Two-dimensional picture arrays and Parikh $q$–matrices

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Abstract. Based on the idea of “$q$–count” of certain subwords of a word and generalizing the notion of Parikh matrix of a word, the notion of Parikh $q$–matrix of a word over an ordered alphabet was introduced. On the other hand, with a two-dimensional picture array of symbols arranged in rows and columns, two kinds of upper triangular matrices, known as row and column Parikh matrices have also been introduced and investigated. Here combining these two kinds of matrices of a picture array, we introduce row/column Parikh $q$–matrix of an array, leading to the concept of $q$–ambiguity of a picture array. Results relating to $q$–ambiguity of picture arrays are derived in the context of these Parikh $q$–matrices of arrays.

1. Introduction

Extending the notion of the classical Parikh vector [12], which gives a count of each distinct symbol in a word, Mateescu et al. [11] introduced the concept of Parikh matrix mapping, which associates with a word $w$ over an ordered alphabet, a matrix, called Parikh matrix of the word $w$. This matrix gives more numerical information in terms of scattered subwords or simply called, subwords of the word $w$ and includes the Parikh vector in the second diagonal above the main diagonal. It is known that the Parikh matrix mapping is not injective. Yet there are words whose Parikh vectors are the same but these words have distinct Parikh matrices.

Generalizing the concept of Parikh matrix mapping, Parikh $q$–matrix mapping was introduced in [7]. This mapping which is a morphism, associates with a word $w \in \Sigma_k^*$, a $k \times k$ upper-triangular matrix, where $\Sigma_k$ is an ordered alphabet with $k$ symbols. The entries in this matrix are non-negative polynomials with integer coefficients in a variable $q$ and the polynomials represent a “$q$–count” of certain subwords of the word $w$. It is shown in [7] that the Parikh $q$–matrix mapping reduces to the Parikh matrix mapping when $q = 1$, by appropriately embedding the $k$–letter alphabet into a $(k + 1)$–letter alphabet. Injectivity is not possessed by the Parikh $q$–matrix mapping also but there are instances when two words have the same Parikh matrix...
but their Parikh $q$–matrices are different.

On the other hand a two-dimensional rectangular digitized picture array or simply an array, is an arrangement in rows and columns of symbols from a finite alphabet. Several combinatorial properties of arrays (or also called two-dimensional words) have been investigated in the literature (see, for example, [4, 5, 6, 9]). In [14], two kinds of matrices, known as row Parikh matrix and column Parikh matrix of a picture array, are defined and these matrices extend the notion of Parikh matrix from words to arrays. The notion of $M$–ambiguity of a picture array is thus introduced in [14] by considering two picture arrays to be $M$–equivalent if their row Parikh matrices are the same and their column Parikh matrices are the same and in particular, conditions that ensure $M$–ambiguity in binary and ternary words are obtained.

Here, based on the notion of $q$–Parikh matrix [7] and row/column Parikh matrices [14] of a picture array, we associate with a picture array, two types of matrices. We call these as row Parikh $q$–matrix and column Parikh $q$–matrix, leading to the notions of $q$–row and $q$–column equivalences of two picture arrays. The notion of $q$–ambiguity of a picture array $A$ is then introduced by defining array $A$ to be $q$–ambiguous if there is another picture array $B$ which is $q$–row and $q$–column equivalent to $A$. Several properties relating to $q$–ambiguity including conditions for $q$–ambiguity of row or column products for binary picture arrays are derived.

