

Matrix Theory (EE5609) Assignment 14

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Abstract—This document proves the existence of inverse of Hilbert Matrix.

All the codes for the figure in this document can be found at

https://github.com/Arko98/EE5609/blob/master/Assignment_14

1 PROBLEM

Prove that the following matrix is invertible and \mathbf{A}^{-1} has integer entries.

$$\mathbf{A} = \begin{pmatrix} 1 & \frac{1}{2} & \cdots & \frac{1}{n} \\ \frac{1}{2} & \frac{1}{3} & \cdots & \frac{1}{n+1} \\ \vdots & \vdots & \cdots & \vdots \\ \frac{1}{n} & \frac{1}{n+1} & \cdots & \frac{1}{2n-1} \end{pmatrix}$$

2 SOLUTION

Let \mathbf{A}_3 be 3×3 matrix i.e

$$\mathbf{A}_3 = \begin{pmatrix} 1 & \frac{1}{2} & \frac{1}{3} \\ \frac{1}{2} & \frac{1}{3} & \frac{1}{4} \\ \frac{1}{3} & \frac{1}{4} & \frac{1}{5} \end{pmatrix} \quad (2.0.1)$$

Now we find the inverse of the matrix \mathbf{A}_3 as follows,

$$\begin{pmatrix} 1 & \frac{1}{2} & \frac{1}{3} & 1 & 0 & 0 \\ \frac{1}{2} & \frac{1}{3} & \frac{1}{4} & 0 & 1 & 0 \\ \frac{1}{3} & \frac{1}{4} & \frac{1}{5} & 0 & 0 & 1 \end{pmatrix} \quad (2.0.2)$$

$$\begin{matrix} R_2 = R_2 - \frac{1}{2}R_1 \\ R_3 = R_3 - \frac{1}{3}R_1 \end{matrix} \rightarrow \begin{pmatrix} 1 & \frac{1}{2} & \frac{1}{3} & 1 & 0 & 0 \\ 0 & \frac{1}{12} & \frac{1}{12} & -\frac{1}{2} & 1 & 0 \\ 0 & \frac{1}{12} & \frac{1}{45} & -\frac{1}{3} & 0 & 1 \end{pmatrix} \quad (2.0.3)$$

$$\begin{matrix} R_3 = R_3 - R_2 \end{matrix} \rightarrow \begin{pmatrix} 1 & \frac{1}{2} & \frac{1}{3} & 1 & 0 & 0 \\ 0 & \frac{1}{12} & \frac{1}{12} & -\frac{1}{2} & 1 & 0 \\ 0 & 0 & \frac{1}{180} & \frac{1}{6} & -1 & 1 \end{pmatrix} \quad (2.0.4)$$

$$\begin{matrix} R_2 = 12R_2 \\ R_3 = 180R_3 \end{matrix} \rightarrow \begin{pmatrix} 1 & \frac{1}{2} & \frac{1}{3} & 1 & 0 & 0 \\ 0 & 1 & 1 & -6 & 12 & 0 \\ 0 & 0 & 1 & 30 & -180 & 180 \end{pmatrix} \quad (2.0.5)$$

$$\begin{matrix} R_2 = R_2 - R_3 \\ R_1 = R_1 - R_3 \end{matrix} \rightarrow \begin{pmatrix} 1 & \frac{1}{2} & 0 & -9 & 60 & -60 \\ 0 & 1 & 0 & -36 & 192 & -180 \\ 0 & 0 & 1 & 30 & -180 & 180 \end{pmatrix} \quad (2.0.6)$$

$$\begin{matrix} R_1 = R_1 - \frac{1}{2}R_2 \end{matrix} \rightarrow \begin{pmatrix} 1 & 0 & 0 & 9 & -36 & 30 \\ 0 & 1 & 0 & -36 & 192 & -180 \\ 0 & 0 & 1 & 30 & -180 & 180 \end{pmatrix} \quad (2.0.7)$$

Hence we see that \mathbf{A}_3 is invertible and the inverse contains integer entries and \mathbf{A}_3^{-1} is given by,

$$\mathbf{A}_3^{-1} = \begin{pmatrix} 9 & -36 & 30 \\ -36 & 192 & -180 \\ 30 & -180 & 180 \end{pmatrix} \quad (2.0.8)$$

Let, \mathbf{A}_4 be 4×4 matrix as follows,

$$\mathbf{A}_4 = \begin{pmatrix} 1 & \frac{1}{2} & \frac{1}{3} & \frac{1}{4} \\ \frac{1}{2} & \frac{1}{3} & \frac{1}{4} & \frac{1}{5} \\ \frac{1}{3} & \frac{1}{4} & \frac{1}{5} & \frac{1}{6} \\ \frac{1}{4} & \frac{1}{5} & \frac{1}{6} & \frac{1}{7} \end{pmatrix} \quad (2.0.9)$$

