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Invertibility of Matrices of Field Elements

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Summary. In this paper the theory of invertibility of matrices of field elements (see e.g. [5], [6]) is developed. The main purpose of this article is to prove that the left invertibility and the right invertibility are equivalent for a matrix of field elements. To prove this, we introduced a special transformation of matrix to some canonical forms. Other concepts as zero vector and base vectors of field elements are also introduced as a preparation.

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The papers [14], [3], [7], [17], [4], [13], [15], [10], [1], [12], [18], [16], [9], [8], [2], and [11] provide the terminology and notation for this paper.

1. Preliminaries

We use the following convention: x, y denote sets, n, m, i, j denote elements of $\mathbb{N}$, and K denotes a field.

Let K be a non empty zero structure and let us consider n. The functor 0_K^n yields a finite sequence of elements of K and is defined by:

(Def. 1) $0_K^n = n \mapsto 0_K$.

Let K be a non empty zero structure and let us consider n. Then 0_K^n is an element of (the carrier of $K)^n$.

In the sequel L denotes a non empty additive loop structure.

The following three propositions are true:

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(1) Every finite sequence x of elements of L is an element of (the carrier of $L)^{\operatorname{len} x}$.

(2) For all finite sequences x_1, x_2 of elements of L such that $\operatorname{len} x_1 = \operatorname{len} x_2$ holds $\operatorname{len}(x_1 + x_2) = \operatorname{len} x_1$.

(3) For all finite sequences x_1, x_2 of elements of L such that $\operatorname{len} x_1 = \operatorname{len} x_2$ holds $\operatorname{len}(x_1 - x_2) = \operatorname{len} x_1$.

In the sequel G is a non empty multiplicative loop structure.

Next we state four propositions:

(4) Let x_1, x_2 be finite sequences of elements of G and given i. If $i \in \operatorname{dom}(x_1 \bullet x_2)$, then $(x_1 \bullet x_2)(i) = (x_1)_i \cdot (x_2)_i$ and $(x_1 \bullet x_2)_i = (x_1)_i \cdot (x_2)_i$.

(5) Let x_1, x_2 be finite sequences of elements of L and i be a natural number. If $\operatorname{len} x_1 = \operatorname{len} x_2$ and $1 \leq i \leq \operatorname{len} x_1$, then $(x_1 + x_2)(i) = (x_1)_i + (x_2)_i$ and $(x_1 - x_2)(i) = (x_1)_i - (x_2)_i$.

(6) For every element a of K and for every finite sequence x of elements of K holds $-a \cdot x = (-a) \cdot x$ and $-a \cdot x = a \cdot -x$.

(7) For all finite sequences x_1, x_2, y_1, y_2 of elements of G such that $\operatorname{len} x_1 = \operatorname{len} x_2$ and $\operatorname{len} y_1 = \operatorname{len} y_2$ holds $x_1 \frown y_1 \bullet x_2 \frown y_2 = (x_1 \bullet x_2) \frown (y_1 \bullet y_2)$.

Let us consider K and let e_1, e_2 be finite sequences of elements of K. We introduce $|(e_1, e_2)|$ as a synonym of $e_1 \cdot e_2$.

Next we state several propositions:

(8) Let x, y be finite sequences of elements of K and a be an element of K. If $\operatorname{len} x = \operatorname{len} y$, then $a \cdot x \bullet y = a \cdot (x \bullet y)$ and $x \bullet a \cdot y = a \cdot (x \bullet y)$.

(9) For all finite sequences x, y of elements of K and for every element a of K such that $\operatorname{len} x = \operatorname{len} y$ holds $|(a \cdot x, y)| = a \cdot |(x, y)|$.

(10) For all finite sequences x, y of elements of K and for every element a of K such that $\operatorname{len} x = \operatorname{len} y$ holds $|(x, a \cdot y)| = a \cdot |(x, y)|$.

