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Preprint No. M 06/07

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Müller (University of Wuppertal)**

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2006

**Impressum:**

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<http://www.tu-ilmenau.de/ifm/>

ISSN xxxx-xxxx

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## An eigenvalue conjecture of P.C. Müller (University of Wuppertal)

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### 1) Definitions

Let  $M = M_n = (m_{ij}) \in \mathbb{R}^{(n,n)}$  be an  $n \times n$  matrix with integer entries  $m_{ij}$  and  $U = U_n$  denote the  $n \times n$  unit matrix. The determinant  $\det(\lambda U - M) = f_M(\lambda)$  is called the *characteristic polynomial* of  $M$ . Value  $\lambda_0$  is an *eigenvalue* of  $M$  if and only if  $f_M(\lambda_0) = 0$ . Vector  $v_0 = v(\lambda_0) \neq \vec{0}$  is an *eigenvector* belonging to  $\lambda_0$  of  $M$  if and only if  $Mv_0 = \lambda_0 v_0$ . Matrices  $M$  and  $N$  are *similar* (briefly:  $M \sim N$ ) if and only if there is a regular matrix  $R$  with  $MR = RN$ ; that yields that both matrices  $M, N$  have the same eigenvalues (with the same multiplicities).

### 2) The conjecture

At the Elgersburg Workshop 2006, P.C. Müller posed the following *eigenvalue conjecture*: The eigenvalues of the matrix

$$A = A_n := (a_{ij}) \in \mathbb{R}^{(n,n)}$$

$$\text{and } a_{ij} = \begin{cases} -i, & \text{for } j = n - i \\ i, & \text{for } j = n - i + 1 \\ 0 & \text{otherwise} \end{cases}$$

are for  $n \in \mathbb{N}$ :  $\lambda_j = \lambda_j(A) = (-1)^{j-1} \cdot j, \quad j = 1, 2, \dots, n.$

### 3) The Proof

Let  $v_{ij} = (-1)^{n+1+i+j} \binom{j-1}{n-i}$ ,  $a_{ij}^* = (-1)^{j-1} \cdot j \cdot \binom{n-j}{i-j}$ . Matrices  $V = (v_{ij})$  and  $A^* = (a_{ij}^*)$  are triangular,  $a_{jj}^* = (-1)^{j-1} \cdot j$ , so these numbers are the eigenvalues of  $A^*$ .

Next we shall show

$$AV = VA^* \tag{1}$$

then the theorem follows.

(i) Matrix  $B = A \cdot V = (b_{ik})$  with

$$\begin{aligned} b_{ik} &= \sum_{j=1}^n a_{ij} v_{jk} \\ &= (-1)^{i+k} \cdot i \cdot \left\{ \binom{k-1}{i-1} + \binom{k-1}{i} \right\} \\ &= (-1)^{i+k} \cdot i \cdot \binom{k}{i} = (-1)^{i+k} \cdot k \cdot \binom{k-1}{i-1} \end{aligned} \tag{2}$$

is an upper triangular matrix.

(ii) Matrix  $B^* = V \cdot A^* = (b_{ik}^*)$  has entries

$$\begin{aligned} b_{ik}^* &= \sum_{j=1}^n v_{ij} \cdot a_{jk}^* \\ &= (-1)^{i+k} \cdot k \cdot \sum_{j=1}^n (-1)^{n+j} \binom{j-1}{n-i} \binom{n-k}{j-k}. \end{aligned} \tag{3}$$

A transformation  $j \longrightarrow n + 1 - j$  gives for the sum of (3)

$$\sum_{j=1}^n (-1)^{n+j} \binom{j-1}{n-i} \binom{n-k}{j-k} = - \sum_{j=1}^n (-1)^j \binom{n-j}{n-i} \binom{n-k}{j-1}.$$

From [G,K,P, page 169] we take the identity

$$\sum_{j=1}^n \binom{n-j}{m} \binom{s}{j-l} (-1)^j = (-1)^{n+m} \binom{s-m-1}{n-m-l} \quad (l, m, n \geq 0).$$

