CALCULUS AND LINEAR ALGEBRA

MATHEMATICS-I

(18MAB101T)

DEPARTMENT OF MATHEMATICS

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Introduction

Matrices find many applications in scientific field and useful in many practical real life problem. For example:

- It is useful in the study of electrical circuits, quantum mechanics and optics
- Matrices play a role in calculation of battery power outputs, resistor conversion of electrical energy into another useful energy using Kirchhoff law of voltage and current
- Matrices can play a vital role in the projection of three dimensional images into two dimensional screens, creating the realistic decreeing motion
- It is useful in wave equation associated with transmitting power through transmission lines
- It can be used to crack or deformities in a solid

Introduction

- In machine learning we often have to deal with structural data, which is generally represented by matrix
- Car designers analyze eigenvalues in order to damp out noise so that the occupant have a quite ride
- It is also used in structural analysis to calculate buckling margins of safty
- Matrices are used in the ranking of web pages in the Google search
- It can also be used in generalization of analytical motion like experimental and derivatives to their high dimensional
- The usages of matrices in computer side application are encryption of message codes with the help of encryptions in the transmission of sensitive and private data
- Matrices are also used in robotics and automation in terms of base elements for the robot movements which are programmed with the calculation of matrices

Definition: Let A be a square matrix. If there exists a scalar λ and non-zero column matrix X such that $AX = \lambda X$, then the scalar λ is called an eigenvalue/characteristic value/latent value of A and X is called the corresponding eigenvector of A.

How to find: We can obtain the eigenvalues and eigenvectors through the following steps:

Step 1: Write the characteristic equation as
$| A-\lambda I |= \lambda^n - S_1\lambda^{n-1} + S_2\lambda^{n-2} + ... + (-1)^n S_n = 0, \quad n = 2, 3, 4 \cdots\cdots,$
where

$S_1 =$ sum of the main diagonal elements of A.

$S_2 =$ sum of the of minor of main diagonal elements of A $\cdots\cdots\cdots$

$S_n =$ determinant of A i.e $| A |$.

Step 2: Find the eigenvalues by factorizing the characteristic equation as $(\lambda_1 - a_1)(\lambda_2 - a_2)\cdots\cdots(\lambda_n - a_n) = 0$ or by synthetic division.

Step 3: Find the eigenvectors X for each value of λ from the linear system of equation $(A - \lambda_i I)X = 0, \quad i = 1, 2, 3\cdots\cdots$

Example: Find the eigenvalues and eigenvectors of $A = \begin{bmatrix} 2 & -2 & 3 \\ 1 & 1 & 1 \\ 1 & 3 & -1 \end{bmatrix}$

Solution:

$$| A - \lambda I | = \begin{vmatrix} 2-\lambda & -2 & 3 \\ 1 & 1-\lambda & 1 \\ 1 & 3 & -1-\lambda \end{vmatrix} = \lambda^3 - S_1\lambda^2 + S_2\lambda - S_3 = 0$$

$S_1 = 2 + 1 - 1 = 2,$

$$S_2 = \begin{vmatrix} 1 & 1 \\ 3 & -1 \end{vmatrix} + \begin{vmatrix} 2 & 3 \\ 1 & -1 \end{vmatrix} + \begin{vmatrix} 2 & -2 \\ 1 & 1 \end{vmatrix} = -4 - 5 + 4 = -5$$

$$S_3 = |A| = \begin{vmatrix} 2 & -2 & 3 \\ 1 & 1 & 1 \\ 1 & 3 & -1 \end{vmatrix} = 6 \quad \Rightarrow \quad \lambda^3 - 2\lambda^2 - 5\lambda - 6 = 0$$

Which can be factorize as
$(\lambda - 1)(\lambda - 3)(\lambda + 2) = 0 \quad \Rightarrow \quad \lambda = 1, \quad -2, \quad 3.$