(11) Let x, y_1, y_2 be finite sequences of elements of K and a be an element of K. If $\operatorname{len} x = \operatorname{len} y_1$ and $\operatorname{len} x = \operatorname{len} y_2$, then $|(x, y_1 + y_2)| = |(x, y_1)| + |(x, y_2)|$.

(12) For all finite sequences x_1, x_2, y_1, y_2 of elements of K such that $\operatorname{len} x_1 = \operatorname{len} x_2$ and $\operatorname{len} y_1 = \operatorname{len} y_2$ holds $|(x_1 \frown y_1, x_2 \frown y_2)| = |(x_1, x_2)| + |(y_1, y_2)|$.

(13) For every element p_1 of (the carrier of $K)^n$ holds $p_1 \bullet n \mapsto 0_K = n \mapsto 0_K$.

Let us consider n, let us consider K, and let A be a square matrix over K of dimension n. We introduce $\operatorname{Inv} A$ as a synonym of $A^{\smile}$.

2. Zero Vector and Base Vectors of Field Elements

Next we state several propositions:

(14) $I_K^{0 \times 0} = 0_K^{0 \times 0}$ and $I_K^{0 \times 0} = \emptyset$.

(15) For every square matrix A over K of dimension 0 holds $A = \emptyset$ and $A = I_K^{0\times 0}$ and $A = 0_K^{0\times 0}$.

(16) Every square matrix over K of dimension 0 is invertible.

(17) For all square matrices A, B, C over K of dimension n holds $(A\cdot B)\cdot C = A\cdot(B\cdot C)$.

(18) Let A, B be square matrices over K of dimension n. Then A is invertible and $B = A^{\smile}$ if and only if $B\cdot A = I_K^{n\times n}$ and $A\cdot B = I_K^{n\times n}$.

(19) Let A be a square matrix over K of dimension n. Then A is invertible if and only if there exists a square matrix B over K of dimension n such that $B\cdot A = I_K^{n\times n}$ and $A\cdot B = I_K^{n\times n}$.

(20) For every finite sequence x of elements of K holds $|(x, 0_K^{\mathrm{len}\,x})| = 0_K$.

(21) For every finite sequence x of elements of K holds $|(0_K^{\mathrm{len}\,x}, x)| = 0_K$.

(22) For every element a of K holds $|(\langle 0_K\rangle, \langle a\rangle)| = 0_K$.

Let K be a non empty set, let n be a natural number, and let a be an element of K. Then $n \mapsto a$ is a finite sequence of elements of K.

Let us consider K and let n, i be natural numbers. The i-versor in K^n yields a finite sequence of elements of K and is defined by:

(Def. 2) The i-versor in $K^n = \mathrm{Replace}(n \mapsto 0_K, i, 1_K)$.

Next we state several propositions:

(23) For all natural numbers n, i holds len (the i-versor in K^n) $= n$.

(24) For all natural numbers i, n such that $1 \leq i \leq n$ holds (the i-versor in K^n)$(i) = 1_K$.

(25) Let i, j, n be natural numbers. Suppose $1 \leq i \leq n$ and $1 \leq j \leq n$ and $i \neq j$. Then (the i-versor in K^n)$(j) = 0_K$.

(26) For all natural numbers i, n such that $1 \leq i \leq n$ holds $I_K^{n\times n}(i) =$ the i-versor in K^n.

(27) For all i, j such that $1 \leq i \leq n$ and $1 \leq j \leq n$ holds ${I_K^{n\times n}}_{i,j} =$ (the i-versor in K^n)(j).

(28) Let A be a square matrix over K of dimension n. Then $A = 0_K^{n\times n}$ if and only if for all elements i, j of $\mathbb{N}$ such that $1 \leq i \leq n$ and $1 \leq j \leq n$ holds $A_{i,j} = 0_K$.

(29) Let A be a square matrix over K of dimension n. Then $A = I_K^{n\times n}$ if and only if for all elements i, j of $\mathbb{N}$ such that $1 \leq i \leq n$ and $1 \leq j \leq n$ holds $A_{i,j} = (i = j \rightarrow 1_K, 0_K)$.

