is,

$$\prod_{I_1 \cup I_2/\{(k,\ell)\}} t_{ij}^{c_{ij} - d_{ij}} t_{ij}^{a_{ij} - b_{ij}} > \prod_{I_1 \cup I_2/\{(k,\ell)\}} t_{ij}^{b_{ij} - a_{ij}} t_{ij}^{d_{ij} - c_{ij}}. \quad (4.3)$$
but the inequality (4.3) is obtained by Lemma 4.0.15. Since $A, B, C, D$ were arbitrary, the proof is complete.

Using the above lemma, we have the following theorem, which solves the TP$_2$-completion problem.

**Theorem 4.0.17** A partial positive matrix $T$ has a TP$_2$-completion if and only if it satisfies the Bruhat inequalities.

**Proof.** Consider a partial positive matrix $T$. First suppose that, the $(k, \ell)$ entry of $T$ is an unspecified entry with neither upper bound nor lower bound obtained from the Bruhat inequalities. By putting a positive number, say $t_{k\ell}$, in the $(k, \ell)$ position of $T$, the resulting matrix still satisfies the Bruhat inequalities. Similarly, if the $(k, \ell)$ entry has only lower bound $\alpha$ (or only upper bound $\beta$) obtained from the Bruhat inequalities, then putting a positive number $t_{k\ell} \geq \alpha$ ($t_{k\ell} \leq \beta$), will result in a matrix that also satisfies the Bruhat inequalities. Thus, without loss of generality, suppose that in the partial TP$_2$ matrix $T$ every unspecified entry has both upper bound and lower bound obtained from the Bruhat inequalities. Consider the unspecified entry in the $(k, \ell)$ position. Let $\alpha$ be the lower bound obtained from the Bruhat inequalities, and $\beta$ be the upper bound obtained from the Bruhat inequalities for $t_{k\ell}$. By Lemma 4.0.16, the interval $[\alpha, \beta]$ is nonempty. Let $t_{k\ell} \in [\alpha, \beta]$, and suppose $W$ is obtained from $T$ by replacing the $(k, \ell)$ unspecified entry by $t_{k\ell}$. We want to show that for every $A >_{DM} B$, with $A, B \in \mathcal{P}_W$, we have $H_W(A) > H_W(B)$. In other words,

$$t_{k\ell}^{a_{ij}} \prod_{t_{ij} \text{ specified}} a_{ij} > t_{k\ell}^{b_{ij}} \prod_{t_{ij} \text{ specified}} b_{ij}. \tag{4.4}$$

40
If $a_{k\ell} = b_{k\ell}$, then the inequality (4.4) holds, since canceling $t_{k\ell}^{a_{k\ell}} = t_{k\ell}^{b_{k\ell}}$ from both sides gives a Bruhat inequality on the specified entries of $T$. Otherwise, the inequality (4.4) is equivalent to one of the following,

$$
\begin{cases}
  t_{k\ell} > \left( \prod_{t_{ij} \text{ specified}} t_{ij}^{b_{ij} - a_{ij}} \right)^{1/(a_{k\ell} - b_{k\ell})}, & \text{if } a_{k\ell} > b_{k\ell} \\
  \left( \prod_{t_{ij} \text{ specified}} t_{ij}^{a_{ij} - b_{ij}} \right)^{1/(a_{k\ell} - b_{k\ell})} > t_{k\ell}, & \text{if } b_{k\ell} > a_{k\ell}.
\end{cases}
$$

By the choice of $t_{k\ell}$ from the interval $[\alpha, \beta]$, the inequality in each case holds. Thus, there is a value $t_{k\ell}$ for the $(k, \ell)$ position in $T$, such that substituting $t_{k\ell}$ in the $(k, \ell)$ unspecified position implies a new partial TP$_2$ matrix that satisfies the Bruhat inequalities. Therefore, the statement is true by reduction on the number of unspecified entries of $T$. \[\qed\]
Chapter 5

Minimal Conditions for a TP$_2$-completion

Theorem 4.0.17 gives a complete solution to the TP$_2$-completion problem. However, it is not a practical solution since it gives infinitely many conditions on the specified entries of a partial TP$_2$ matrix to have a TP$_2$-completion. The aim of this chapter is to reduce these conditions to finitely many polynomial conditions. It is shown that there is a close connection between the TP$_2$-completion problem and polyhedral cones. That is, the set of ordered pairs of matrices $A, B$ considered in the exponents for the Bruhat inequalities for a partial TP$_2$ matrix in Theorem 4.0.17, is equivalent to a finitely generated cone. It is then shown that every condition presented in Theorem 4.0.17 can be obtained from the conditions induced by generators for the cone. Thus, conditions induced by the set of generators for the cone are sufficient for TP$_2$-completable which are finitely many in number. Moreover, these conditions are minimal (with respect to set inclusion).
5.1 Cones and Generators

The first part of this section presents the basic facts about cones and generators, and can be omitted if reader is familiar with cones. Most of the following definitions and results about cones are taken from the books [5] and [29].

A hyperplane in \( \mathbb{R}^n \) is the set of vectors \( x = (x_1, \ldots, x_n) \) such that

\[
a_1x_1 + \ldots + a_nx_n = c
\]

for some \( c, a_1, \ldots, a_n \in \mathbb{R} \). Let \( f(x) = a_1x_1 + \ldots + a_nx_n - c \). Each of the inequalities \( f(x) \geq 0 \) or \( f(x) \leq 0 \) defines a (closed) half-space.

**Definition 5.1.1** A subset \( C \) of \( \mathbb{R}^n \) that is closed under addition and positive scalar multiplication, is called a convex cone.

Given a cone \( C \), a subset \( S \) of \( C \) is called a set of generators for the cone \( C \), if for every vector \( v \in C \), \( v \) is a linear combination of the elements of \( S \) with nonnegative coefficients. We may also say \( C \) is generated by \( S \).

If a cone \( C \) is generated by a finite set of vectors, then \( C \) is called finitely generated.

Therefore, if \( C \) is generated by the set \( S = \{v_1, v_2, \ldots, v_k\} \subset C \), with \( k \in \mathbb{N} \), then

\[
C = \{a_1v_1 + \ldots + a_kv_k \mid a_i \geq 0\},
\]

this is denoted by \( \text{cone}\{v_1, \ldots, v_k\} = C \).

Let \( C \) be a cone in \( \mathbb{R}^n \). A vector \( v \in C \) is called an extreme vector in \( C \) if it cannot be written as a linear combination of two or more non-collinear vectors in \( C \) with positive coefficients. That is, if \( v = a_1v_1 + \ldots + a_kv_k \), with non-collinear vectors \( v_i \in C \) and with \( a_i > 0 \), for \( i = 1, 2, \ldots, k \), then \( k = 1 \) and \( v = a_1v_1 \). This implies
that if \( v \) is an extreme vector in \( C \), then the set of generators for \( C \) contains a vector collinear with \( v \), say \( av \), for some \( a > 0 \).

If a cone \( C \) is the intersection of a finite number of closed half-spaces, and \( 0 \) belongs to the boundary of each of these half-spaces, then \( C \) is called polyhedral. In other words, a cone \( C \) in \( \mathbb{R}^n \) is polyhedral if

\[
C = \{ x \in \mathbb{R}^n | Ax \geq 0 \}
\]

for some \( m \)-by-\( n \) matrix \( A \). The following (Farkas-Minkowski-Weyl) theorem is proved in [5] and [29].

**Theorem 5.1.2** A convex cone is finitely generated if and only if it is polyhedral.

For an \( m \)-by-\( n \) partial TP_2 matrix \( T \), let

\[
C_T = \{ M \in P_T \mid M \succeq_{DM} 0 \} = \{ M \in P_T \mid M(p,q) \geq 0 \text{ for all } (p,q) \in [m] \times [n] \}.
\]

If \( C_T = \{0\} \), then there is at most one specified entry in each row and each column of \( T \). In this case, the pattern is TP_2-completable by Corollary 7.0.15 in Chapter 7. Thus, in a similar way to Chapter 4, we consider only the partial TP_2 matrices with at least two specified entries in a line, and therefore, for the rest of this chapter, we have \( C_T \neq \{0\} \).

Notice that, for every ordered pair of matrices \((A, B)\), with \( A, B \in P_T \) and \( A >_{DM} B \), we have \( A - B \in P_T \) and \( A - B >_{DM} 0 \), thus \( A - B \in C_T \). On the other hand, for every \( M = (m_{ij}) \in C_T \) with \( M \neq 0 \), let \( A = (a_{ij}) \) and \( B = (b_{ij}) \) be defined as follows

\[
a_{ij} = \begin{cases} m_{ij}, & \text{if } m_{ij} > 0 \\ 0, & \text{otherwise} \end{cases} \quad \text{and} \quad b_{ij} = \begin{cases} -m_{ij}, & \text{if } m_{ij} < 0 \\ 0, & \text{otherwise} \end{cases}
\]
Since $M >_{DM} 0$, we have $A >_{DM} B$ with $A, B \in P_T$. Therefore, there is a one-to-one correspondence between the set of ordered pairs of matrices $(A, B)$ with $A, B \in P_T$ and $A >_{DM} B$ and the set $C_T$. This gives us the following result.

**Corollary 5.1.3** A partial positive matrix $T$ has a TP$_2$-completion if and only if it satisfies $H_T(M) \geq 1$, for all $M \in C_T$.