Eigenvector for $\lambda = 1$: $\begin{bmatrix} 2-1 & -2 & 3 \\ 1 & 1-1 & 1 \\ 1 & 3 & -1-1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}.$

i.e. $\begin{bmatrix} 1 & -2 & 3 \\ 1 & 0 & 1 \\ 1 & 3 & -2 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}.$

$$\begin{aligned} x_1 - 2x_2 + 3x_3 &= 0 \\ x_1 + 0 + x_3 &= 0 \\ x_1 + 3x_2 - 2x_3 &= 0. \end{aligned}$$

$$\Rightarrow \quad \frac{x_1}{-3} = -\frac{x_2}{-3} = \frac{x_1}{3} \quad \Rightarrow \quad \frac{x_1}{-1} = \frac{x_2}{1} = \frac{x_1}{1} \quad \Rightarrow \quad X_1 = \begin{bmatrix} -1 \\ 1 \\ 1 \end{bmatrix}.$$

Eigenvector for $\lambda = -2$: $\begin{bmatrix} 4 & -2 & 3 \\ 1 & 3 & 1 \\ 1 & 3 & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$

$$\begin{aligned} 4x_1 - 2x_2 + 3x_3 &= 0 \\ x_1 + 3x_2 + x_3 &= 0. \end{aligned}$$

Solving the above equation as $x_3 = -(x_1 + 3x_3) \quad \Rightarrow x_1 - 11x_2 = 0$, then we get $X_2 = \begin{bmatrix} 11 \\ 1 \\ -14 \end{bmatrix}$.

Eigenvector for $\lambda = 3$: $$\begin{bmatrix} -1 & -2 & 3 \\ 1 & -2 & 1 \\ 1 & 3 & -4 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$$

$$\begin{aligned} -x_1 - 2x_2 + 3x_3 &= 0 \\ x_1 - 2x_2 + x_3 &= 0 \\ x_1 + 3x_2 - 4x_3 &= 0. \end{aligned}$$

$$\Rightarrow \quad \frac{x_1}{5} = -\frac{x_2}{-5} = \frac{x_1}{5} \quad \Rightarrow \quad \frac{x_1}{1} = \frac{x_2}{1} = \frac{x_1}{1} \quad \Rightarrow \quad X_3 = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix}.$$

Example: Find the eigenvalues and eigenvectors of $A = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{bmatrix}$

Solution:

$$| A - \lambda I | = \begin{vmatrix} 1-\lambda & 0 & 0 \\ 0 & 1-\lambda & 1 \\ 0 & 1 & 1-\lambda \end{vmatrix} = \lambda^3 - S_1\lambda^2 + S_2\lambda - S_3 = 0$$

$$S_1 = 1+1+1 = 3, \quad S_2 = \begin{vmatrix} 1 & 1 \\ 1 & 1 \end{vmatrix} + \begin{vmatrix} 1 & 0 \\ 0 & 1 \end{vmatrix} + \begin{vmatrix} 1 & 0 \\ 0 & 1 \end{vmatrix} = 0+1+1 = 2$$

$$S_3 = | A | = \begin{vmatrix} 1 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{vmatrix} = 0 \;\Rightarrow\; \lambda^3 - 3\lambda^2 + 2\lambda = 0 \;\Rightarrow \lambda(\lambda-1)(\lambda-2) = 0$$

$\Rightarrow \lambda = 0, \quad 1, \quad 2.$

Eigenvector for $\lambda = 0$: $\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$

$$\begin{aligned} x_1 + 0x_2 + 0x_3 &= 0 \\ 0x_1 + x_2 + x_3 &= 0 \\ 0x_1 + x_2 + x_3 &= 0. \end{aligned}$$

$\Rightarrow \quad x_1 = 0$ and $x_2 = -x_3$. If we take $x_3 = k \Rightarrow x_2 = -k$

$$\Rightarrow \quad X_1 = \begin{bmatrix} 0 \\ -k \\ k \end{bmatrix} = \begin{bmatrix} 0 \\ -1 \\ 1 \end{bmatrix}.$$

Eigenvector for $\lambda = 1$: $\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$

$$\begin{aligned} 0x_1 + 0x_2 + 0x_3 &= 0 \\ 0x_1 + 0x_2 + x_3 &= 0 \\ 0x_1 + x_2 + 0x_3 &= 0 \end{aligned}$$

$\Rightarrow \quad x_2 = 0 \;$ and $\; x_3 = 0.$ Taking $\; x_1 = k \quad \Rightarrow \quad X_2 = \begin{bmatrix} k \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}.$