3. Conditions of Invertibility

One can prove the following propositions:

(30) For all square matrices A, B over K of dimension n holds $(A \cdot B)^{\mathrm{T}} = B^{\mathrm{T}} \cdot A^{\mathrm{T}}$.

(31) For every square matrix A over K of dimension n such that A is invertible holds A^{T} is invertible and $(A^{\mathrm{T}})^{\smile} = (A^{\smile})^{\mathrm{T}}$.

(32) Let x be a finite sequence of elements of K and a be an element of K. Given i such that $1 \leq i \leq \operatorname{len} x$ and $x(i) = a$ and for every j such that $j \neq i$ and $1 \leq j \leq \operatorname{len} x$ holds $x(j) = 0_K$. Then $\sum x = a$.

(33) Let f_1, f_2 be finite sequences of elements of K. Then $\operatorname{dom}(f_1 \bullet f_2) = \operatorname{dom} f_1 \cap \operatorname{dom} f_2$ and for every i such that $i \in \operatorname{dom}(f_1 \bullet f_2)$ holds $(f_1 \bullet f_2)(i) = (f_1)_i \cdot (f_2)_i$.

(34) Let x, y be finite sequences of elements of K and given i. Suppose $\operatorname{len} x = m$ and $y = x \bullet$ the i-versor in K^m and $1 \leq i \leq m$. Then $y(i) = x(i)$ and for every j such that $j \neq i$ and $1 \leq j \leq m$ holds $y(j) = 0_K$.

(35) Let x be a finite sequence of elements of K. Suppose $\operatorname{len} x = m$ and $1 \leq i \leq m$. Then $|(x, \text{the } i\text{-versor in } K^m)| = x(i)$ and $|(x, \text{the } i\text{-versor in } K^m)| = x_i$.

(36) For all m, i such that $1 \leq i \leq m$ holds $|(\text{the } i\text{-versor in } K^m, \text{the } i\text{-versor in } K^m)| = 1_K$.

(37) Let a be an element of K and P, Q be square matrices over K of dimension n. Suppose that $n > 0$ and $a \neq 0_K$ and $P_{1,1} = a^{-1}$ and for every i such that $1 < i \leq n$ holds $P(i) =$ the i-versor in K^n and $Q_{1,1} = a$ and for every j such that $1 < j \leq n$ holds $Q_{1,j} = -a \cdot P_{1,j}$ and for every i such that $1 < i \leq n$ holds $Q(i) =$ the i-versor in K^n. Then P is invertible and $Q = P^{\smile}$.

(38) Let a be an element of K and P be a square matrix over K of dimension n. Suppose $n > 0$ and $a \neq 0_K$ and $P_{1,1} = a^{-1}$ and for every i such that $1 < i \leq n$ holds $P(i) =$ the i-versor in K^n. Then P is invertible.

(39) Let A be a square matrix over K of dimension n. Suppose $n > 0$ and $A_{1,1} \neq 0_K$. Then there exists a square matrix P over K of dimension n such that

(i) P is invertible,

(ii) $(A \cdot P)_{1,1} = 1_K$,

(iii) for every j such that $1 < j \leq n$ holds $(A \cdot P)_{1,j} = 0_K$, and

(iv) for every i such that $1 < i \leq n$ and $A_{i,1} = 0_K$ holds $(A \cdot P)_{i,1} = 0_K$.

(40) Let A be a square matrix over K of dimension n. Suppose $n > 0$ and $A_{1,1} \neq 0_K$. Then there exists a square matrix P over K of dimension n such that

(i) P is invertible,
(ii) $(P \cdot A)_{1,1} = 1_K$,
(iii) for every i such that $1 < i \leq n$ holds $(P \cdot A)_{i,1} = 0_K$, and
(iv) for every j such that $1 < j \leq n$ and $A_{1,j} = 0_K$ holds $(P \cdot A)_{1,j} = 0_K$.