Now, expressing \mathbf{A}_4 using \mathbf{A}_3 we get,

$$\mathbf{A}_4 = \begin{pmatrix} \mathbf{A}_3 & \mathbf{u} \\ \mathbf{u}^T & d \end{pmatrix} \quad (2.0.10)$$

where,

$$\mathbf{u} = \begin{pmatrix} \frac{1}{4} \\ \frac{1}{5} \\ \frac{1}{6} \end{pmatrix} \quad (2.0.11)$$

$$\mathbf{d} = \begin{pmatrix} \frac{1}{7} \end{pmatrix} \quad (2.0.12)$$

Now assuming \mathbf{A}_4 has an inverse, then from (2.0.10), the inverse of \mathbf{A}_4 can be written as follows,

$$\mathbf{A}_4^{-1} = \begin{pmatrix} \mathbf{A}_3^{-1} + \mathbf{A}_3^{-1}\mathbf{u}\mathbf{X}^{-1}\mathbf{u}^T\mathbf{A}_3^{-1} & -\mathbf{A}_3^{-1}\mathbf{u}\mathbf{X}^{-1} \\ -\mathbf{X}^{-1}\mathbf{u}^T\mathbf{A}_3^{-1} & \mathbf{X}^{-1} \end{pmatrix} \quad (2.0.13)$$

where,

$$\mathbf{X} = \mathbf{d} - \mathbf{u}^T\mathbf{A}_3^{-1}\mathbf{u} \quad (2.0.14)$$

Now, the assumption of \mathbf{A}_4 being invertible will hold if and only if \mathbf{A}_3 is invertible, which has been proved in (2.0.8) and \mathbf{X} from (2.0.14) is invertible. We now prove that \mathbf{X} is invertible as follows,

$$\mathbf{X} = \left(\frac{1}{7}\right) - \begin{pmatrix} \frac{1}{4} & \frac{1}{5} & \frac{1}{6} \end{pmatrix} \begin{pmatrix} 9 & -36 & 30 \\ -36 & 192 & -180 \\ 30 & -180 & 180 \end{pmatrix} \begin{pmatrix} \frac{1}{4} \\ \frac{1}{5} \\ \frac{1}{6} \end{pmatrix} \quad (2.0.15)$$

$$\Rightarrow \mathbf{X} = \left(\frac{1}{2800}\right) \quad (2.0.16)$$

Hence, \mathbf{X} is a square invertible matrix as it has linearly independent columns, hence \mathbf{X}^{-1} is given by,

$$\mathbf{X}^{-1} = (2800) \quad (2.0.17)$$

Hence, \mathbf{A}_4 is invertible. Now putting the values of \mathbf{A}_3^{-1} , \mathbf{X}^{-1} and \mathbf{u} we get,

$$\mathbf{A}_3^{-1} + \mathbf{A}_3^{-1}\mathbf{u}\mathbf{X}^{-1}\mathbf{u}^T\mathbf{A}_3^{-1} = \begin{pmatrix} 16 & -120 & 240 \\ -120 & 1200 & -2700 \\ 240 & -2700 & 6480 \end{pmatrix} \quad (2.0.18)$$

$$-\mathbf{A}_3^{-1}\mathbf{u}\mathbf{X}^{-1} = \begin{pmatrix} -140 \\ 1680 \\ -4200 \end{pmatrix} \quad (2.0.19)$$

$$-\mathbf{X}^{-1}\mathbf{u}^T\mathbf{A}_3^{-1} = \begin{pmatrix} -140 & 1680 & -4200 \end{pmatrix} \quad (2.0.20)$$

$$\mathbf{X}^{-1} = (2800) \quad (2.0.21)$$

Putting values from (2.0.18), (2.0.19), (2.0.20) and (2.0.21) into (2.0.13) we get,

$$\mathbf{A}_4^{-1} = \begin{pmatrix} 16 & -120 & 240 & -140 \\ -120 & 1200 & -2700 & 1680 \\ 240 & -2700 & 6480 & -4200 \\ -140 & 1680 & -4200 & 2800 \end{pmatrix} \quad (2.0.22)$$

Hence, from (2.0.22) we prove that, \mathbf{A}_4 is invertible and has integer entries. Hence by induction we conclude that as \mathbf{A}_{n-1} will always have inverse with integer entries hence, \mathbf{A}_n will also have inverse with integer entries for all integer n .

Hence Proved.