Eigenvector for $\lambda = 2$: $\begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 1 \\ 0 & 1 & -1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$

$$\begin{aligned} -x_1 + 0x_2 + 0x_3 &= 0 \\ 0x_1 - x_2 + x_3 &= 0 \\ 0x_1 + x_2 - x_3 &= 0 \end{aligned}$$

$\Rightarrow \; x_1 = 0$ and $x_2 = x_3$. If $x_3 = k \;\Rightarrow\; x_2 = k \Rightarrow X_3 = \begin{bmatrix} 0 \\ k \\ k \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \\ 1 \end{bmatrix}.$

Example: Find the eigenvalues and eigenvectors of $A = \begin{bmatrix} 2 & 1 & 1 \\ 2 & 3 & 2 \\ 3 & 3 & 4 \end{bmatrix}$

Solution: Here $\mid A - \lambda I \mid = \lambda^3 - 9\lambda^2 + 15\lambda - 7 = 0 \Rightarrow \lambda = 1, \;\; 1, \;\; 7,$ some eigenvalues are repeated. Therefore we find the eigenvectors as:

Eigenvector for $\lambda = 7$: $\begin{bmatrix} -5 & 1 & 1 \\ 2 & -4 & 2 \\ 3 & 3 & -3 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$

$$\Rightarrow \quad \frac{x_1}{12-6} = -\frac{x_2}{-6-6} = \frac{x_3}{6+12} \quad \Rightarrow \quad \frac{x_1}{1} = \frac{x_2}{2} = \frac{x_3}{3} \quad \Rightarrow \quad X_1 = \begin{bmatrix} 1 \\ 2 \\ 3 \end{bmatrix}.$$

Eigenvector for $\lambda = 1$: $\begin{bmatrix} 1 & 1 & 1 \\ 2 & 2 & 2 \\ 3 & 3 & 3 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$

Here we observe that all rows are linearly dependent

$$\Rightarrow \quad x_1 + x_2 + x_3 = 0.$$

Now we will construct two linearly independent eigenvectors from the same equation assuming the followings:

$$\text{Assume } x_1 = 0 \quad \Rightarrow x_3 = -x_2 \quad \text{hence} \quad X_2 = \begin{bmatrix} 0 \\ k \\ -k \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \\ -1 \end{bmatrix}.$$

Similarly assuming

$$x_2 = 0 \quad \Rightarrow x_3 = -x_1 \quad \text{hence} \quad X_3 = \begin{bmatrix} k \\ 0 \\ -k \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \\ -1 \end{bmatrix}.$$

Symmetric Matrix: A real matrix A is said to be symmetric if $A = A^T$, where T stands for transpose.
Orthogonal Matrix: Let X_1 and X_2 be two column matrices of same order. Then X_1 and X_2 are said to be orthogonal if $X_1^T X_2 = 0$
Example: Find the eigenvalues and eigenvectors of

$$A = \begin{bmatrix} 6 & -2 & 2 \\ -2 & 3 & -1 \\ 2 & -1 & 3 \end{bmatrix}$$

Solution: Here we can see that $A = A^T$, which implies it is a symmetric matrix.
Now $| A - \lambda I | = \lambda^3 - 12\lambda^2 + 36\lambda - 32 = 0 \Rightarrow \lambda = 2, \; 2, \; 8$, some eigenvalues are repeated. Therefore we find the eigenvectors as:

Eigenvector for $\lambda = 8$:

$$\begin{bmatrix} -2 & -2 & 2 \\ -2 & -5 & -1 \\ 2 & -1 & -5 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$$

$$\Rightarrow \quad \frac{x_1}{25-1} = -\frac{x_2}{10+2} = \frac{x_3}{2+10} \quad \Rightarrow \quad \frac{x_1}{2} = \frac{x_2}{-1} = \frac{x_3}{1} \quad \Rightarrow \quad X_1 = \begin{bmatrix} 2 \\ -1 \\ 1 \end{bmatrix}.$$

Eigenvector for $\lambda = 2$: $\begin{bmatrix} 4 & -2 & 2 \\ -2 & 1 & -1 \\ 2 & -1 & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$ Here one can observe that all rows are linearly dependent $\Rightarrow \quad -2x_1 + x_2 - x_3 = 0.$