(41) Let A be a square matrix over K of dimension n. Suppose $n > 0$ and $A_{1,1} \neq 0_K$. Then there exist square matrices P, Q over K of dimension n such that
(i) P is invertible,
(ii) Q is invertible,
(iii) $(P \cdot A \cdot Q)_{1,1} = 1_K$,
(iv) for every i such that $1 < i \leq n$ holds $(P \cdot A \cdot Q)_{i,1} = 0_K$, and
(v) for every j such that $1 < j \leq n$ holds $(P \cdot A \cdot Q)_{1,j} = 0_K$.

4. A Transformation of Matrix to Some Canonical Form

We now state the proposition

(42) Let D be a non empty set, m, n, i, j be elements of $\mathbb{N}$, and A be a matrix over D of dimension $m \times n$. Then $\mathrm{Swap}(A, i, j)$ is a matrix over D of dimension $m \times n$.

Let us consider K, let n be an element of $\mathbb{N}$, and let i_0 be a natural number. The functor $\mathrm{SwapDiagonal}(K, n, i_0)$ yields a square matrix over K of dimension n and is defined as follows:

(Def. 3) $\mathrm{SwapDiagonal}(K, n, i_0) = \mathrm{Swap}(I_K^{n \times n}, 1, i_0)$.

Next we state a number of propositions:

(43) Let n be an element of $\mathbb{N}$, i_0 be a natural number, and A be a square matrix over K of dimension n. Suppose $1 \leq i_0 \leq n$ and $A = \mathrm{SwapDiagonal}(K, n, i_0)$. Let i, j be natural numbers. Suppose $1 \leq i \leq n$ and $1 \leq j \leq n$. Suppose $i_0 \neq 1$. Then
(i) if $i = 1$ and $j = i_0$, then $A_{i,j} = 1_K$,
(ii) if $i = i_0$ and $j = 1$, then $A_{i,j} = 1_K$,
(iii) if $i = 1$ and $j = 1$, then $A_{i,j} = 0_K$,
(iv) if $i = i_0$ and $j = i_0$, then $A_{i,j} = 0_K$, and
(v) if $i \neq 1$ and $i \neq i_0$ or $j \neq 1$ and $j \neq i_0$, then if $i = j$, then $A_{i,j} = 1_K$ and if $i \neq j$, then $A_{i,j} = 0_K$.

(44) Let n be an element of $\mathbb{N}$, A be a square matrix over K of dimension n, and i be a natural number. If $1 \leq i \leq n$, then $(\mathrm{SwapDiagonal}(K, n, 1))_{i,i} = 1_K$.

(45) Let n be an element of $\mathbb{N}$, A be a square matrix over K of dimension n, and i, j be natural numbers. If $1 \leq i \leq n$ and $1 \leq j \leq n$, then if $i \neq j$, then $(\mathrm{SwapDiagonal}(K, n, 1))_{i,j} = 0_K$.

(46) Let given K, n, i_0 be elements of $\mathbb{N}$, and A be a square matrix over K of dimension n. Suppose that

(i) $1 \leq i_0$,

(ii) $i_0 \leq n$,

(iii) $i_0 = 1$, and

(iv) for all natural numbers i, j such that $1 \leq i \leq n$ and $1 \leq j \leq n$ holds if $i = j$, then $A_{i,j} = 1_K$ and if $i \neq j$, then $A_{i,j} = 0_K$.

Then $A = \mathrm{SwapDiagonal}(K, n, i_0)$.

(47) Let given K, n, i_0 be elements of $\mathbb{N}$, and A be a square matrix over K of dimension n. Suppose that

(i) $1 \leq i_0$,

(ii) $i_0 \leq n$,

(iii) $i_0 \neq 1$, and

(iv) for all natural numbers i, j such that $1 \leq i \leq n$ and $1 \leq j \leq n$ holds if $i = 1$ and $j = i_0$, then $A_{i,j} = 1_K$ and if $i = i_0$ and $j = 1$, then $A_{i,j} = 1_K$ and if $i = 1$ and $j = 1$, then $A_{i,j} = 0_K$ and if $i = i_0$ and $j = i_0$, then $A_{i,j} = 0_K$ and if $i \neq 1$ and $i \neq i_0$ or $j \neq 1$ and $j \neq i_0$, then if $i = j$, then $A_{i,j} = 1_K$ and if $i \neq j$, then $A_{i,j} = 0_K$.