**Proof.** For $A = (a_{ij})$ and $B = (b_{ij})$ with $A, B \in P_T$ and $A >_{DM} B$, a Bruhat inequality of the form \( \prod_{t_{ij} \text{ specified}} t_{ij}^{a_{ij}} > \prod_{t_{ij} \text{ specified}} t_{ij}^{b_{ij}} \) can be written as \( \prod_{t_{ij} \text{ specified}} t_{ij}^{a_{ij} - b_{ij}} > 1 \), with $A - B >_{DM} 0$. By the above discussion and Theorem 4.0.17, we have $T$ is TP$_2$-completable if and only if \( \prod_{t_{ij} \text{ specified}} t_{ij}^{m_{ij}} \geq 1 \), for all $M \in C_T$. \[\square\]

For an $m$-by-$n$ partial TP$_2$ matrix $T$ (or pattern $\mathcal{P}$), let $X$ be an $m$-by-$n$ matrix whose entries are variables $x_{ij}$ in the positions of the specified entries of $T$ ($\mathcal{P}$) and zero in the positions of the unspecified entries of $T$ ($\mathcal{P}$), such that sum of the entries in each row or column is zero. Moreover, let the variables $x_{ij}$ satisfy \( \sum_{(i,j) \in [p] \times [q]} x_{ij} \geq 0 \), for all $(p, q) \in [m] \times [n]$. We call $X$ the parameterized pattern of $T$ ($\mathcal{P}$). Considering the lexicographical order for the variables $x_{ij}$, the inequalities \( \sum_{(i,j) \in [p] \times [q]} x_{ij} \geq 0 \), for all $(p, q) \in [m] \times [n]$ define a set of half-spaces in $\mathbb{R}^d$, with $d$ equal to the number of distinct variables $x_{ij}$ in $X$. Since the row sum vectors and column sum vectors of $X$ are zero, $d$ is strictly less than the number of specified entries of $T$. The set $C_T$ is equivalent to the solution set of these linear inequalities which is the intersection of the corresponding half-spaces. Therefore, $C_T$ is a polyhedral cone and there exists an $m$-by-$d$ matrix $A_T$ such that

\[ C_T \equiv \{ x \in \mathbb{R}^n | A_T x \geq 0 \}. \]
Using Theorem 5.1.2, $C_T$ is a finitely generated cone. Let $C_T = \text{cone}\{G_1, \ldots, G_r\}$.

For a polyhedral cone $C = \{x \in \mathbb{R}^n | Ax \geq 0\}$, with an $m$-by-$n$ matrix $A$, the lineality space of $C$ is the linear space

$$\{x \in \mathbb{R}^n | Ax = 0\}.$$

If the lineality space of $C$ has dimension 0, $C$ is called pointed.

**Lemma 5.1.4** For an $m$-by-$n$ partial $TP_2$ matrix $T$, the cone $C_T$ is pointed.

**Proof.** Consider the parameterized pattern $X$ of $T$ with half-space inequalities as follows

$$\sum_{(i,j) \in [p] \times [q]} x_{ij} \geq 0, \text{ for all } (p, q) \in [m] \times [n]. \quad (5.1)$$

Consider the lexicographical order for the variables $x_{ij}$. Let $A_T x \geq 0$ be the matrix inequality form of the inequalities in (5.1). For $i \in [m]$, if there is only 0 or 1 specified entry in the row $i$ of $T$, then all of the entries in the row $i$ of $X$ are zero, and so there is no parameter in the row $i$ of $X$. Thus, without loss of generality, suppose there are more than one specified entry in each row of $T$ which implies at least one variable in each row of $X$. Suppose the first variable in the first row lies in the column $j_0$, for some $j_0 \in [n]$, i.e. $x_{1j_0} \neq 0$ and $x_{1k} = 0$ for all $k < j_0$. Thus, using the half-space inequality $x_{1j_0} \geq 0$, in the first row of $A_T = (a_{ij})$, we have $a_{11} = 1$ and $a_{1k} = 0$ for all $k \neq 1$. Therefore, the equation $A_T x = 0$ implies $x_{1j_0} = 0$. If there is a variable $x_{1j_1}$, with $j_1 \neq j_0$ that is not a scalar multiple of $x_{1j_0}$ and is the second in the given order for the variables, then the second row of $A_T$, has entries equal to 1 in the $(2, j_0)$ and $(2, j_1)$ positions and 0 otherwise, (since we have $x_{1j_0} + x_{1j_1} \geq 0$). Since $x_{1j_0} = 0$, the equation $A_T x = 0$ implies $x_{1j_1} = 0$. Similarly, we can show that if $A_T x = 0$, then all
of the variables in the first row of $X$ are zero. Repeating this process on the next rows of $X$, implies that the only solution to the equation $A_{7}x = 0$, is $x = 0$. Therefore, the dimension of the lineality space of $C_{7}$ is zero, which means $C_{7}$ is pointed.

Let $C = \text{cone}\{v_{1}, v_{2}, \ldots, v_{r}\}$ be a cone in $\mathbb{R}^{n}$, for some vectors $v_{1}, v_{2}, \ldots, v_{r} \in C$. The set $\{v_{1}, v_{2}, \ldots, v_{r}\}$ is called a Hilbert basis for $C$ if each integral vector $a$ in $C$ can be written as a nonnegative integral combination of $v_{1}, v_{2}, \ldots, v_{r}$. An integral Hilbert basis is a Hilbert basis that contains only integral vectors.

For an $m$-by-$n$ matrix $A$, the system of linear inequalities $Ax \geq 0$ is rational (integral) if $A$ is a rational (integral) matrix. A rational polyhedral cone is a polyhedral cone obtained by a rational system of inequalities, that is, if it is equal to $\{x \in \mathbb{R}^{n} | Ax \geq 0\}$, for an $m$-by-$n$ rational matrix $A$.

The following Theorem is easy to prove; see [29].

**Theorem 5.1.5** Each rational polyhedral cone $C$ is generated by an integral Hilbert basis. If $C$ is pointed, then $C$ has a unique minimal integral Hilbert basis (minimal with respect to set inclusion).

For a given partial TP$_2$ matrix $T$ and the parameterized pattern $X$ of $T$, the coefficients in the inequalities for the half-spaces, $\sum_{(i,j) \in [p] \times [q]} x_{ij} \geq 0$, are integers for all $(p, q) \in [m] \times [n]$. Thus, the matrix $A_{T}$ is integral. Therefore, the cone $C_{T}$ is a rational polyhedral cone. Using Theorem 5.1.5, $C_{T}$ has a unique integral Hilbert basis, say $\{G_{1}, \ldots, G_{r}\}$. For each $G_{\ell} = (g_{\ell\ell})$, with $\ell = 1, 2, \ldots, r$, there corresponds a Bruhat inequality of the form $\prod_{i,j \text{ specified}} t^{g_{ij}}_{ij} > 1$ which is equivalent to the following
Inequality

\[ \prod_{\text{specified } i,j} t_{ij}^{a_{ij}} > \prod_{\text{specified } i,j} t_{ij}^{b_{ij}} \]  

(5.2)

with

\[
\begin{cases}
    a_{ij} = g_{ij}, & \text{if } g_{ij} > 0 \\
    b_{ij} = -g_{ij}, & \text{if } g_{ij} < 0 \\
    a_{ij} = b_{ij} = 0, & \text{if } g_{ij} = 0.
\end{cases}
\]

Note that, the inequality (5.2) is a polynomial inequality on the specified entries of \( T \). This implies that each of the generators for this cone corresponds to a polynomial inequality on the specified entries of the given partial TP\(_2\) matrix. On the other hand, these inequalities are sufficient conditions for \( T \) to satisfy the conditions presented in Theorem 4.0.17. In other words, there are finitely many polynomial inequalities for a partial TP\(_2\) matrix \( T \) to be TP\(_2\)-completable. This is the content of the next Theorem.

### 5.2 Main Result

**Theorem 5.2.1** Let \( T \) be a partial positive matrix and \( C_T = \text{cone}\{G_1, G_2, \ldots, G_r\} \). Then \( T \) is TP\(_2\)-completable if and only if it satisfies the finitely many polynomial inequalities on the specified entries of \( T \) of the form \( H_T(G_i) \geq 1, i \in [r] \).

**Proof.** Using Corollary 5.1.3, if \( T \) is TP\(_2\)-completable, then it satisfies inequalities of the form \( H_T(M) \geq 1 \), for all \( M \in C_T \), in particular for matrices \( M \in \{G_1, G_2, \ldots, G_r\} \). For the converse, let \( G_\ell = (g_{\ell_{ij}}) \) and suppose \( H_T(G_\ell) \geq 1 \), for all \( \ell \in [r] \). Let \( M \in C_T \) be an arbitrary matrix, thus there exist scalars
\[ c_1, c_2, \ldots, c_r \text{ with } c_\ell \geq 0, \text{ for } \ell = 1, 2, \ldots, r, \text{ such that } M = c_1 G_1 + \ldots + c_r G_r, \]

so \( m_{ij} = c_1 g_{1ij} + c_2 g_{2ij} + \ldots + c_r g_{rij} \). We have

\[ H_T(G_i) \geq 1 \Rightarrow \prod_{t_{ij} \text{ specified}} t_{ij}^{g_{ij}} \geq 1 \Rightarrow \prod_{t_{ij} \text{ specified}} t_{ij}^{c_i g_{ij}} \geq 1. \]

Multiplying these inequalities for \( \ell = 1, 2, \ldots, r \), implies

\[ \prod_{t_{ij} \text{ specified}} t_{ij}^{c_1 g_{1ij} + c_2 g_{2ij} + \ldots + c_r g_{rij}} \geq 1 \iff \prod_{t_{ij} \text{ specified}} t_{ij}^{m_{ij}} \geq 1 \iff H_T(M) \geq 1. \]

Using Corollary 5.1.3, the proof is complete. \( \blacksquare \)

**Theorem 5.2.2** A pattern \( \mathcal{P} \) is TP\(_2\)-completable if and only if the minimal conditions for TP\(_2\)-completable are just the positivity of the specified entries and of the specified 2-by-2 minors.

**Proof.** Consider a partial TP\(_2\) matrix \( T \) with pattern \( \mathcal{P} \). The conditions of the positivity of the specified entries and positivity of the fully specified 2-by-2 minors are just the conditions for being a partial TP\(_2\) matrix. By Theorem 5.1.5, the Hilbert basis for a given rational cone is unique and minimal, thus none of the elements of the basis can be expressed as a positive linear combination of the others. Therefore, if there is a condition obtained in Theorem 5.2.1 that is not just being partial TP\(_2\), then the pattern \( \mathcal{P} \) is not TP\(_2\)-completable. \( \blacksquare \)
Chapter 6

Algorithm

In this chapter, it is described how the conditions obtained in Theorem 5.2.1 can be computed for a given pattern of specified entries.

Theorem 5.2.1 characterizes the set of finitely many polynomial inequalities on the specified entries of a partial TP$_2$ matrix $T$, such that if $T$ satisfies them, then $T$ is TP$_2$-completable. In order to find these inequalities for a given partial TP$_2$ matrix $T$ in practice, consider the polyhedral cone that is the intersection of half-spaces obtained from the parametrized pattern of $T$. Then find the generators for this cone. The Bruhat inequalities induced by these generators, along with the positivity of the specified entries, are all of the sufficient conditions for TP$_2$-completability of $T$. The only remaining question here is how to find the generators of a cone by having the inequalities for the half-spaces. For a given system of linear inequalities $Ax \geq 0$, with $A$ an $m$-by-$n$ matrix and $x$ a vector in $\mathbb{R}^n$, there are algorithms that find the set of generators for the polyhedral cone that consists of the solutions to the linear inequalities $Ax \geq 0$. Pivoting and the double description method are such algorithms;
see [13]. We use the cdd+ program written by Fukuda [12] which is explained here briefly, followed by examples. The following definitions and the result are from [13].