2. Preliminaries

A word $w = w_1w_2\ldots w_n$ $(n \geq 1)$ over a finite alphabet $\Sigma$, is a sequence of symbols $w_i \in \Sigma$ for $1 \leq i \leq n$. The set $\Sigma^*$ is the collection of all words that can be formed over $\Sigma$ and contains the empty word $\lambda$ with no symbols. The notation $|w|$ denotes the length of the word $w$. The number of occurrences of a symbol $a$ in a word $w$ is denoted by $|w|_a$. For any word $w = w_1w_2\ldots w_n$, we denote by $w^t$ the word $w$ written vertically. For example, if $w = aab$ over $\{a,b\}$, then $w^t$ is $a \cdot a \cdot b$. A word $u = x_1x_2\cdots x_n$ over an alphabet $\Sigma$ with $x_i \in \Sigma$ for $1 \leq i \leq n$, is called a subword of $w$, if $w = v_1x_1v_2x_2\cdots v_{n-1}x_{n-1}v_n$ where $v_i \in \Sigma^*$. Also, the count of distinct occurrences of a word $u$ as a subword in the word $w$ is denoted by $|w|_u$. For other notions related to subwords of a word and Parikh matrix of a word, we refer to [11]. The notion of Parikh $q$–matrix mapping introduced in [7], is now recalled. Let $\mathcal{M}[q]$ be the collection of polynomials in the variable $q$ with coefficients from the set $\mathbb{N}$ of all non-negative integers. Let $\mathcal{M}_k[q]$ be the set of $k \times k$ upper triangular matrices having entries in $\mathcal{M}[q]$. Throughout this paper, for $k \geq 1$, the ordered alphabet $\Sigma_k = \{a_1 < a_2 < \cdots < a_k\}$. When we use the alphabet $\{a < b\}$ or $\{a < b < c\}$, it is understood that $a = a_1$, $b = a_2$ and $c = a_3$.

**Definition 1** [7] The Parikh $q$–matrix mapping $\psi_q$ is the morphism $\psi_q : \Sigma_k^* \rightarrow \mathcal{M}_k[q]$ defined as follows: $\psi_q(\lambda) = I_k$, with $I_k$ the $k \times k$ identity matrix and $\psi_q(a_j) = (m_{rs})_{1 \leq r,s \leq k}$ where

(i) $m_{jj} = q$

(ii) $m_{ii} = 1$, for $1 \leq i \leq k$ and $i \neq j$

(iii) $m_{jj+1} = 1$, if $j < k$

and all other entries of $\psi_q(a_j)$ are zero.

Extending the mapping $\psi_q$ from $\Sigma_k$ to $\Sigma_k^*$, we have $\psi_q(w_1w_2\cdots w_n) = \psi_q(w_1)\psi_q(w_2)\cdots \psi_q(w_n)$, for $w_i \in \Sigma_k$ where the operation on the right side is the usual matrix multiplication.

**Example 1** Consider the word $w = abaac$ over $\Sigma_3 = \{a < b < c\}$, setting $a_1 = a$, $a_2 = b$, $a_3 = c$. The Parikh $q$–matrix of $w$ is given by
Definition 2 (corresponding notion in [10] considered for words. This notion is now recalled. A notion called partial sum of two Parikh $q$-matrices was introduced in [1], motivated by a corresponding notion in [10] for words. This notion is now recalled.

Theorem 1 ([7]) Suppose $w \in \Sigma_k^*$. Consider $w$ as a word over $\Sigma_{k+1}$ and let $\psi_q(w)$ be the Parikh $q$-matrix in $\mathcal{M}_{k+1}[q]$. Then $\psi_q(w)$ evaluated at $q = 1$ is the Parikh matrix $\psi_{\mathcal{M}}(w)$.

A notion called partial sum of two Parikh $q$-matrices was introduced in [1], motivated by a corresponding notion in [10] considered for words. This notion is now recalled.