Assume $x_1 = 0 \quad \Rightarrow x_3 = x_2$ hence $X_2 = \begin{bmatrix} 0 \\ k \\ k \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \\ 1 \end{bmatrix}.$

For the nest eigenvalue $\lambda = 2$, we consider $X_3 = \begin{bmatrix} a \\ b \\ c \end{bmatrix}$

As the matrix A is symmetric, so the eigenvectors are orthogonal.

$$\therefore X_1^T X_3 = 0 \quad \Rightarrow \begin{bmatrix} 2 & -1 & 1 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} = 0 \quad \Rightarrow 2a - b + c = 0. \text{ again}$$

$$X_2^T X_3 = 0 \quad \Rightarrow \begin{bmatrix} 0 & 1 & 1 \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix} = 0 \quad \Rightarrow b + c = 0.$$

Solving the above two equations we get $a = b = -c \qquad \Rightarrow X_3 = \begin{bmatrix} 1 \\ 1 \\ -1 \end{bmatrix}.$

Example: Find the eigenvalues and eigenvectors of

$$A = \begin{bmatrix} 2 & -1 & 1 \\ -1 & 2 & -1 \\ 1 & -1 & 2 \end{bmatrix}.$$

Property 1: Every square matrix and it's transpose has same eigenvalues.

Example: If $A = \begin{bmatrix} 1 & -2 \\ -5 & 4 \end{bmatrix} \quad \Rightarrow \lambda^2 - 5\lambda - 6 = 0 \quad \Rightarrow \lambda = 6, \quad -1.$

$A^T = \begin{bmatrix} 1 & -5 \\ -2 & 4 \end{bmatrix} \quad \Rightarrow \lambda^2 - 5\lambda - 6 = 0 \quad \Rightarrow \lambda = 6, \quad -1.$

Property 2: If $\lambda_1,\ \lambda_2,\ \lambda_3, \cdots\cdots \lambda_n$ are the eigenvalues of the matrix A then $\frac{1}{\lambda_1},\ \frac{1}{\lambda_2},\ \frac{1}{\lambda_3}, \cdots\cdots \frac{1}{\lambda_n}$ are the eigenvalues of A^{-1}.

Proof: Let λ be the eigenvalue of a matrix $A \quad \Rightarrow \quad AX = \lambda X$, where X is an eigenvector $X \neq 0$. If we multiply A^{-1} with $AX = \lambda X$ as below:

$A^{-1}AX = A^{-1}\lambda X \quad \Rightarrow IX = \lambda A^{-1}X \quad \Rightarrow \frac{1}{\lambda}X = A^{-1}X.$

$\therefore \frac{1}{\lambda}$ is the eigenvalue of A^{-1}.

Property 3: If $\lambda_1,\ \lambda_2,\ \lambda_3,\cdots\cdots\lambda_n$ are the eigenvalues of the matrix A, then $\lambda_1^2,\ \lambda_2^2,\ \lambda_3^2,\cdots\cdots\lambda_n^2$ are the eigenvalues of A^2.

Proof: Let λ be the eigenvalue of a matrix A.
$\therefore AX = \lambda X$, where X is an eigenvector $X \neq 0$. If we multiply A with $AX = \lambda X$ as below:

$$AAX = A\lambda X \quad \Rightarrow A^2X = \lambda AX \quad \Rightarrow A^2X = \lambda^2 X \ .$$

$\therefore \lambda^2$ is the eigenvalue of A^2.

Property 4: If $\lambda_1,\ \lambda_2,\ \lambda_3,\cdots\cdots\lambda_n$ are the eigenvalues of the matrix A, then $k\lambda_1,\ k\lambda_2,\ k\lambda_3,\cdots\cdots k\lambda_n$ are the eigenvalues of kA.

Proof: Let λ be the eigenvalue of a matrix A.
$\therefore AX = \lambda X \quad \Rightarrow \quad kAX = k(\lambda X) = (k\lambda)X.$

$\therefore k\lambda$ is the eigenvalue of kA.

Property 5: The eigenvalues of a real symmetric matrix are all real.