For an $m$-by-$n$ matrix $A$ and a vector $v \in \mathbb{R}^n$, the zero set $Z(v)$, is the set of indices of rows of $A$ for which the inner product with $v$ is zero. Recall that for an $m$-by-$n$ matrix $A$, $A[\alpha:,:\beta]$ denotes the submatrix of $A$ lying in rows $\alpha$ and columns $\beta$, with $\alpha \subseteq [m], \beta \subseteq [n]$.

**Proposition 6.0.3** Let $v$ be a vector in the cone $C$. Then,

(a) $v$ is an extreme vector of $C$ if and only if the rank of the matrix $A[Z(v),[n]]$ is $n - 1$.

(b) $v$ is a nonnegative linear combination of extreme vectors of $C$.

**Corollary 6.0.4** Let $S$ be a minimal set of generators for $C$, with respect to the set inclusion. Then $S$ is the set of extreme vectors of $C$.

By Lemma 5.1.4, $C_T$ is pointed. Thus, using Theorem 5.1.5, the minimal set of generators for the cone $C_T$ is unique up to scalar multiplication.

Notice that, since the cone $C_T$ is pointed, rank of $A_T$ equals $n$. In particular, this implies that $m \geq n$. On the other hand, $C_T$ is a polyhedral cone that is the intersection of some half-spaces in which each row of $A_T$ determines one of these half-spaces. By Proposition 6.0.3, each extreme vector $v$ is part of the line consisting of solutions of a matrix equation $A_T[Z(v),[n]]x = 0$, where $A_T[Z(v),[n]]$ is a submatrix of $A_T$ of size $(n - 1)$-by-$n$ and has rank $n - 1$. However, when $m$ is large, it would be computationally too expensive to look at all of the subsets of the set of the rows of $A_T$ with cardinality $n - 1$. In order to cut down on the sets that one needs to
consider, linear programming pivoting has been used. Several people have used such an algorithm, and Fukuda's method is of this type [12].

The generators obtained from running the cdd+ program are vectors in $\mathbb{R}^d$, with $d$ the number of variables in $X$. In order to convert these to the generators for the cone $C_T$, let $g_i = (g_{i1}, \ldots, g_{id})$ be a generator obtained from running the cdd+ program. Substitute $g_{ik}$ in the position of the $k$th variable of the parameterized pattern $X$. The resulting matrix $G_i$ is one of the generators for the cone $C_T$. Note that, each $G_i$ may be taken to be an integral matrix by Theorem 5.1.5. The set of such matrices gives the polynomial inequalities that are sufficient for the TP$_2$-completablity of the partial TP$_2$ matrix $T$.

Since Fukuda has used the double description method, we explain it here briefly. For details see [12].

Let $d, m, n \geq 1$ and $A \in M_{m,d}$ and $R \in M_{d,n}$. For a system of linear inequalities $Ax \geq 0$, with $A$ an $m$-by-$d$ matrix, $C(A)$ denotes the polyhedral cone that is the intersection of all of the half-spaces obtained by the inequalities $Ax \geq 0$. The ordered pair $(A, R)$ is said to be a double description pair or simply a DD pair if

$$Ax \geq 0 \text{ if and only if } x = R\lambda \text{ for some } \lambda \in \mathbb{R}^n, \lambda \geq 0.$$ 

The following is Minkowski's Theorem about polyhedral cones, [13].

**Theorem 6.0.5** For any $m$-by-$d$ real matrix $A$, there exists a $d$-by-$n$ real matrix $R$ such that $(A, D)$ is a DD pair, i.e. the cone $C(A)$ is generated by the columns of $R$.

The following is Weyl's Theorem for polyhedral cones, [13].
**Theorem 6.0.6** For any $d$-by-$n$ real matrix $R$, there exists an $m$-by-$d$ real matrix $A$ such that $(A, R)$ is a DD pair, i.e. the set of all positive linear combinations of the columns of $R$ is the polyhedral cone $C(A)$.

Therefore, by Theorems 6.0.5 and 6.0.6, a polyhedral cone $C$ can be represented by two methods, one as nonnegative linear combinations of the set of generators, and the other as the intersection of a set of halfspaces. The first one is called the V-representation and the second one is called the H-representation of the cone $C$; see [12]. Via Fukuda's computer program in C++, cdd+, either one of the H-representation or V-representation of a polyhedron cone (the solution set to a non-homogeneous system of linear inequalities) gives the other representation. In this text, we have the H-representation and would like to obtain the V-representation. Consider the cone $C$ that is the solution to the system of linear inequalities $Ax \geq 0$, with $A$ an $m$-by-$d$ matrix, and suppose $C$ is generated by the vectors $v_1, \ldots, v_r$. The following two formats show how the H-representation and V-representation of a polyhedral cone is described in cdd+, respectively. We omit the unnecessary parts of the program for our purpose.

<table>
<thead>
<tr>
<th>H-representation</th>
<th>V-representation</th>
</tr>
</thead>
<tbody>
<tr>
<td>begin</td>
<td>begin</td>
</tr>
<tr>
<td>\begin{align*} m &amp; \quad d+1 \quad \text{integer} \quad \text{and} \ 0 &amp; \quad A \end{align*}</td>
<td>\begin{align*} r &amp; \quad d+1 \quad \text{real} \ 0 &amp; \quad v_1 \ \vdots &amp; \quad \vdots \ 0 &amp; \quad v_r \end{align*}</td>
</tr>
<tr>
<td>end</td>
<td>end</td>
</tr>
</tbody>
</table>

In the H-representation, 0 denotes the zero vector in $R^m$ and in the V-representation,
0 is the real number zero. The vectors \( v_i \) are row vectors. The following examples give conditions for TP2-completablility of some patterns using cdd+.

In the following examples, \( t_{ij} \) is used to show the specified entries of a partial TP2 matrix, and \( x_{ij} \) denotes the unspecified entries.

**Example 6.0.7** Consider the 3-by-3 partial TP2 matrix \( T \) with the pattern \( P \) that has only one unspecified entry in the (2, 2) position.

\[
T = \begin{pmatrix}
t_{11} & t_{12} & t_{13} \\
t_{21} & ? & t_{23} \\
t_{31} & t_{32} & t_{33}
\end{pmatrix}, \quad P = \begin{pmatrix}
x & x & x \\
x & ? & x \\
x & x & x
\end{pmatrix}
\]

Therefore, the cone \( C_T \) consists of the matrices of the following form

\[
X = \begin{pmatrix}
x_1 & x_2 & -x_1 - x_2 \\
x_3 & 0 & -x_3 \\
-x_1 - x_3 & -x_2 & x_1 + x_2 + x_3
\end{pmatrix},
\]

satisfying

\[
x_1 \geq 0, \quad x_1 + x_2 \geq 0, \quad x_1 + x_3 \geq 0, \quad x_1 + x_2 + x_3 \geq 0.
\]

In order to find the set of generators for \( C_T \), we use cdd+, and for this, we need to write the half-space inequalities for the cone \( C_T \) in a matrix inequality form. That is,

\[
\begin{pmatrix}
1 & 0 & 0 \\
1 & 1 & 0 \\
1 & 0 & 1 \\
1 & 1 & 1
\end{pmatrix} \begin{pmatrix}
x_1 \\
x_2 \\
x_3
\end{pmatrix} \geq \begin{pmatrix}
0 \\
0 \\
0
\end{pmatrix}
\]

(6.1)
Therefore, $A_T$ is a 4-by-3 matrix, thus, $m = 4$ and $d = 3$. Hence, the H-representation form for $C_T$ is as follows

\begin{verbatim}
H-representation
begin
  4  4  integer
  0  1  0  0
  0  1  1  0
  0  1  0  1
  0  1  1  1
end
\end{verbatim}

Running the cdd+ program gives us the V-representation form of the cone $C_T$ as follows.

\begin{verbatim}
V-representation
begin
  4  4  real
  0  0  0  1
  0  0  1  0
  0  1  0  -1
  0  1  -1  0
end
\end{verbatim}

Thus, the set of generators for the cone with half-space inequalities given in (6.1) is
the following set.

\[
S = \left\{ \begin{pmatrix} 0 \\ 0 \\ 1 \\ -1 \end{pmatrix}, \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}, \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \begin{pmatrix} 1 \\ 0 \end{pmatrix} \right\}
\]

In order to find the generators for the cone \( C_T \), we substitute each vector \((x_1, x_2, x_3) \in S\), separately, in \( X \in C_T \). This gives the following matrices \( G_1, G_2, G_3 \) and \( G_4 \)

\[
G_1 = \begin{pmatrix} 0 & 0 & 0 \\ 1 & 0 & -1 \\ -1 & 0 & 1 \end{pmatrix}, \quad G_2 = \begin{pmatrix} 0 & 1 & -1 \\ 0 & 0 & 0 \\ 0 & -1 & 1 \end{pmatrix},
\]

\[
G_3 = \begin{pmatrix} 1 & 0 & -1 \\ -1 & 0 & 1 \\ 0 & 0 & 0 \end{pmatrix}, \quad G_4 = \begin{pmatrix} 1 & -1 & 0 \\ 0 & 0 & 0 \\ -1 & 1 & 0 \end{pmatrix}
\]

Therefore, the conditions for TP\(_2\)-completable of \( T \) are the following,

\[
H_T(G_i) \geq 1, \quad \text{for } i = 1, 2, 3, 4
\]

These are equivalent to the polynomial inequalities on the specified entries of \( T \) of following form, respectively,

\[
t_{21}t_{33} > t_{23}t_{31}, \quad t_{12}t_{33} > t_{13}t_{32}, \quad t_{11}t_{23} > t_{13}t_{21}, \quad t_{11}t_{32} > t_{12}t_{31}.
\]

The above inequalities together with \( t_{ij} > 0 \), for all specified entries \( t_{ij} \), are the sufficient polynomial inequalities on the specified entries of \( T \) for TP\(_2\)-completable.