Replace in this equation  $m$  by  $(n-i)$ ,  $s$  by  $(n-k)$  and  $l$  by 1 to obtain

$$\begin{aligned} - \sum_{j=1}^n \binom{n-j}{n-i} \binom{n-k}{j-1} (-1)^j &= (-1)^{i-1} \binom{i-1-k}{i-1} \\ &= \frac{(-1)^{i-1} \cdot (i-1-k) \cdot (i-2-k) \cdot \dots \cdot (1-k)}{1 \cdot 2 \cdot \dots \cdot (i-1)} \\ &= \frac{(k-1) \cdot (k-2) \cdot \dots \cdot (k-(i-1))}{1 \cdot 2 \cdot \dots \cdot (i-1)} \\ &= \binom{k-1}{i-1}. \end{aligned} \tag{4}$$

and from equations (3),(4) follow  $b_{ik}^* = b_{ik}$ .

This proves (1) and the eigenvalue conjecture of P.C. Müller. □

#### 4) Remark concerning the motivation

We solve the problem for some small values of  $n$ , say,  $n = 1, 2, 3$ .

Given matrix  $E'_n = (e'_{ij})$  with

$$e'_{ij} = \begin{cases} 1, & \text{if } i + j = n + 1 \\ 0 & \text{otherwise.} \end{cases}$$

The matrix  $A'_n = E'_n \cdot A_n = (a'_{ij})$  is a lower triangular matrix with diagonal entries

$$a'_{jj} = n + 1 - j.$$

Therefore the eigenvalues of  $A'_n$  are  $\lambda'_j = j$ ,  $j = 1, 2, \dots, n$ .

Next calculate matrix  $V_n$  such that the  $j$ -th column of  $V_n$  represents an eigenvector to eigenvalue  $\lambda'_j = j$  of matrix  $A'_n$ :

$$V_1 = (1), \quad V_2 = \begin{pmatrix} 0 & 1 \\ 1 & -1 \end{pmatrix}, \quad V_3 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 1 & -2 \\ 1 & -1 & 1 \end{pmatrix}.$$

Clearly,  $V_n$  is non-singular and the inverse matrices are:

$$V_1^{-1} = (1), \quad V_2^{-1} = \begin{pmatrix} 1 & 1 \\ 1 & 0 \end{pmatrix}, \quad V_3^{-1} = \begin{pmatrix} 1 & 1 & 1 \\ 2 & 1 & 0 \\ 1 & 0 & 0 \end{pmatrix}.$$

Now calculate  $A_n^* = V_n^{-1} \cdot A_n \cdot V_n$ :

$$A_1^* = (1), \quad A_2^* = \begin{pmatrix} 1 & 0 \\ 1 & -2 \end{pmatrix}, \quad A_3^* = \begin{pmatrix} 1 & 0 & 0 \\ 2 & -2 & 0 \\ 1 & -2 & 3 \end{pmatrix}.$$

For  $n = 1, 2, 3$  is  $A_n \sim A_n^*$ . From this matrices  $V_n$  and  $A_n^*$  follow immediately the matrices  $V = (v_{ij})$  and  $A^* = (a_{ij}^*)$  (see 3)).

### 5) Concluding remark

Matrix  $A(x, y) = (a_{ij}(x, y))$ , where

$$a_{ij}(x, y) = \begin{cases} i \cdot x, & \text{if } i + j = n \\ i \cdot y, & \text{if } i + j = n + 1 \\ 0 & \text{otherwise,} \end{cases}$$

has for  $x, y \in \mathbb{R}$  and  $|x| = y > 0$  the following eigenvalues

$$\begin{aligned} n \text{ odd} : & \quad (-1)^{j-1} \cdot j \cdot y, \text{ and} \\ n \text{ even} : & \quad (-1)^j \cdot j \cdot x. \end{aligned}$$

### 6) Reference

[G,K,P]: Graham, R.L.; D.E. Knuth and O. Patashnik: Concrete Mathematics, Addison-Wesley Publishing Company, ... New York ... 1989