Proof: Let λ be the eigenvalue of a matrix A.

$$AX = \lambda X \tag{1}$$

Taking conjugate on both sides of (1) we get $\bar{A}\bar{X} = \bar{\lambda}\bar{X}$. As A is real

$\therefore A = \bar{A} \quad \Rightarrow A\bar{X} = \bar{\lambda}\bar{X}$. Taking transpose on both side one can get

$(A\bar{X})^T = (\bar{\lambda}\bar{X})^T \quad \Rightarrow \quad \bar{X}^T A^T = \bar{\lambda}^T \bar{X}^T \quad \Rightarrow \bar{X}^T A = \bar{\lambda}\bar{X}^T$

($\because A$ is symmetric $A = A^T$ and λ is a scalar). Now post multiply by X

$\bar{X}^T AX = \bar{\lambda}\bar{X}^T X \quad \Rightarrow \bar{X}^T \lambda X = \bar{\lambda}\bar{X}^T X \quad \Rightarrow \lambda \bar{X}^T X = \bar{\lambda}\bar{X}^T X \quad \Rightarrow \lambda = \bar{\lambda}$.

Property 6: If $\lambda_1,\ \lambda_2,\ \lambda_3, \cdots\cdots \lambda_n$ are the eigenvalues of the matrix A, then trace of A=sum of eigenvalues $= \lambda_1 + \lambda_2 + \lambda_3, \cdots\cdots + \lambda_n$ and product of eigenvalues of A=$\mid A \mid$ i.e $\mid A \mid = \lambda_1.\lambda_2.\lambda_3, \cdots\cdots \lambda_n$.

Property 6: Eigenvalues of a triangular matrix are just the diagonal elements of the matrix.

Proof: Let $A = \begin{bmatrix} a_{11} & 0 & 0 \\ a_{21} & a_{22} & 0 \\ a_{31} & a_{32} & a_{33} \end{bmatrix}$

$$\Rightarrow | A - \lambda I | = \begin{vmatrix} a_{11} - \lambda & 0 & 0 \\ a_{21} & a_{22} - \lambda & 0 \\ a_{31} & a_{32} & a_{33} - \lambda \end{vmatrix} = 0$$

$$\Rightarrow (a_{11} - \lambda)(a_{22} - \lambda)(a_{33} - \lambda) = 0.$$

$$\Rightarrow \lambda = a_{11}, \quad a_{22}, \quad a_{33}.$$

Example: Find the sum and product of the eigenvalues of a matrix
$A = \begin{bmatrix} -2 & 2 & -3 \\ 2 & 1 & 6 \\ -1 & -2 & 0 \end{bmatrix}$.

Proof: We know sum of eigenvalues of A=Sum of he leading diagonal elements of A=trace of A=-2+1+0=-1.

Product of the
eigenvalues=$\mid A \mid = -2(0-12) - 2(0-6) - 3(-4+1) = 45$.

Example: Two of the eigenvalues of $A = \begin{bmatrix} 3 & -1 & 1 \\ -1 & 5 & -1 \\ 1 & -1 & 3 \end{bmatrix}$ are 3 and 6.

Find the eigenvalues of A^{-1}.

Solution: Let $\lambda_1,\ \lambda_2,\ \lambda_3$ are eigenvalues of A.
$\Rightarrow \lambda_1 + \lambda_2 + \lambda_3 = 3 + 5 + 3 = 11$

As $\lambda_1 = 3, \quad \lambda_2 = 6 \quad \Rightarrow \lambda_3 = 2$

$\therefore$ Eigenvalues of A^{-1} are $\frac{1}{2}, \quad \frac{1}{3}, \quad \frac{1}{6}.$

Example: If 2 and 3 are eigenvalues of $A = \begin{bmatrix} 3 & 10 & 5 \\ -2 & -3 & -4 \\ 3 & 5 & 7 \end{bmatrix}$. Find the eigenvalues of A^{-1} and A^3.

Solution: Let $\lambda_1, \ \lambda_2, \ \lambda_3$ are eigenvalues of A.

$\Rightarrow \lambda_1 + \lambda_2 + \lambda_3 = 3 + 2 + \lambda_3 = 3 - 3 + 7 = 7 \quad \Rightarrow \lambda_3 = 2$

$\therefore$ Eigenvalues of A^{-1} are $\frac{1}{2}, \quad \frac{1}{2}, \quad \frac{1}{3}.$

and eigenvalues of A^3 are $2^3, \quad 2^3, \quad 3^3.$

Example: Find the constant a and b such that $\begin{bmatrix} a & 4 \\ 1 & b \end{bmatrix}$ matrix has 3 and -2 as eigenvalues.