Since they are just the conditions for being partial TP\(_2\), it follows that there is a TP\(_2\)-
completion for the partial TP₂ matrix \( T \). Hence, the pattern \( \mathcal{P} \) is TP₂-completable.

Note that, this is also shown in Lemma 7.0.4, in Chapter 7.

**Example 6.0.8** Consider the following partial TP₂ matrix \( T \) with the pattern \( \mathcal{P} \).

\[
T = \begin{pmatrix}
t_{11} & x_{12} & t_{13} \\
x_{21} & t_{22} & t_{23} \\
t_{31} & t_{32} & t_{33}
\end{pmatrix}, \quad \mathcal{P} = \begin{pmatrix}
\times & ? & \times \\
? & \times & \times \\
\times & \times & \times
\end{pmatrix}
\]

Therefore, we have

\[
C_T = \left\{ X = \begin{pmatrix}
x_1 & 0 & -x_1 \\
0 & x_2 & -x_2 \\
-x_1 & -x_2 & x_1 + x_2
\end{pmatrix} \mid x_1 \geq 0, x_1 + x_2 \geq 0 \right\}
\]

Again we use cdd+ to find the set of generators for \( C_T \). For this, we need to write the half-space inequalities for the cone \( C_T \) in a matrix inequality form. That is,

\[
\begin{pmatrix}
1 & 0 \\
1 & 1
\end{pmatrix}
\begin{pmatrix}
x_1 \\
x_2
\end{pmatrix}
\leq
\begin{pmatrix}
0 \\
0
\end{pmatrix}
\]

(6.2)

Therefore, \( A_T \) is a 2-by-2 matrix, thus, \( m = 2 \) and \( d = 2 \). Hence, the H-representation form for \( C_T \) is as follows
H-representation

\begin{verbatim}
begin
  2  3 integer
  0  1  0
  0  1  1
end
\end{verbatim}

Running the cdd+ program gives us the V-representation form of the cone \( C_T \) as follows.

V-representation

\begin{verbatim}
begin
  2  3 real
  0  1  -1
  0  0  1
end
\end{verbatim}

Thus, the set of generators for the cone with half-space inequalities given in (6.2) is the following set.

\[ S = \left\{ \begin{pmatrix} 1 \\ -1 \end{pmatrix}, \begin{pmatrix} 0 \\ 1 \end{pmatrix} \right\} \]

In order to find the generators for the cone \( C_T \), we substitute \((x_1, x_2) = (1, -1)\) and then \((x_1, x_2) = (0, 1)\), separately, in \( X \in C_T \). This gives the following matrices \( G_1 \) and \( G_2 \),
Note that, we have $x_1 G_1 + (x_1 + x_2) G_2 = X$. Therefore, the conditions for TP$_2$-completability of $T$ are the following,

$$H_T(G_1) \geq 1 \text{ and } H_T(G_2) \geq 1$$

These are respectively equivalent to

$$t_{11} t_{23} t_{32} > t_{13} t_{22} t_{31} \text{ and } t_{22} t_{33} > t_{23} t_{32}.$$  \hspace{1cm} (6.3)

In other words, the partial matrix $T$ is TP$_2$-completatable if and only if the specified entries of $T$ are positive and the polynomial inequalities (6.3) on the specified entries of $T$ hold. Since the inequality $t_{11} t_{23} t_{32} > t_{13} t_{22} t_{31}$ is not (nor obtained from) a determinantal inequality on fully specified 1-by-1 and 2-by-2 submatrices, the pattern $P$ is not TP$_2$-completatable. The following is an example of a partial TP$_2$ matrix with pattern $P$ that does not have a TP$_2$-completion,

$$A = \begin{pmatrix} 1 & x_{12} & 2 \\ x_{21} & 1 & 1 \\ 1 & 1 & 3 \end{pmatrix}$$

From inequalities $\det A[\{1, 2\}, \{2, 3\}] > 0$ and $\det A[\{1, 3\}, \{1, 2\}] > 0$, we have $2 < x_{12} < 1$ which is impossible, thus $A$ does not have a TP$_2$-completion. Notice that, the pattern $P$ is one of the patterns listed in Proposition 7.0.5 in Chapter 7.
Example 6.0.9 Consider the following partial TP$_2$ matrix $T$ with pattern $\mathcal{P}$.

\[
T = \begin{pmatrix}
  t_{11} & x_{12} & x_{13} & t_{14} \\
  x_{21} & t_{22} & t_{23} & x_{24} \\
  t_{31} & t_{32} & t_{33} & t_{34}
\end{pmatrix}, \quad \mathcal{P} = \begin{pmatrix}
  \times & ? & ? & \times \\
  ? & \times & \times & ? \\
  \times & \times & \times & \times
\end{pmatrix}
\]

The parameterized pattern of $T$ is of the following form:

\[
C_T = \begin{pmatrix}
  x_1 & 0 & 0 & -x_1 \\
  0 & x_2 & -x_2 & 0 \\
  -x_1 & -x_2 & x_2 & x_1
\end{pmatrix} \quad \text{s.t. } x_1 \geq 0, \ x_1 + x_2 \geq 0
\]

Thus, the H-representation is the same as of the Example 6.0.8. Therefore, running the cdd+ program will give the same V-representation. However, substituting the generators for V-representation in the parameterized pattern of $T$ will give us the following generators for $C_T$:

\[
G_1 = \begin{pmatrix}
  1 & 0 & 0 & -1 \\
  0 & -1 & 1 & 0 \\
  -1 & 1 & -1 & 1
\end{pmatrix}, \quad G_2 = \begin{pmatrix}
  0 & 0 & 0 & 0 \\
  0 & 1 & -1 & 0 \\
  0 & -1 & 1 & 0
\end{pmatrix}
\]

Therefore, the conditions for TP$_2$-completable of the partial positive matrix $T$ are the following,

\[
H_T(G_1) \geq 1 \text{ and } H_T(G_2) \geq 1
\]

These are respectively equivalent to

\[
t_{11}t_{23}t_{32}t_{34} > t_{14}t_{22}t_{33}t_{31} \quad (6.4)
\]
Thus, there is a TP$_2$-completion for the partial matrix $T$ if and only if the specified entries of $T$ are positive and the polynomial inequalities (6.4) on the specified entries of $T$ hold. Since the inequality on the left hand side is not (nor obtained from) a determinantal inequality on fully specified 1-by-1 and 2-by-2 submatrices, it implies that there is no TP$_2$-completion for $T$, and thus the pattern $P$ is not TP$_2$-completable.

The following is an example of a partial TP$_2$ matrix with pattern $P$ that does not have a TP$_2$-completion.

\[
A = \begin{pmatrix}
1 & x_{12} & x_{13} & 1 \\
x_{21} & 1 & 1 & x_{24} \\
1 & 2 & 8 & 2
\end{pmatrix}
\]

Using the determinantal inequalities $\det A[[1, 3], \{1, 2, 4\}] > 0$, $\det A[[1, 3], \{1, 3, 4\}] > 0$ and $\det A[[1, 2], \{2, 3\}] > 0$, respectively, $1 < x_{12} < 2$, $4 < x_{13} < 8$ and $x_{13} < x_{12}$. This is impossible which means there is no TP$_2$-completion for $A$.

**Remark 6.0.10** The minimal polynomial inequalities induced by the Bruhat order on permutations are not necessarily sufficient for TP$_2$-completable.

Consider the inequality $t_{11}t_{23}t_{3}t_{3} > t_{14}t_{22}t_{33}t_{31}$ in Example 6.0.9. The set of indices in each side of this inequality, does not form a permutation since row 3 is repeated. Moreover, the set of indices in each side cannot be partitioned into two or more subsets such that the corresponding subsets lie in a Bruhat inequality on permutations. In order to show this, suppose there is such a partition, and consider the subset of indices
containing the (3,2) entry on the left side of the inequality. Then, the corresponding subset on the right side, contains an entry lying in the column 2, there is only one such entry (2,2). Thus, on the left side there is an entry lying in the row 2, that is (2,3). This implies that, on the right side there is an entry lying in the column 3, (3,3). At this point, the column indices form a permutation, however, they lie in a reversed Bruhat inequality, \( t_{23}t_{32} < t_{22}t_{33} \). Therefore, the other entries must be taken into account. For instance, choosing the (1,1) entry on the left side, implies there is an entry lying in the column 1 on the right side (3,1). This means an entry on the row 3 is present on the left side, since (3,2) is already taken, the entry (3,4) is the only choice. Finally, the only entry on the right side lying in the column 4 is the (1,4) entry. This uses all of the entries in the inequality (6.4). Therefore, it is impossible to decompose the inequality (6.4) into a product of two or more inequalities with indices lying on the Bruhat inequalities on permutations.

Example 6.0.11 Let

\[
T = \left( \begin{array}{cccc}
  t_{11} & x_{12} & x_{13} & t_{14} \\
  x_{21} & t_{22} & t_{23} & x_{24} \\
  x_{31} & t_{32} & t_{33} & x_{34} \\
  t_{41} & x_{42} & x_{43} & t_{44}
\end{array} \right), \quad
P = \left( \begin{array}{ccc}
  \times & ? & \times \\
  \times & \times & ? \\
  \times & \times & ? \\
  \times & ? & \times
\end{array} \right)
\]

Therefore, we have

\[
C_T = \begin{cases}
  x_1 & 0 & 0 & -x_1 \\
  0 & x_2 & -x_2 & 0 \\
  0 & -x_2 & x_2 & 0 \\
  -x_1 & 0 & 0 & x_1
\end{cases} \quad \text{s.t. } x_1 \geq 0, \ x_1 + x_2 \geq 0
\]

62
The H-representation and thus the V-representation of the cone $C_T$ are also the same as those in the Example 6.0.8. Hence, we have the following generators for the cone $C_T$.

$$G_1 = \begin{pmatrix} 1 & 0 & 0 & -1 \\ 0 & -1 & 1 & 0 \\ 0 & 1 & -1 & 0 \\ -1 & 0 & 0 & 1 \end{pmatrix}, \quad G_2 = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & -1 & 0 \\ 0 & -1 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

Therefore, the conditions for TP$_2$-compleatability of the partial positive $T$ are the following,

$$H_T(G_1) \geq 1 \text{ and } H_T(G_2) \geq 1.$$ 

These are respectively equivalent to

$$t_{11}t_{23}t_{32}t_{44} > t_{14}t_{22}t_{33}t_{41} \text{ and } t_{22}t_{33} > t_{23}t_{32}$$

Thus, these polynomial inequalities together with positivity of the specified entries are sufficient conditions on the specified entries of $T$ to have a TP$_2$-completion. This also implies that the pattern $P$ is not TP$_2$-completable. The following is an example of a partial TP$_2$ matrix with pattern $P$ that does not have a TP$_2$-completion.

$$A = \begin{pmatrix} 1 & x_{12} & x_{13} & 1 \\ x_{21} & 1 & 1 & x_{24} \\ x_{31} & 1 & 3 & x_{34} \\ 1 & x_{42} & x_{43} & 2 \end{pmatrix}$$
The inequality $t_{11}t_{23}t_{32}t_{44} > t_{14}t_{22}t_{33}t_{41}$ in $A$ is equivalent to $2 > 3$ which is impossible. So there is no TP$_2$-completion for $A$.