Example 2 If we consider the words $x = ab^2$ and $y = bab$ over $\Sigma_3$, then we have

$$M_1 = \psi_q(x) = \begin{pmatrix} q & q^2 & (1 + q) \\ 0 & q^2 & (1 + q) \\ 0 & 0 & 1 \end{pmatrix}, \quad M_2 = \psi_q(y) = \begin{pmatrix} q & q & 1 \\ 0 & q & (1 + q) \\ 0 & 0 & 1 \end{pmatrix},$$

and $M_3 = M_1 \oplus M_2 = \begin{pmatrix} q^2 & (q + q^2) & (2 + q) \\ 0 & q^2 & 2(1 + q) \\ 0 & 0 & 1 \end{pmatrix}$.

where $M_3$ is the partial sum of the two Parikh $q$-matrices $M_1$ and $M_2$, but one can verify that it is not a Parikh $q$-matrix. In fact, if $M_3$ is a Parikh $q$-matrix, then the entry in the second row and third column of the matrix $M_3$ corresponds to the $q$-counting polynomial $S_{w,b}$ [7] and this polynomial can have only number one as constant term as shown in page 486 in [1] while it is number 2 in $M_3$.

3. Row and column Parikh $q$-matrices of a picture array

We first recall the definition of a picture array or simply called an array when it is clear from the context.

Let $m, n$ be two natural numbers. A picture array $A$ over $\Sigma_k$ of size $m \times n$ is a rectangular array of symbols from $\Sigma_k$ in $m$ number of rows and $n$ number of columns and is of the form

$$A = \begin{pmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{m1} & \cdots & a_{mn} \end{pmatrix}.$$ We also write $A$ as $A = (a_{ij})_{m \times n}$ or simply as $A = (a_{ij})$, if $m, n$ are understood. A subarray $X$ of $A$ with two rows and two columns, referred to as a $2 \times 2$ subarray, which is said to occur in $A$, is an array in the form

$$a_{ij} \cdots a_{ip}$$ for some $i, j, p, l$ with $1 \leq i < l \leq m$ and $1 \leq j < p \leq n$.

Let $\mathcal{PA}_k$ denote the set of all picture arrays over $\Sigma_k$. We denote by $M_1 \circ M_2$, the column concatenation and by $M_1 \circ M_2$, the row concatenation of picture arrays $M_1, M_2$ in $\mathcal{PA}_k$ respectively. We note that $M_1 \circ M_2$ is well defined if and only if the arrays have the same number of rows. Likewise $M_1 \circ M_2$ is well defined if and only if the arrays have the same number of columns.

We now define row Parikh $q$-matrix and column Parikh $q$-matrix of a picture array.
Definition 3 For $m, n \geq 1$, let $A \in \mathcal{PA}_k$ be an array over $\Sigma_k$. Let $x_i$ be the horizontal words in the $m$ rows of $A$ and $y_j$ be the vertical words in the $n$ columns of $A$. Let $\psi_q(x_i)$ and $\psi_q(y_j)$ be the Parikh $q$-matrices of $x_i$ and $y_j$ respectively. Then the row Parikh $q$-matrix $M^r_q(A)$ is defined as $M^r_q(A) = \psi_q(x_1) \oplus \cdots \oplus \psi_q(x_m)$ and the column Parikh $q$-matrix $M^c_q(A)$ is defined as $M^c_q(A) = \psi_q(y_1) \oplus \cdots \oplus \psi_q(y_n)$.

Example 3 Consider the array $A$ over $\Sigma_3 = \{a < b < c\}$ which is given by

$$
A = \begin{bmatrix}
a & b & a & a & b \\
b & a & b & a & b
\end{bmatrix}
$$

The Parikh $q$-matrices $\psi_q(x_i)$, $1 \leq i \leq 3$ of the words in the rows $x_1 = abaab$, $x_2 = aabba$, $x_3 = babab$ are respectively

$$
\begin{pmatrix}
q^3 & 2q^2 + q^3 & 1 + 2q + q^2 \\
0 & q^2 & 1 + q \\
0 & 0 & 1
\end{pmatrix},
\begin{pmatrix}
q^3 & 2q^2 + q^3 & 1 + 2q + q^2 \\
0 & q^2 & 1 + q \\
0 & 0 & 1
\end{pmatrix},
\begin{pmatrix}
q^2 & 2q^2 & 1 + 2q \\
0 & q^3 & 1 + q + q^2 \\
0 & 0 & 1
\end{pmatrix}
$$