Solution: $a + b = 3 - 2 = 1$ and $ab - 4 = 3 \times -2 = -6$

$\therefore b = 1 - a \quad \Rightarrow \quad a(1-a) - 4 = -6 \quad \Rightarrow a(1-a) = -2$

$\Rightarrow a = 2, \ -1 \quad \Rightarrow b = -1, \ 2.$

Example: Two eigenvalues of $A = \begin{bmatrix} 4 & 6 & 6 \\ 1 & 3 & 2 \\ -1 & -5 & -2 \end{bmatrix}$ are equal and they are double the third. Find the eigenvalues of A^2.

Solution: Let the third eigenvalue is λ. Therefore the three eigenvalues are $\lambda, \ 2\lambda, \ 2\lambda$. $\quad \Rightarrow \lambda + 2\lambda + 2\lambda = 4 + 3 - 2 \quad \Rightarrow 5\lambda = 5 \quad \Rightarrow \quad \lambda = 1$

$\therefore$ The eigenvalues are $1, \ 2, \ 2$ and eigenvalues of A^2 are $1, \ 4, \ 4$.

Statement: Every square matrix satisfies it's own characteristics equation.
i.e If A is any $n \times n$ matrix and
$\lambda^n - S_1\lambda^{n-1} + S_2\lambda^{n-2} - S_3\lambda^{n-3} \cdots\cdots + (-1)^n S_n = 0$
is the characteristic equation then
$A^n - S_1A^{n-1} + S_2A^{n-2} - S_3A^{n-3} \cdots\cdots + (-1)^n S_n = 0.$

Example: Verify Cayley-Hamilton theorem and hence find A^{-1} for

$$A = \begin{bmatrix} 8 & -8 & 2 \\ 4 & -3 & -2 \\ 3 & -4 & 1 \end{bmatrix}.$$

Solution: The characteristic equation can be obtain from

$$\begin{vmatrix} 8-\lambda & -8 & 2 \\ 4 & -3-\lambda & -2 \\ 3 & -4 & 1-\lambda \end{vmatrix} = 0 \quad \Rightarrow \lambda^3 - 6\lambda^2 + 11\lambda - 6 = 0$$

Now we need to show that $A^3 - 6A^2 + 11A - 6I = 0$. For that we find the followings:

$$A^2 = A.A = \begin{bmatrix} 8 & -8 & 2 \\ 4 & -3 & -2 \\ 3 & -4 & 1 \end{bmatrix} \begin{bmatrix} 8 & -8 & 2 \\ 4 & -3 & -2 \\ 3 & -4 & 1 \end{bmatrix} = \begin{bmatrix} 26 & -32 & -2 \\ 14 & -15 & -4 \\ 11 & -16 & 3 \end{bmatrix}$$

$$A^3 = A^2.A = \begin{bmatrix} 26 & -32 & -2 \\ 14 & -15 & -4 \\ 11 & -16 & 3 \end{bmatrix} \begin{bmatrix} 8 & -8 & 2 \\ 4 & -3 & -2 \\ 3 & -4 & 1 \end{bmatrix} = \begin{bmatrix} 74 & -104 & 10 \\ 40 & -51 & -24 \\ 33 & -52 & 13 \end{bmatrix}$$

Now $A^3 - 6A^2 + 11A - 6I = \begin{bmatrix} 74 & -104 & 10 \\ 40 & -51 & -24 \\ 33 & -52 & 13 \end{bmatrix} - \begin{bmatrix} 156 & -192 & -12 \\ 84 & -90 & -24 \\ 66 & -93 & 18 \end{bmatrix} +$

$$\begin{bmatrix} 88 & -88 & -22 \\ 44 & -33 & -22 \\ 33 & 44 & 11 \end{bmatrix} - \begin{bmatrix} 6 & 0 & 0 \\ 0 & 6 & 0 \\ 0 & 0 & 6 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} = 0.$$