The above example is in particular important since it gives an inequality on the entries of a TP$_2$ matrix that was not known before, that is $\frac{t_{11}t_{41}}{t_{14}t_{44}} > \frac{t_{22}t_{32}}{t_{23}t_{33}}$. This is already shown by the above example. However, since we have noticed this result in an early work without considering the relationship between TP$_2$ matrices and the Bruhat order, we give a proof for this result by only considering the definition of the TP$_2$ matrix.

**Theorem 6.0.12** For every TP$_2$ matrix (and therefore every TP matrix) $T = (t_{ij})$ of size $m$-by-$n$ with $m \geq 4$ and $n \geq 4$, we have

$$\frac{t_{pq}t_{sw}}{t_{pw}t_{st}} > \frac{t_{qu}t_{rv}}{t_{qw}t_{ru}}$$

with $1 \leq p < q < r < s \leq m$ and $1 \leq t < u < v < w \leq n$.

**Proof.** Using Lemma 2.1.1, it is enough to prove the statement for a matrix of size 4-by-4. Since $T$ is TP$_2$, every 2-by-2 minor, in particular the consecutive ones, are positive. Therefore, we have

$$\frac{t_{12}}{t_{12}} > \frac{t_{22}}{t_{32}} > \frac{t_{32}}{t_{42}} > \frac{t_{42}}{t_{44}} > \frac{t_{22}t_{41}t_{33}}{t_{32}t_{43}} > \frac{t_{22}t_{41}t_{33}}{t_{32}t_{43}} > \frac{t_{22}t_{41}t_{33}}{t_{32}t_{43}}.$$

Thus,

$$t_{11}t_{22} > \frac{t_{22}t_{41}t_{33}t_{14}t_{22}}{t_{44}t_{32}t_{23}}.$$

which implies

$$\frac{t_{11}t_{41}}{t_{14}t_{44}} > \frac{t_{22}t_{32}}{t_{23}t_{33}}.$$
Example 6.0.13 Consider the following partial $TP_2$ matrix $T$ with pattern $P$.

\[
T = \begin{pmatrix}
  t_{11} & t_{12} & x_{13} & x_{14} & t_{15} \\
  t_{21} & t_{22} & t_{23} & x_{24} & x_{25} \\
  x_{31} & t_{32} & t_{33} & t_{34} & x_{35} \\
  x_{41} & x_{42} & t_{43} & t_{44} & t_{45} \\
  t_{51} & x_{52} & x_{53} & t_{54} & t_{55}
\end{pmatrix}, \quad P = \begin{pmatrix}
  x & x & ? & ? & x \\
  x & x & ? & ? & ? \\
  ? & x & x & x & ? \\
  ? & ? & x & x & x \\
  x & ? & ? & x & x
\end{pmatrix}
\]

The parameterized pattern of $T$ if the following

\[
X = \begin{pmatrix}
  x_1 & x_2 & 0 & 0 & -x_1 - x_2 \\
  x_3 & x_4 & -x_3 - x_4 & 0 & 0 \\
  0 & -x_2 - x_4 & x_5 & x_2 + x_3 - x_5 & 0 \\
  0 & 0 & x_3 + x_4 - x_5 & x_6 & -x_3 - x_4 + x_5 - x_6 \\
  -x_1 - x_3 & 0 & 0 & -x_2 - x_4 + x_5 - x_6 & x_1 + x_2 + x_3 + x_4 - x_5 + x_6
\end{pmatrix}
\]

and the half-space inequalities obtained from $X$ are the following,

\[
\begin{align*}
x_1 & \geq 0, \\
x_1 + x_2 & \geq 0, \\
x_1 + x_3 & \geq 0, \\
x_1 + x_2 + x_3 + x_4 & \geq 0, \\
x_1 - x_4 + x_5 & \geq 0, \\
x_1 + x_2 + x_3 + x_4 - x_5 + x_6 & \geq 0.
\end{align*}
\]

Therefore, there is a 6-by-6 matrix of the following form that describes the cone with half-space inequalities, i.e. $m = 6$ and $d = 6$,
Running cdd+, will result in the following V-representation,

Thus, the H-representation of the cone is as follows

<table>
<thead>
<tr>
<th>H-representation</th>
</tr>
</thead>
<tbody>
<tr>
<td>begin</td>
</tr>
<tr>
<td>6     7      integer</td>
</tr>
<tr>
<td>0 1 0 0 0 0 0</td>
</tr>
<tr>
<td>0 1 1 0 0 0 0</td>
</tr>
<tr>
<td>0 1 0 1 0 0 0</td>
</tr>
<tr>
<td>0 1 1 1 1 0 0</td>
</tr>
<tr>
<td>0 1 0 0 -1 1 0</td>
</tr>
<tr>
<td>0 1 1 1 1 -1 1</td>
</tr>
<tr>
<td>end</td>
</tr>
</tbody>
</table>

Running cdd+, will result in the following V-representation,
Substituting the generators in the V-representation into the parameterized pattern $X$ will result the following generators for $C_T$

$$G_1 = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & -1 & 0 \\ 0 & 0 & -1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix}, \quad G_2 = \begin{pmatrix} 0 & 1 & 0 & 0 & -1 \\ 0 & -1 & 1 & 0 & 0 \\ 0 & 0 & -1 & 1 & 0 \\ 0 & 0 & 0 & -1 & 1 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix},$$

$$G_3 = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 \\ 1 & -1 & 0 & 0 & 0 \\ 0 & 1 & -1 & 0 & 0 \\ 0 & 0 & 1 & -1 & 0 \\ -1 & 0 & 0 & 1 & 0 \end{pmatrix}, \quad G_4 = \begin{pmatrix} 1 & -1 & 0 & 0 & 0 \\ -1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix},$$
These matrices imply the following polynomial inequalities.

\[
G_5 = \begin{pmatrix}
0 & 0 & 0 & 0 & 0 \\
0 & 1 & -1 & 0 & 0 \\
0 & -1 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
\end{pmatrix}, \quad G_6 = \begin{pmatrix}
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & -1 \\
0 & 0 & 0 & -1 & 1 \\
\end{pmatrix}
\]

Thus, these polynomial inequalities together with positivity of the specified entries are sufficient conditions on the specified entries of \(T\) to have a TP\(_2\)-completion. The second and third conditions imply that pattern \(P\) is not TP\(_2\)-completable.

**Example 6.0.14** Consider the following pattern \(P\).
The parameterized pattern of $\mathcal{P}$ is the following,

$$
\begin{pmatrix}
\times & \times & ? & ? & ? & \times \\
\times & \times & \times & ? & ? & ? \\
? & \times & \times & \times & ? & ? \\
? & ? & \times & \times & ? & ? \\
? & ? & ? & \times & \times & \times \\
\times & ? & ? & ? & \times & \times \\
\end{pmatrix}
$$

Running the cdd+ will result in the following generators for the cone $C_7$.

$$
G_1 = \begin{pmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 1 & -1 \\
0 & 0 & 0 & -1 & 1 \\
\end{pmatrix}, \\
G_2 = \begin{pmatrix}
0 & 1 & 0 & 0 & 0 & 0 & -1 \\
0 & -1 & 1 & 0 & 0 & 0 \\
0 & 0 & -1 & 1 & 0 \\
0 & 0 & 0 & 0 & -1 & 1 \\
0 & 0 & 0 & 0 & 0 & 0 \\
\end{pmatrix}, \\
G_3 = \begin{pmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
1 & -1 & 0 & 0 & 0 & 0 \\
0 & 1 & -1 & 0 & 0 & 0 \\
0 & 0 & 1 & -1 & 0 & 0 \\
0 & 0 & 0 & 1 & -1 \\
-1 & 0 & 0 & 0 & 1 & 0 \\
\end{pmatrix}, \\
G_4 = \begin{pmatrix}
1 & -1 & 0 & 0 & 0 & 0 \\
-1 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 \\
\end{pmatrix}
$$
Thus, these polynomial inequalities together with positivity of the specified entries of $T$

\[ G_5 = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & -1 & 0 & 0 & 0 \\ 0 & -1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}, \quad G_6 = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & -1 & 0 & 0 \\ 0 & 0 & -1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}, \quad G_7 = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & -1 & 0 & 0 \\ 0 & 0 & -1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \]

The above matrices imply the following polynomial inequalities on the specified entries of $T$.

\[ t_{55}t_{66} > t_{56}t_{65} \]
\[ t_{12}t_{23}t_{34}t_{45}t_{56} > t_{16}t_{22}t_{33}t_{44}t_{55} \]
\[ t_{21}t_{32}t_{43}t_{54}t_{65} > t_{22}t_{33}t_{44}t_{55}t_{61} \]
\[ t_{11}t_{22} > t_{12}t_{21} \]
\[ t_{22}t_{33} > t_{23}t_{32} \]
\[ t_{33}t_{44} > t_{34}t_{43} \]
\[ t_{44}t_{55} > t_{45}t_{54} \]

Thus, these polynomial inequalities together with positivity of the specified entries are sufficient conditions on the specified entries of $T$ to have a TP$_2$-completion.
Similarly to the previous example, the second and third conditions imply that pattern $\mathcal{P}$ is not $\text{TP}_2$-completable.

A pattern that has specified and unspecified entries in each line alternatively, is called checkerboard pattern. If the entry $(1, 1)$ in a checkerboard pattern is specified, the pattern is called odd checkerboard pattern, otherwise it is called even checkerboard pattern.