The row Parikh $q$-matrix of $A$ is

$$
\begin{pmatrix}
q^6 & 6q^2 + 2q^3 & 3 + 6q + 2q^2 \\
0 & q^3 & 3 + 3q + q^2 \\
0 & 0 & 1
\end{pmatrix}
$$

In a similar manner, the column Parikh $q$-matrix of $A$ is

$$
\begin{pmatrix}
q^8 & 1 + 5q + 2q^2 & 4 + 2q \\
0 & q^5 & 5 + 2q \\
0 & 0 & 1
\end{pmatrix}
$$

4. Picture arrays and $q$-ambiguity

We first extend the notion of $M$-ambiguity [14] of a picture array to $q$-ambiguity.

Definition 4 For $m, n \geq 1$, two arrays $A, B \in \mathcal{PA}_k$ over $\Sigma_k$ are said to be

(i) $q$-row equivalent if $M^r_q(A) = M^r_q(B)$ and

(ii) $q$-column equivalent if $M^c_q(A) = M^c_q(B)$.

The arrays $A$ and $B$ are $q$-equivalent if $A$ and $B$ are both $q$-row equivalent and $q$-column equivalent and we say that $A$ (as well as $B$) is $q$-ambiguous. An array $A \in \mathcal{PA}_k$ is said to be $q$-unambiguous if it is not $q$-ambiguous.

Example 4 The array $A_1 \in \mathcal{PA}_3$ given by $A_1 = \begin{bmatrix} a & b & a & b & a \ b & a & a & b \ a & b & b & a \ \end{bmatrix}$ is $q$-ambiguous, since $M^r_q(A_1) = M^c_q(A_1)$.

$$
M^r_q(A_1) = \begin{pmatrix}
q^4 & 2q + 2q^2 & 2 + 2q \\
0 & q^4 & 2 + 2q \\
0 & 0 & 1
\end{pmatrix}
\quad \text{and} \quad
M^c_q(A_1) = \begin{pmatrix}
q^4 & 2 + 2q & 2 \\
0 & q^4 & 4 \\
0 & 0 & 1
\end{pmatrix}
$$

where the array $A_2$ is given by $\begin{bmatrix} b & a & a & b \\
 a & b & b & a \\
 a & b & b & a \\
\end{bmatrix}$.

In [14], the authors have given a condition for $M$-ambiguity of $A \in \mathcal{PA}_2$, which is stated in the following theorem.

Theorem 2 ([14]) An array $A \in \mathcal{PA}_2$ over $\Sigma_2 = \{a < b\}$ is $M$-ambiguous if either the $2 \times 2$ subarray $W_1$ or the $2 \times 2$ subarray $W_2$, occurs in $A$, where $W_1 = \begin{bmatrix} a & b & b & a \ b & a & a & b \ \end{bmatrix}$ and $W_2 = \begin{bmatrix} b & a & b \ a & b & a \ \end{bmatrix}$.

In the case of Parikh $q$-matrices for arrays, we observe the following interesting property in Lemma 1.
**Lemma 1** An array in \( \mathcal{PA}_2 \), having either \( W_1 = \begin{pmatrix} a & b \\ b & a \end{pmatrix} \) or \( W_2 = \begin{pmatrix} b & a \\ a & b \end{pmatrix} \) as its subarray, need not be \( q \)-ambiguous, treating the array as an array over \( \Sigma_3 \).