Finding A^{-1}: Let us premultiply the equation $A^3 - 6A^2 + 11A - 6I = 0$ by A^{-1}, then we get: $A^2 - 6A + 11I - 6A^{-1} = 0 \quad \Rightarrow 6A^{-1} = [A^2 - 6A + 11I]$.

$$\Rightarrow 6A^{-1} = \begin{bmatrix} 26 & -32 & -2 \\ 14 & -15 & -4 \\ 11 & -16 & 3 \end{bmatrix} - \begin{bmatrix} 48 & -48 & -12 \\ 24 & -18 & -12 \\ 18 & -24 & 6 \end{bmatrix} + \begin{bmatrix} 11 & 0 & 0 \\ 0 & 11 & 0 \\ 0 & 0 & 11 \end{bmatrix}$$

$$\Rightarrow A^{-1} = \frac{1}{6} \begin{bmatrix} -11 & 16 & 10 \\ -10 & 14 & 8 \\ -7 & 8 & 8 \end{bmatrix}.$$

Example: Using Cayley-Hamilton theorem find the inverse of $A = \begin{bmatrix} 2 & 1 \\ 1 & -5 \end{bmatrix}$.

Solution: The characteristic equation can be obtain from

$$\begin{vmatrix} 2-\lambda & 1 \\ 1 & -5-\lambda \end{vmatrix} = 0 \quad \Rightarrow \lambda^2 + 3\lambda - 11 = 0 \quad \Rightarrow A^2 + 3A - 11I = 0.$$

$$\Rightarrow A + 3I = 11A^{-1} \qquad \Rightarrow A^{-1} = \frac{1}{11}[A + 3I] = \frac{1}{11}\begin{bmatrix} 5 & 1 \\ 1 & -2 \end{bmatrix}.$$

Example: Verify Cayley-Hamilton theorem for the matrix $A = \begin{bmatrix} 1 & 2 & -2 \\ -1 & 3 & 0 \\ 0 & -2 & 1 \end{bmatrix}$ and use it to find A^{-1} and A^4.

Solution: The characteristic equation can be obtain from

$$\begin{vmatrix} 1-\lambda & 2 & -2 \\ -1 & 3-\lambda & 0 \\ 0 & -2 & 1-\lambda \end{vmatrix} = 0 \quad \Rightarrow \lambda^3 - 5\lambda^2 + 9\lambda - 1 = 0$$

$$A^2 = A.A = \begin{bmatrix} 1 & 2 & -2 \\ -1 & 3 & 0 \\ 0 & -2 & 1 \end{bmatrix}\begin{bmatrix} 1 & 2 & -2 \\ -1 & 3 & 0 \\ 0 & -2 & 1 \end{bmatrix} = \begin{bmatrix} -1 & 12 & -4 \\ -4 & 7 & 2 \\ 2 & -8 & 1 \end{bmatrix}$$

$$A^3 = A^2.A = \begin{bmatrix} -1 & 12 & -4 \\ -4 & 7 & 2 \\ 2 & -8 & 1 \end{bmatrix} \begin{bmatrix} 1 & 2 & -2 \\ -1 & 3 & 0 \\ 0 & -2 & 1 \end{bmatrix} = \begin{bmatrix} -13 & 42 & -2 \\ -11 & 9 & 10 \\ 10 & -22 & -3 \end{bmatrix}$$

Now $A^3 - 5A^2 + 9A - I = \begin{bmatrix} -13 & 42 & -2 \\ -11 & 9 & 10 \\ 10 & -22 & -3 \end{bmatrix} - 5 \begin{bmatrix} -1 & 12 & -4 \\ -4 & 7 & 2 \\ 2 & -8 & 1 \end{bmatrix} +$

$9 \begin{bmatrix} 1 & 2 & -2 \\ -1 & 3 & 0 \\ 0 & -2 & 1 \end{bmatrix} - \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} = 0.$

Multiplying by A^{-1} gives $A^{-1} = A^2 - 5A + 9I = \begin{bmatrix} 3 & 2 & 6 \\ 1 & 1 & 2 \\ 2 & 2 & 5 \end{bmatrix}$

Multiplying by A gives $A^4 = 5A^3 - 9A^2 + A = \begin{bmatrix} -55 & 104 & 24 \\ -20 & -15 & 32 \\ 32 & -42 & -23 \end{bmatrix}$.