**Example 6.0.15** Consider the odd checkerboard pattern of size 4-by-4, $\mathcal{P}$ and the partial $\text{TP}_2$ matrix $T$ with pattern $\mathcal{P}$.

\[
T = \begin{pmatrix}
t_{11} & x_{12} & t_{13} & x_{14} \\
x_{21} & t_{22} & x_{23} & t_{24} \\
t_{31} & x_{32} & t_{33} & x_{34} \\
x_{41} & t_{42} & x_{43} & t_{44}
\end{pmatrix}, \quad \mathcal{P} = \begin{pmatrix}
\times & ? & ? \\
? & \times & ? \\
\times & ? & ? \\
? & \times & ?
\end{pmatrix}
\]

Thus, the parameterized pattern of $T$ and generators for the cone $C_T$, are the following, respectively.

\[
C_T = \left\{ \begin{pmatrix} x_1 & 0 & -x_1 & 0 \\ 0 & x_2 & 0 & -x_2 \\ -x_1 & 0 & x_1 & 0 \\ 0 & -x_2 & 0 & x_2 \end{pmatrix} \right\} \text{ s.t. } x_1 \geq 0, x_2 \geq 0, x_1 + x_2 \geq 0
\]

The generators of $C_T$ are the following

\[
G_1 = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & -1 \\ 0 & 0 & 0 & 0 \\ 0 & -1 & 0 & 1 \end{pmatrix}, \quad G_2 = \begin{pmatrix} 1 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 \\ -1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}
\]
Therefore, the conditions for a partial positive matrix $T$ with pattern $P$, odd checkerboard pattern of size 4-by-4, are

$$t_{22}t_{44} > t_{24}t_{42}, \ t_{11}t_{33} > t_{13}t_{31}.$$ 

Thus, $P$ is TP$_2$-completable.

**Example 6.0.16** Let $P$ be the even checkerboard pattern of size 4-by-4.

$$P = \begin{pmatrix}
? & \times & ? & \times \\
\times & ? & \times & ? \\
? & \times & ? & \times \\
\times & ? & \times & ? \\
\end{pmatrix}$$

Therefore,

$$\begin{equation}
C_T = \left\{ \begin{pmatrix}
0 & x_1 & 0 & -x_1 \\
x_2 & 0 & -x_2 & 0 \\
0 & -x_1 & 0 & x_1 \\
-x_2 & 0 & x_2 & 0 \\
\end{pmatrix} \right\} \text{ s.t. } x_1 \geq 0, \ x_2 \geq 0, \ x_1 + x_2 \geq 0
\end{equation}$$

$G_1 = \begin{pmatrix}
0 & 0 & 0 & 0 & 0 \\
1 & 0 & -1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
-1 & 0 & 1 & 0 & 0 \\
\end{pmatrix}$, \quad $G_2 = \begin{pmatrix}
0 & 1 & 0 & -1 \\
0 & 0 & 0 & 0 \\
0 & -1 & 0 & 1 \\
0 & 0 & 0 & 0 \\
\end{pmatrix}$

The conditions for TP$_2$-completability are the following inequalities together with having positive specified entries,

$$t_{21}t_{43} > t_{23}t_{41}, \ t_{12}t_{34} > t_{14}t_{32}.$$ 

Therefore, the even checkerboard pattern of size 4-by-4 is also TP$_2$-completable.
Example 6.0.17 Consider the 5-by-5 even checkerboard \( P \).

\[
P = \begin{pmatrix}
? \times ? \times ? \\
\times \times ? \times ? \\
? \times ? \times ? \\
\times \times ? \times ? \\
? \times ? \times ?
\end{pmatrix}
\]

Thus \( X \), the parameterized pattern of \( P \), is the following.

\[
X = \begin{pmatrix}
0 & x_1 & 0 & -x_1 & 0 \\
x_2 & 0 & x_3 & 0 & -x_2 - x_3 \\
0 & x_4 & 0 & -x_4 & 0 \\
-x_2 & 0 & -x_3 & 0 & x_2 + x_3 \\
0 & -x_1 - x_4 & 0 & x_1 + x_4 & 0
\end{pmatrix}
\]

Thus, the H-representation and V-representation os \( C_T \) are of the following form, respectively.

---

**H-representation**

```
begin
  8  5  integer
  0  1  0  0  0
  0  0  1  0  0
  0  1  1  0  0
  0  1  1  1  0
  0  0  1  1  0
  0  1  1  0  1
  0  1  1  1  1
  0  1  0  0  1
end
```
and

V-representation

begin

<table>
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<tr>
<th></th>
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<th>5</th>
<th>real</th>
</tr>
</thead>
<tbody>
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<td>0</td>
<td>1</td>
<td>-1 0</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0 -1</td>
</tr>
<tr>
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<td>0</td>
<td>0</td>
<td>1 0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0 1</td>
</tr>
</tbody>
</table>

end

We have

\[
G_1 = \begin{pmatrix}
0 & 0 & 0 & 0 & 0 \\
1 & 0 & -1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
-1 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0
\end{pmatrix}, \quad G_2 = \begin{pmatrix}
0 & 1 & 0 & -1 & 0 \\
0 & 0 & 0 & 0 & 0 \\
0 & -1 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0
\end{pmatrix}
\]

\[
G_3 = \begin{pmatrix}
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & -1 \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & -1 & 0 & 1 \\
0 & 0 & 0 & 0 & 0
\end{pmatrix}, \quad G_4 = \begin{pmatrix}
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & -1 & 0 \\
0 & 0 & 0 & 0 & 0 \\
0 & -1 & 0 & 1 & 0
\end{pmatrix}
\]

Considering the specified entries are positive, the conditions for TP_2-completeness are

\[t_{21}t_{43} > t_{23}t_{41}, \quad t_{12}t_{34} > t_{14}t_{32},\]

74
and

\[ t_{23}t_{45} > t_{25}t_{43}, \ t_{32}t_{54} > t_{34}t_{52}. \]

These are just conditions for being partial TP\(_2\), so the even checkerboard pattern of size 5-by-5 is TP\(_2\)-completable.

**Example 6.0.18** Consider the 5-by-5 odd checkerboard \( P \).

\[
P = \begin{pmatrix}
  \times & ? & \times & ? & \times \\
  ? & \times & ? & \times & ? \\
  \times & ? & \times & ? & \times \\
  ? & \times & ? & \times & ? \\
  \times & ? & \times & ? & \times 
\end{pmatrix}
\]

Thus, we have

\[
X = \begin{pmatrix}
  x_1 & 0 & x_2 & 0 & -x_1 - x_2 \\
  0 & x_3 & 0 & -x_3 & 0 \\
  x_4 & 0 & x_5 & 0 & -x_4 - x_5 \\
  0 & -x_3 & 0 & x_3 & 0 \\
  -x_1 - x_4 & 0 & -x_2 - x_5 & 0 & x_1 + x_2 + x_4 + x_5 
\end{pmatrix}
\]

By a process similar to previous examples we have

\[
G_1 = \begin{pmatrix}
  0 & 0 & 0 & 0 & 0 \\
  0 & 0 & 0 & 0 & 0 \\
  0 & 0 & 1 & 0 & -1 \\
  0 & 0 & 0 & 0 & 0 \\
  0 & 0 & -1 & 0 & 1 
\end{pmatrix}, \quad G_2 = \begin{pmatrix}
  0 & 0 & 0 & 0 & 0 \\
  0 & 1 & 0 & -1 & 0 \\
  0 & 0 & 0 & 0 & 0 \\
  0 & -1 & 0 & 1 & 0 \\
  0 & 0 & 0 & 0 & 0 
\end{pmatrix}
\]
The third inequality implies that the odd checkerboard of size 5-by-5 is not TP₂-completable. Since every 6-by-6 checkerboard (both odd and even), contains the 5-by-5 odd checkerboard, the above example implies that none of the checkerboards of size 6-by-6 or larger is TP₂-completable.

**Example 6.0.19** This example shows that the generators in the cone $C_T$, do not need to be 0,1 matrices. Let

$$
G_3 = \begin{pmatrix}
1 & 0 & 0 & 0 & -1 \\
0 & -1 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & -1 & 0 \\
-1 & 0 & 0 & 0 & 1
\end{pmatrix}, \quad G_4 = \begin{pmatrix}
0 & 0 & 1 & 0 & -1 \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0
\end{pmatrix}
$$

$$
G_5 = \begin{pmatrix}
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
1 & 0 & -1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
-1 & 0 & 1 & 0 & 0
\end{pmatrix}, \quad G_6 = \begin{pmatrix}
1 & 0 & -1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
-1 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0
\end{pmatrix}
$$

Considering the specified entries are positive, the conditions for TP₂-completablity are

$$
t_{33}t_{55} > t_{35}t_{53}, \quad t_{22}t_{44} > t_{24}t_{42},
$$

$$
t_{11}t_{24}t_{42}t_{55} > t_{15}t_{22}t_{44}t_{51}, \quad t_{13}t_{35} > t_{15}t_{33},
$$

$$
t_{31}t_{53} > t_{33}t_{51}, \quad t_{11}t_{33} > t_{13}t_{31}.
$$
We have
\[
P = \begin{pmatrix}
   \times & ? & ? & ? & \times \\
   ? & \times & ? & \times \\
   ? & ? & \times & \times \\
   ? & \times & ? & \times \\
   \times & ? & \times & ? & ? 
\end{pmatrix}
\]

The following matrices are the generators for \( C_7 \).

\[
X = \begin{pmatrix}
   x_1 & 0 & 0 & 0 & -x_1 \\
   0 & x_2 & 0 & -x_2 & 0 \\
   0 & 0 & -x_2 & x_2 & 0 \\
   0 & -x_2 & x_2 & -x_1 & 0 & x_1 \\
   -x_1 & 0 & x_1 & 0 & 0 
\end{pmatrix}
\]

This also implies that the pattern \( P \) is not TP\(_2\)-completable, since the conditions for TP\(_2\)-completability of the partial positive matrix \( T \) are the following

\[
t_{11}t_{24}t_{33}t_{42}t_{55}t_{53} > t_{15}t_{22}t_{34}t_{43}^2t_{51}
\]

and

\[
t_{22}t_{34}t_{45} > t_{24}t_{33}t_{42}.
\]

77
Notice that, it is impossible to decompose the inequality (6.5) into product of two or more inequalities such that the corresponding matrices are 0,1 matrices. This can be checked directly using the conditions that $G_i \sim_{ELS} 0$ and $G_i \geq_{DM} 0$. It is also a direct result from knowing that the conditions obtained here are minimal conditions.
Chapter 7

TP₂-completable Patterns

Proposition 7.0.1 An m-by-n pattern with no specified entry is TP₂-completable for all m, n ≥ 1.