Then $A = \mathrm{SwapDiagonal}(K, n, i_0)$.

(48) Let A be a square matrix over K of dimension n and i_0 be an element of $\mathbb{N}$. Suppose $1 \leq i_0 \leq n$. Then

(i) for every j such that $1 \leq j \leq n$ holds $(\mathrm{SwapDiagonal}(K, n, i_0) \cdot A)_{i_0,j} = A_{1,j}$ and $(\mathrm{SwapDiagonal}(K, n, i_0) \cdot A)_{1,j} = A_{i_0,j}$, and

(ii) for all i, j such that $i \neq 1$ and $i \neq i_0$ and $1 \leq i \leq n$ and $1 \leq j \leq n$ holds $(\mathrm{SwapDiagonal}(K, n, i_0) \cdot A)_{i,j} = A_{i,j}$.

(49) For every element i_0 of $\mathbb{N}$ such that $1 \leq i_0 \leq n$ holds $\mathrm{SwapDiagonal}(K, n, i_0)$ is invertible and $(\mathrm{SwapDiagonal}(K, n, i_0))^{\smile} = \mathrm{SwapDiagonal}(K, n, i_0)$.

(50) For every element i_0 of $\mathbb{N}$ such that $1 \leq i_0 \leq n$ holds $(\mathrm{SwapDiagonal}(K, n, i_0))^{\mathrm{T}} = \mathrm{SwapDiagonal}(K, n, i_0)$.

(51) Let A be a square matrix over K of dimension n and j_0 be an element of $\mathbb{N}$. Suppose $1 \leq j_0 \leq n$. Then

(i) for every i such that $1 \leq i \leq n$ holds $(A \cdot \mathrm{SwapDiagonal}(K, n, j_0))_{i,j_0} = A_{i,1}$ and $(A \cdot \mathrm{SwapDiagonal}(K, n, j_0))_{i,1} = A_{i,j_0}$, and

(ii) for all i, j such that $j \neq 1$ and $j \neq j_0$ and $1 \leq i \leq n$ and $1 \leq j \leq n$ holds $(A \cdot \mathrm{SwapDiagonal}(K, n, j_0))_{i,j} = A_{i,j}$.

(52) Let A be a square matrix over K of dimension n. Then $A = 0_K^{n \times n}$ if and only if for all i, j such that $1 \leq i \leq n$ and $1 \leq j \leq n$ holds $A_{i,j} = 0_K$.

5. Left/Right Invertibility and Invertibility

The following four propositions are true:

(53) Let A be a square matrix over K of dimension n. Suppose $A \neq 0_K^{n\times n}$. Then there exist square matrices B, C over K of dimension n such that

(i) B is invertible,

(ii) C is invertible,

(iii) $(B \cdot A \cdot C)_{1,1} = 1_K$,

(iv) for every i such that $1 < i \leq n$ holds $(B \cdot A \cdot C)_{i,1} = 0_K$, and

(v) for every j such that $1 < j \leq n$ holds $(B \cdot A \cdot C)_{1,j} = 0_K$.

(54) Let A, B be square matrices over K of dimension n. Suppose $B \cdot A = I_K^{n\times n}$. Then there exists a square matrix B_2 over K of dimension n such that $A \cdot B_2 = I_K^{n\times n}$.

(55) Let A be a square matrix over K of dimension n. Then the following statements are equivalent

(i) there exists a square matrix B_1 over K of dimension n such that $B_1 \cdot A = I_K^{n\times n}$,

(ii) there exists a square matrix B_2 over K of dimension n such that $A \cdot B_2 = I_K^{n\times n}$.

(56) For all square matrices A, B over K of dimension n such that $A \cdot B = I_K^{n\times n}$ holds A is invertible and B is invertible.

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