**Proof** Consider an array \( A = \begin{pmatrix} a & b & a \\ b & a & b \end{pmatrix} \in \mathcal{PA}_2 \) over \( \Sigma_3 = \{a < b < c\} \). Although the array \( A \) has a subarray \( \begin{pmatrix} a & b \\ b & a \end{pmatrix} \) which is \( q \)-ambiguous, \( A \) is \( q \)-unambiguous which can be seen as follows:

The arrays having the same \( q \)-column equivalent Parikh matrix as that of \( A \), are the following arrays:

\[
B_1 = \begin{pmatrix} b & a & a \\ a & b & b \end{pmatrix}, \quad B_2 = \begin{pmatrix} a & a & b \\ b & b & a \end{pmatrix}
\]

But each of these arrays has a row Parikh \( q \)-matrix which is different from the row Parikh \( q \)-matrix of \( A \) and hence \( A \) is \( q \)-unambiguous. □

We recall now two results from [2, 3].

**Lemma 2** [3] Let \( z \) be a word over \( \Sigma_2 = \{a < b\} \) with the property \( |z|_a = |z|_b \). Then \( x = abzba \) and \( y = bazab \) are \( q \)-equivalent, treating \( x, y \) as words over \( \Sigma_3 \).

**Lemma 3** ([2]) Let \( x, y \) be two words over \( \Sigma_2 \). Let \( |x|_a = |x|_b \) and \( |y|_a = |y|_b \). Then \( xy \) and \( yx \) are \( q \)-equivalent, treating \( x, y \) as words over \( \Sigma_3 \).

We now provide in Lemma 4, a special kind of \( q \)-ambiguous array in \( \mathcal{PA}_2 \), treating the array as an array over \( \Sigma_3 \). We make use of Lemmas 2 and 3.

**Lemma 4** The arrays \( M_1 \) and \( M_2 \) given below, over the binary alphabet \( \Sigma_2 = \{a < b\} \) are \( q \)-ambiguous, treating the arrays as arrays over \( \Sigma_3 = \{a < b < c\} \).

\[
M_1 = \begin{pmatrix} a & b & x & b & a \\ b & a & y & a & b \end{pmatrix}, \quad M_2 = \begin{pmatrix} b & a & y & a & b \\ a & b & x & b & a \end{pmatrix}
\]

where \( z_1, z_2 \in \Sigma_2, z_1 \neq z_2 \), and \( x, y, w \in \Sigma_2 \) such that \( |x| = |y| = |w|, |x|_a = |x|_b, |y|_a = |y|_b \) and \( |w|_a = |w|_b \).

**Proof** We note that the first two and the last two columns of \( M_1 \) and \( M_2 \) are the same. But they are in a different order. Also using Lemma 3, we have \( \psi_q(xwy) = \psi_q(xyw) = \psi_q(ywx) \). Therefore, \( M_2^q(M_1) = M_2^q(M_2) \).

To prove \( q \)-row equivalence, we use the Lemma 2. Thus \( \psi_q(z_1z_2z_2wz_2) = \psi_q(z_2z_1wz_1z_2) \). Also the first and third rows of the array \( M_1 \) are same as the third and first rows of the array \( M_2 \) respectively. Hence \( M_2^q(M_1) = M_2^q(M_2) \). □

Using the Lemma 3, conditions for two arrays are now obtained such that the array obtained by their column concatenation is \( q \)-ambiguous.

**Theorem 3** Let \( A, B \) be two arrays of sizes \( m \times n \) and \( m \times l \) respectively in \( \mathcal{PA}_2 \) over \( \Sigma_2 = \{a < b\} \) such that the \( i^{th} \) row of each of the arrays \( A, B \) has the same number \( a \)'s and \( b \)'s. Then the arrays \( A \circ B \) and \( B \circ A \) are \( q \)-ambiguous, treating the arrays as arrays over \( \Sigma_3 = \{a < b < c\} \).