Proof. This simply means that there is a TP₂ matrix of size m-by-n for all m, n ≥ 1, which is true by Example 2.1.2, and Lemma 2.1.1.

Lemma 7.0.2 Every pattern of size 2-by-n, for n ≥ 1, is TP₂-completable.

Proof. Let P be a pattern of size 2 × n and consider a partial TP₂ matrix T with pattern P as follows

\[ T = \begin{pmatrix} t_{11} & t_{12} & \ldots & t_{1k} \\ t_{21} & t_{22} & \ldots & t_{2k} \end{pmatrix} \]

where the entries are either specified or unspecified. Since T is partial TP₂, the specified entries are positive. Using Lemma 2.1.3, T is TP₂-completable if and only if there exist values for the unspecified entries such that

\[ \frac{t_{11}}{t_{21}} > \frac{t_{12}}{t_{22}} > \ldots > \frac{t_{1k}}{t_{2k}}. \]
Since every entry appears only once in the sequence of inequalities in (7.1), there is always a value for each of the unspecified entries such that the inequalities in (7.1) hold. Since $T$ is arbitrary, the pattern $P$ is $TP_2$-completable.

**Proposition 7.0.3** If a pattern $P$ is $TP_2$-completable, then its transpose $P^t$ is also $TP_2$-completable.

**Proof.** For every partial $TP_2$ matrix $T^t$ with the pattern $P^t$, the partial $TP_2$ matrix $(T^t)^t$ has the pattern $P$. Therefore there is a $TP_2$-completion for it, say $A$. Using Proposition 2.1.7, $A^t$ is a $TP_2$ matrix and a $TP_2$-completion for $T^t$.

**Lemma 7.0.4** Every pattern $P$ of size $m$-by-$n$ with only one unspecified entry is $TP_2$-completable.

**Proof.** First consider an $m$-by-$n$ pattern $P_1$ in which the only unspecified entry lies in the $(k, \ell)$ position with at least one of $k$ or $\ell$ in the set $\{1, m, n\}$. Let $T_1$ be any partial $TP_2$ matrix with pattern $P_1$. Using Lemmas 2.1.6 and 7.0.2, $T_1$ is $TP_2$-completable. Thus, the pattern $P_1$ is $TP_2$-completable. Now consider an $m$-by-$n$ pattern $P$ in which the only unspecified entry is in the $(k, \ell)$ position, with neither $k$ nor $\ell$ lying in the set $\{1, m, n\}$. Therefore, there is a 3-by-3 subpattern of $P$, say $P_2$, of the following form. Let $T_2$ be an arbitrary partial $TP_2$ matrix with pattern $P_2$, with specified entries $t_{ij}$ and unspecified entries $x_{ij}$.

\[
P_2 = \begin{pmatrix}
x & x & x \\
x & ? & x \\
x & x & x
\end{pmatrix}, \quad T_2 = \begin{pmatrix}
t_{11} & t_{12} & t_{13} \\
t_{21} & x_{22} & t_{23} \\
t_{31} & t_{32} & t_{33}
\end{pmatrix}.
\]
From the inequalities $\det T_2[\{1, 2\}, \{1, 2\}] > 0$ and $\det T_2[\{1, 2\}, \{2, 3\}] > 0$ we have

$$\frac{t_{12}t_{21}}{t_{11}} < x_{22} < \frac{t_{12}t_{23}}{t_{13}}$$

and from the inequalities $\det T_2[\{2, 3\}, \{2, 3\}] > 0$ and $\det T_2[\{2, 3\}, \{1, 2\}] > 0$ we have

$$\frac{t_{23}t_{32}}{t_{33}} < x_{22} < \frac{t_{11}t_{32}}{t_{31}}.$$ 

Since $T_2$ is partial $TP_2$, both of these intervals are non-empty. Moreover, these intervals have a nonempty intersection because $\frac{t_{12}t_{21}}{t_{11}} < \frac{t_{12}t_{23}}{t_{13}}$ and $\frac{t_{23}t_{32}}{t_{33}} < \frac{t_{11}t_{32}}{t_{31}}$. Therefore, there is a value for $x_{22}$ that makes $T_2$ a TP$_2$ matrix. Since this is true for every partial TP$_2$ matrix of the given pattern, the pattern $P_2$ is TP$_2$-completable. Now, consider a partial TP$_2$ matrix $T$ with pattern $P$, and with size larger than 3-by-3. Using Lemma 2.1.6, $T$ is TP$_2$-completable. \[\square\]

**Proposition 7.0.5** Every 3-by-3 pattern is TP$_2$-completable except the following eight patterns.

\[
P_1 = \begin{pmatrix}
  x & ? & x \\
  ? & x & x \\
  x & x & x 
\end{pmatrix}, \quad
P_2 = \begin{pmatrix}
  x & ? & x \\
  x & x & ? \\
  x & x & x 
\end{pmatrix}, \quad
P_3 = \begin{pmatrix}
  x & x & x \\
  ? & x & x \\
  x & ? & x 
\end{pmatrix}
\]

\[
P_4 = \begin{pmatrix}
  x & x & x \\
  x & x & ? \\
  x & ? & x 
\end{pmatrix}, \quad
P_5 = \begin{pmatrix}
  x & ? & x \\
  ? & x & x \\
  x & ? & x 
\end{pmatrix}, \quad
P_6 = \begin{pmatrix}
  x & ? & x \\
  x & x & ? \\
  ? & x & x 
\end{pmatrix}
\]

\[
P_7 = \begin{pmatrix}
  x & x & ? \\
  ? & x & x \\
  x & ? & x 
\end{pmatrix}, \quad
P_8 = \begin{pmatrix}
  ? & x & x \\
  x & x & ? \\
  x & ? & x 
\end{pmatrix}
\]

81
Proof. Let

\[ T_1 = \begin{pmatrix} 1 & x_{12} & 2 \\ x_{21} & 1 & 1 \\ 1 & 1 & 3 \end{pmatrix}, \quad T_2 = \begin{pmatrix} 2 & z_{12} & 1 \\ 1 & 1 & z_{23} \\ 1 & 3 & 1 \end{pmatrix}. \]

In order to have a TP₂-completion for the partial TP₂ matrices \( T_1 \) and \( T_2 \), the following inequalities must hold,

\[ \det T_1[\{1, 2\}, \{2, 3\}] > 0, \quad \det T_1[\{1, 3\}, \{1, 2\}] > 0, \]

and

\[ \det T_2[\{1, 2\}, \{1, 2\}] > 0, \quad \det T_2[\{1, 3\}, \{2, 3\}] > 0. \]

Thus, 2 < \( x_{12} \) < 1, and 3 < \( z_{12} \) < 2, respectively, which none of them is possible. Thus, there is no TP₂-completion for \( T_1 \) and \( T_2 \) which implies the patterns \( P_1 \) and \( P_2 \) are not TP₂-completable. Using Proposition 7.0.3, the pattern \( P_3 = P_2^t \), is also not TP₂-completable. Considering \( T_4 = R_3 T_1 R_3 \) as a partial TP₂ matrix with the pattern \( P_4 \), and using Lemma 2.1.8, the pattern \( P_4 \) is also not TP₂-completable. For the patterns \( P_5, \ldots, P_8 \), note that the entry (3, 3) in \( T_1 \) and the entry (3, 1) in \( T_2 \), do not appear in the inequalities considered for \( x_{12} \) and \( z_{12} \), thus the above discussion is valid for these patterns as well and they are not TP₂-completable.

A matrix \( A \) is said to contain matrix \( B \) **contiguously**, if \( B \) is a submatrix of \( A \), and both rows and columns of \( A \) containing \( B \) lie in a consecutive set of numbers.

**Lemma 7.0.6** Every partial TP₂ matrix \( T \) can be extended to any larger partial TP₂ matrix \( T_i \) that contains \( T \) contiguously.
Proof. It is enough to show that a new exterior column may be inserted into a partial TP$_2$ matrix $T$, such that the resulting matrix is still partial TP$_2$. Suppose $T$, is an $m$-by-$n$ partial TP$_2$ matrix, consider a column $C = (c_{i(n+1)})$ of size $m$-by-1. If the entry $c_{i(n+1)}$ is unspecified, then $t_{i(n+1)}$ is also unspecified, otherwise, $t_{i(n+1)}$ can be any positive number. Now, suppose $c_{i(n+1)}$ is an specified entry. Consider all 2-by-2 minors with all specified entries except $t_{i(n+1)}$. In each of them, $t_{i(n+1)}$ is in the lower right corner, so they all generate a lower bound for $t_{i(n+1)}$. Since there are finitely many of those minors, $t_{i(n+1)}$ can be chosen large enough so that it satisfies all of the inequalities. This can be repeated to all of the specified entries from first row to the last row. By the construction, the resulting matrix is partial TP$_2$ and the proof is complete.

The obvious analog of lemma 7.0.6 is not true for interior line insertions. That is, it is not always possible to insert a line to a partial TP$_2$ matrix and stay partial TP$_2$; see the example on page 14.

Lemma 7.0.7 Let $\mathcal{P}$ be a pattern that is not TP$_2$-completable. Then every pattern that contains $\mathcal{P}$ as a contiguous subpattern is also not TP$_2$-completable.

Proof. Suppose that pattern $\mathcal{P}_1$ contains the pattern $\mathcal{P}$ contiguously, and let $T$ be a partial TP$_2$ matrix with pattern $\mathcal{P}$ such that there is no TP$_2$-completion for $T$. Using Lemma 7.0.6, $T$ can be extended to a partial TP$_2$ matrix $T_1$ with pattern $\mathcal{P}_1$. If the pattern $\mathcal{P}_1$ is TP$_2$-completable, then there is a TP$_2$-completion for $T_1$, say $A_1$. But the submatrix of $A_1$ that corresponds to $T$ forms a TP$_2$-completion for $T$, which is a contradiction. 

83
Corollary 7.0.8 Every contiguous subpattern of a TP₂-completable pattern is TP₂-completable.

Lemma 7.0.9 Let \( P \) be an \( m \times n \) pattern. If column \( j \) of \( P \) for \( j = 2, 3, \ldots, n-1 \), is fully specified, then \( P \) is TP₂-completable iff the subpattern \( P_1 \) lying in the columns 1, 2, \ldots, \( j \), and the subpattern \( P_2 \) lying in the columns \( j, j+1, \ldots, n \) are both TP₂-completable.