**Proof** Since the \( i^{th} \) row of each of the arrays \( A, B \) has the same number \( a \)'s and \( b \)'s, the \( i^{th} \) row of each of \( A \circ B \) and \( B \circ A \) has the same number \( a \)'s and \( b \)'s. Therefore \( \psi_q(x_iy_i) = \psi_q(y_ix_i) \),
where \( x_i \) and \( y_i \) are the words in the \( i^{th} \) rows of \( A \) and \( B \) respectively. Thus using the Lemma 3, we have

\[
M^q(x \circ y) = \psi_q(x_1y_1) \oplus \psi_q(x_2y_2) \oplus \cdots \oplus \psi_q(x_my_m)
\]

Therefore \( A \circ B \) and \( B \circ A \) are \( q \)-row equivalent.

Since both the arrays \( A \circ B \) and \( B \circ A \) have the same columns but in a different order, we have \( M^q(A \circ B) = M^q(B \circ A) \). Thus they are \( q \)-column equivalent. Hence the arrays \( A \circ B \) and \( B \circ A \) are \( q \)-ambiguous.

**Remark 1** Corresponding result similar to the Theorem 3 remains true for \( A \circ B \), where \( A, B \) be two arrays of sizes \( m \times n \) and \( l \times n \) respectively in \( \mathcal{P} \mathcal{A}_2 \) over \( \Sigma_2 = \{a < b\} \) such that the \( i^{th} \) column of each of \( A, B \) has the same number \( a \)'s and \( b \)'s.

We recall now the \( q \)-weak ratio property [2] of words.

**Definition 5** Two words \( x, y \in \Sigma_2^* \) satisfy a \( q \)-weak ratio property, if they have weak ratio property [13] and satisfy one of the following conditions: for each \( 1 \leq i \leq k - 1 \),

(i) \( |x|_{a_i} = |x|_{a_{i+1}} \) and \( |y|_{a_i} = |y|_{a_{i+1}} \).

(ii) \( S_{x,a_i}(q) = q^{x|x_{a_{i+1}} - q^{|x|_{a_i}}} \).

and it is denoted by \( u \sim_q v \).

Using this \( q \)-weak ratio property, the authors characterized in [2], the words over a binary alphabet whose Parikh \( q \)-matrices commute.

**Lemma 5** ([2]) If two words \( u_1 \) and \( u_2 \) over binary alphabet \( \Sigma_2 \) satisfy \( q \)-weak ratio property, then their Parikh \( q \)-matrices commute, which means \( \psi_q(u_1u_2) = \psi_q(u_2u_1) \).

We extend Lemma 5 for a binary picture array as follows.

**Theorem 4** Let \( A, B \in \mathcal{P} \mathcal{A}_2 \) be two arrays of sizes \( m \times n \) and \( m \times l \) respectively with \( \Sigma_2 = \{a < b\} \) such that the \( i^{th} \) row of \( A \) and the \( i^{th} \) row of \( B \) satisfy \( q \)-weak ratio property. Therefore the arrays \( A \circ B \) and \( B \circ A \) are \( q \)-ambiguous, treating the arrays as arrays over \( \Sigma_3 = \{a < b < c\} \).

**Proof** For \( 1 \leq i \leq m \), let \( x_i \) and \( y_i \) be the words in the \( i^{th} \) rows of \( A \) and \( B \) respectively so that the words in the \( i^{th} \) rows of \( A \circ B \) and \( B \circ A \) are \( x_iy_i \) and \( y_ix_i \) respectively.

Let the \( i^{th} \) row of \( A \) and the \( i^{th} \) row of \( B \) satisfy \( q \)-weak ratio property. Then by Lemma 5 we have \( \psi_q(x_iy_i) = \psi_q(y_ix_i) \). Now we see that

\[
M^q(x \circ y) = \psi_q(x_1y_1) \oplus \psi_q(x_2y_2) \oplus \cdots \oplus \psi_q(x_my_m)
\]

Therefore \( A \circ B \) and \( B \circ A \) are \( q \)-row equivalent.