Proof. Using Corollary 7.0.8, if \( P \) is TP₂-completable, then each of the subpatterns \( P_1 \) and \( P_2 \) is TP₂-completable. For the converse, consider a partial TP₂ matrix \( T \) with pattern \( P \). Let \( T_1 \) be the submatrix lying in the columns 1, 2, \ldots, \( j \), and \( T_2 \) be the submatrix lying in the columns \( j, j+1, \ldots, n \). By the assumption, there is a TP₂-completion for \( T_1 \) and \( T_2 \), say \( A_1 \) and \( A_2 \), respectively. Let \( A'_2 \) obtained from \( A_2 \) by deleting the first column. Using Lemma 2.1.6, the augmented matrix \([A_1 | A'_2]\) is a TP₂-completion for \( T \). Since \( T \) was arbitrary, the pattern \( P \) is TP₂-completable. \( \blacksquare \)

Lemma 7.0.9 is true if “column” is replaced by “row”.

Remark 7.0.10 Insertion of a new line into a partial TP₂ matrix (or a pattern) can change the TP₂-completability of the partial TP₂ matrix (or pattern).

Example 7.0.11 Let

\[
P_1 = \begin{pmatrix} \times & ? & \times \\ ? & \times & \times \\ \times & \times & \times \end{pmatrix}, \quad P'_1 = \begin{pmatrix} \times & \times & ? & \times \\ \times & \times & \times \\ \times & \times & \times \end{pmatrix}
\]

84
By Proposition 7.0.5, the pattern $P_1$ is not TP$_2$-completable, while by Lemmas 7.0.9 and 7.0.4 the pattern $P'$ which is obtained from $P_1$ by inserting the second column is TP$_2$-completable.

**Example 7.0.12** Let

$$P_2 = \begin{pmatrix} ? & x & x \\ x & ? & x \\ x & x & x \end{pmatrix}, \quad P'_2 = \begin{pmatrix} x & ? & x & x \\ x & x & ? \\ x & x & x & x \end{pmatrix}$$

By Proposition 7.0.5, the pattern $P_2$ is TP$_2$-completable, while using Lemma 7.0.6 and proposition 7.0.5, the pattern $P'_2$ resulting from inserting a fully specified exterior column from left to $P_2$ is not TP$_2$-completable.

Thus, inserting a new interior or exterior line may not preserve TP$_2$-completablility.

**Remark 7.0.13** The condition of being contiguous in Lemma 7.0.8 is necessary.

The following pattern $P_1$ is not TP$_2$-completable, however, by Lemmas 7.0.4 and 7.0.9, $P_2$, which contains $P_1$, but not continguously, is TP$_2$-completable.

$$P_1 = \begin{pmatrix} x & ? & x \\ ? & x & x \\ x & x & x \end{pmatrix}, \quad P_2 = \begin{pmatrix} x & x & ? & x \\ ? & x & x & x \\ x & x & x & x \end{pmatrix}$$

One of the questions about TP$_2$-completablility is: which line insertions, and to where, do not change the TP$_2$-completablility of a given pattern. Using Lemmas 7.0.9 and 2.1.6, it is clear that if a line in a pattern is fully specified, then inserting another fully specified line immediately before or after that line will not change the TP$_2$-completablility of the pattern. The following Lemma gives another case of line insertion for which the TP$_2$-completablility does not change.
Lemma 7.0.14 Let $P$ be an $m$-by-$n$ pattern, and let $P'$ be a pattern obtained from $P$ by inserting a line, between any two consecutive lines or outside of the boundaries with 0 or 1 specified entry. Then $P$ is $TP_2$-completable iff $P'$ is $TP_2$-completable.

Proof. Without loss of generality, suppose $P'$ is obtained from $P$ by inserting the $(j+1)$th column. Suppose $P$ is $TP_2$-completable and consider a partial $TP_2$ matrix $T'$ with pattern $P'$. Let $T$ be a $TP_2$-completion of $T'$ without considering the column $j+1$, this is possible because $P$ is $TP_2$-completable. First suppose there is no specified entry in the column $j + 1$ of $P'$, this is the same as inserting a line to the $TP_2$ matrix $T$ which is possible by Lemma 2.1.9. Now suppose the only unspecified entry in the column $j + 1$ of $P'$ is $p_{i(j+1)}$, for some $i = 1, 2, \ldots, m$. First consider the submatrix lying in the rows $1, 2, \ldots, i$. Using similar method used in the proof of Lemma 2.1.9, there is a value for $p_{i-1(j+1)}$ such that the resulting submatrix is partial $TP_2$. Repeating this process the submatrix lying in the rows $1, 2, \ldots, i$ is $TP_2$-completable. Similarly, the submatrix lying in the rows $i, i + 1, \ldots, m$ is $TP_2$-completable. These two submatrices together form a $TP_2$-completion for $T'$. Since $T'$ was arbitrary, the pattern $P'$ is $TP_2$-completable. Now suppose $P'$ is $TP_2$-completable, and let $T$ be a partial $TP_2$ matrix with pattern $P$. Let $T'$ be a partial $TP_2$ matrix obtained from $T$ by inserting a column $j$ with 0,1 specified entry. Using Corollary 5.1.3, the Bruhat inequalities are exactly the same since the column $j$ in every matrix $A \in CT'$ is zero. Thus $T$ has a $TP_2$-completion iff $T'$ has a $TP_2$-completion. Since $T$ was arbitrary, this implies that $P$ is $TP_2$-completable.

Corollary 7.0.15 An $m$-by-$n$ pattern with at most one specified entry in each row and each column is $TP_2$-completable.
Proof. Proposition 7.0.1 and Lemmas 7.0.14 and 7.0.6 imply this statement.

Lemma 7.0.16 If all of the unspecified entries in a pattern $\mathcal{P}$ occur in only one row (or column), then $\mathcal{P}$ is $TP_2$-completable.

Proof. Without loss of generality, suppose the unspecified entries occur only in row $i$ (the proof for a column is similar). By Lemma 2.1.6 it is enough to show that the $3 \times n$ (or $n \times 3$) subpattern lying in the rows $i-1, i, i+1$ is $TP_2$-completable. Again using Lemma 2.1.6 it is enough to consider the subpatterns of the following from.

\[
P_1 = \begin{pmatrix} \times & \times & \times \\ \times & ? & \times \\ \times & \times & \times \end{pmatrix}, \quad P_2 = \begin{pmatrix} \times & \times & \ldots & \times & \times \\ \times & ? & \ldots & ? & \times \\ \times & \times & \ldots & \times & \times \end{pmatrix},
\]

\[
P_3 = \begin{pmatrix} \times & \ldots & \times & \ldots & \times \\ ? & \ldots & ? & \ldots & ? \\ \times & \ldots & \times & \ldots & \times \end{pmatrix}
\]

By Lemma 7.0.4, the pattern $P_1$ is $TP_2$-completable. Every partial $TP_2$ matrix with pattern $P_2$ is $TP_2$-completable by using a similar method to that used in the proof of Lemma 2.1.9. Thus the pattern $P_2$ is also $TP_2$-completable. And the pattern $P_3$ is just the result of insertion of an interior line with no specified entries into a 2-by-$n$ $TP_2$ matrix which is possible by Lemma 7.0.14.

Note that, a simple proof for the above Lemma is to use Theorem 5.2.1. Since $C_7 = \{0\}$, there is no "extra" condition for $TP_2$-completability of the pattern. In other words, it is $TP_2$-completable.
Corollary 7.0.17 If a pattern $P$ is not TP$_2$-completable, then there exist at least two unspecified entries lying in different, adjacent rows and columns of the pattern.

According to the following Lemma, four patterns $P_1, P_2, P_3, P_4$ listed in the Proposition 7.0.5 and every pattern containing them contiguously are the only patterns that have exactly two unspecified entries and are not TP$_2$-completable.

Lemma 7.0.18 An $m$-by-$n$ pattern $P$ with exactly two unspecified entries is TP$_2$-completable if and only if it does not contiguously contain the patterns $P_1, P_2, P_3, P_4$ listed in Proposition 7.0.5.

Proof. If the unspecified entries do not lie in some contiguous rows or columns, then there is a fully specified line (row or column or both) between them, so the pattern can be divided into two subpatterns each with only one unspecified entry. By Lemmas 7.0.4 and 7.0.9, the pattern is TP$_2$-completable. If they both lie in the same row or column, by Corollary 7.0.16 the pattern is TP$_2$-completable. If one of the unspecified entries occurs in the corner and the other one lie on the contiguous row and column, it is enough to show that the 3-by-3 subpattern containing them is TP$_2$-completable.

Without loss of generality, consider the following case, with $A$ a partial TP$_2$ matrix with pattern $P$.

$$P = \begin{pmatrix} ? & \times & \times \\ \times & ? & \times \\ \times & \times & \times \end{pmatrix}, \quad A = \begin{pmatrix} x_{11} & a_{12} & a_{13} \\ a_{21} & x_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix}$$

From $detA[\{1, 2, 3\}, \{2, 3\}] > 0$ and $detA[\{2, 3\}, \{1, 2\}] > 0$, the unspecified entry $x_{22}$ satisfies, respectively,

$$\frac{a_{23}a_{32}}{a_{33}} < x_{22} < \frac{a_{12}a_{23}}{a_{13}}$$
and

\[ x_{22} < \frac{a_{21}a_{23}}{a_{31}}. \]

So if \( x_{22} \) is chosen such that the inequalities in (7.2) hold

\[ \frac{a_{23}a_{32}}{a_{33}} < x_{22} < \min\left\{ \frac{a_{12}a_{23}}{a_{13}}, \frac{a_{21}a_{23}}{a_{31}} \right\}, \quad (7.2) \]

then choosing large enough number \( x_{11} \) such that \( x_{11} > \frac{a_{12}a_{21}}{x_{22}} \) gives a TP2 matrix. Since the interval obtained in (7.2) is nonempty, \( \mathcal{P} \) is TP2-completable. Finally, if the unspecified entries lie in contiguous rows and columns and none of them occur in the corner, then the pattern contains one of the 3-by-3 subpatterns listed in Proposition 7.0.5, contiguously. by Lemma 7.0.8 the original pattern is not TP2-completable. \( \square \)
Bibliography