Since the columns of the arrays \( A \circ B \) and \( B \circ A \) are the same, arranged in different order, we have \( M^q(A \circ B) = M^q(B \circ A) \). Thus they are \( q \)-column equivalent. ■

**Remark 2** The converse of Theorem 4 need not be true always, as seen from the following example.
Example 5 Consider $A = \begin{pmatrix} a & b & b \\ b & b & a \\ a & b & b \end{pmatrix}$ and $B = \begin{pmatrix} b & b & a \\ a & b & b \\ a & b & b \end{pmatrix}$. Then we have

$$A \circ B = \begin{pmatrix} a & b & b & b & b & a \\ b & b & a & a & b & b \end{pmatrix}, B \circ A = \begin{pmatrix} b & b & a & a & b & b \\ a & b & b & b & b & a \end{pmatrix}.$$ 

Since the rows of $A \circ B$ and $B \circ A$ are the same except that they are in different order, we have $M^q(A \circ B) = M^q(B \circ A)$. Also $A \circ B$ and $B \circ A$ have the same columns again in different order so that $M^c(A \circ B) = M^c(B \circ A)$. Hence the arrays $A \circ B$ and $B \circ A$ are $q$-ambiguous. But the first rows of $A$ and $B$ are $abb$ and $bba$ respectively. It can be shown that they do not satisfy the $q$-weak ratio property.

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References

[1] Bera S and Mahalingam K, Some Algebraic Aspects of Parikh $q$–Matrices. *Int. J. Found. Comput. Sci.* 27(4): 479-500 (2016).
[2] Bera S and Mahalingam K, On commuting Parikh $q$–matrices. Manuscript submitted to Journal Fundamenta Informaticae (under review), 2016.
[3] Bera S, Ceterchi R, Mahalingam K and Subramanian K G, Parikh $q$–matrices and $q$–ambiguous words. *Int. J. Found. Comput. Sci.* Accepted for publication (To appear), 2018.
[4] Berth V and Tijdeman R, Balance properties of multi-dimensional words. *Theor. Comput. Sci.* 273(1-2): 197-224 (2002).
[5] Carpi A and de Luca A, Repetitions, Fullness and Uniformity In Two-Dimensional Words. *Int. J. Found. Comput. Sci.* 15(2): 355-383 (2004).
[6] Carpi A and de Luca A, Repetitions and Boxes in Words and Pictures. Jewels are Forever. 295-306 (1999).
[7] Egecioglu O and Ibarra O H, A $q$–Analogue of the Parikh Matrix Mapping. In: K.G. Subramanian et al. (eds.) “Formal Models, Languages and Applications”. *World Scientific* 97-111 (2017).
[8] Fosse S and Richomme G, Some characterizations of Parikh matrix equivalent binary words, *Inf. Process. Lett.* 92(2): 77-82(2004).
[9] Kulkarni M S and Mahalingam K, Two-Dimensional Palindromes and Their Properties. Proc. 11th Int. Conf. Language and Automata Theory and Applications (LATA 2017), Lecture Notes in Computer Science 10168: 155-167 (2017).
[10] Mateescu A, Algebraic aspects of Parikh matrices, Lecture Notes in Computer Science 3113 : 170-180 (2004).
[11] Mateescu A, Salomaa A, Salomaa K and Yu S, A Sharpening of the Parikh Mapping, *RAIRO-Theor. Inform. and Appl.* 35(6):551-564 (2001).
[12] Parikh R J, On context-free languages. *J. Association for Computing Machinery* 4: 570-581 (1966).
[13] Subramanian K G, Miin Huey A and Nagar A K, On Parikh Matrices, *Int. J. Found. Comp. Sci.* 20(2) : 211-219 (2009).
[14] Subramanian K G, Mahalingam K, Abdullah R and Nagar A K, Two-Dimensional Digitized Picture Arrays and Parikh Matrices, *Int. J. Found. Comput. Sci.* 24(3): 393-408 (2013).