



Linear Algebra



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Abstract—This book provides solved examples on Linear Algebra.

1 JUNE 2019

1.1. Consider the vector space \mathbb{P}_n of real polynomials in x of degree $\leq n$. Define

$$T : \mathbb{P}_2 \rightarrow \mathbb{P}_3 \quad (1.1.1)$$

by

$$(Tf)(x) = \int_0^x f(t) dt + f'(x). \quad (1.1.2)$$

Then find the matrix representation of T with respect to the bases

$$\{1, x, x^2\} \text{ and } \{1, x, x^2, x^3\} \quad (1.1.3)$$

1.2. Let $P_A(x)$ denote the characteristic polynomial of a matrix A . Then for which of the following matrices is

$$P_A(x) - P_{A^{-1}}(x) \quad (1.2.1)$$

a constant?

$$\begin{array}{ll} \text{a) } \begin{pmatrix} 3 & 3 \\ 2 & 4 \end{pmatrix} & \text{c) } \begin{pmatrix} 3 & 2 \\ 4 & 3 \end{pmatrix} \\ \text{b) } \begin{pmatrix} 4 & 3 \\ 2 & 3 \end{pmatrix} & \text{d) } \begin{pmatrix} 2 & 3 \\ 3 & 4 \end{pmatrix} \end{array}$$

1.3. Which of the following matrices is not diagonalizable over \mathbb{R} ?

$$\begin{array}{ll} \text{a) } \begin{pmatrix} 2 & 0 & 1 \\ 0 & 3 & 0 \\ 0 & 0 & 2 \end{pmatrix} & \text{c) } \begin{pmatrix} 2 & 0 & 1 \\ 0 & 3 & 0 \\ 0 & 0 & 3 \end{pmatrix} \\ \text{b) } \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix} & \text{d) } \begin{pmatrix} 1 & -1 \\ 2 & 4 \end{pmatrix} \end{array}$$

1.4. What is the rank of the following matrix?

$$\begin{pmatrix} 1 & 1 & 1 & 1 & 1 \\ 1 & 2 & 2 & 2 & 2 \\ 1 & 2 & 3 & 3 & 3 \\ 1 & 2 & 3 & 4 & 4 \\ 1 & 2 & 3 & 4 & 5 \end{pmatrix} \quad (1.4.1)$$

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1.5. Let V denote the vector space of real valued continuous functions on the close interval $[0, 1]$. Let W be the subspace of V spanned by $\{\sin x, \cos x, \tan x\}$. Find the dimension of W over \mathbb{R} .

1.6. Let V be the vector space of polynomials in the variable t of degree at most 2 over \mathbb{R} . An inner product on V is defined by

$$f^T g = \int_0^1 f(t)g(t) dt, \quad f, g \in V. \quad (1.6.1)$$

Let

$$W = \text{span}\{1 - t^2, 1 + t^2\} \quad (1.6.2)$$

and W^\perp be the orthogonal complement of W in V . Which of the following conditions is satisfied for all $h \in W^\perp$?

- a) h is an even function
- b) h is an odd function
- c) $h(t) = 0$ has a real solution
- d) $h(0) = 0$

1.7. Consider solving the following system by Jacobi iteration scheme

$$\begin{pmatrix} 1 & 2m & -2m \\ n & 1 & n \\ 2m & 2m & 1 \end{pmatrix} (x) = \begin{pmatrix} 1 \\ 2 \\ 1 \end{pmatrix} \quad (1.7.1)$$

where $m, n \in \mathbb{Z}$. With any initial vector, the scheme converges provided m, n satisfy

- a) $m + n = 3$
- b) $m > n$
- c) $m < n$
- d) $m = n$

1.8. Consider a Markov Chain with state space $\{0, 1, 2, 3, 4\}$ and transition matrix

$$P = \begin{matrix} & \begin{matrix} 0 & 1 & 2 & 3 & 4 \end{matrix} \\ \begin{matrix} 0 \\ 1 \\ 2 \\ 3 \\ 4 \end{matrix} & \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ \frac{1}{3} & \frac{1}{3} & \frac{1}{3} & 0 & 0 \\ 0 & \frac{1}{3} & \frac{1}{3} & \frac{1}{3} & 0 \\ 0 & 0 & \frac{1}{3} & \frac{1}{3} & \frac{1}{3} \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \end{matrix} \quad (1.8.1)$$

Then find

$$\lim_{n \rightarrow \infty} p_{23}^{(n)} \quad (1.8.2)$$

1.9. Let $L(\mathbb{R})^n$ be the space of \mathbb{R} -linear maps from \mathbb{R}^n to \mathbb{R}^n . If $\text{Ker}(T)$ denotes the kernel of T then which of the following are true?

- a) There exists $T \in L(\mathbb{R}^5) \setminus \{0\}$ such that $\text{Range}(T) = \text{Ker}(T)$
- b) There does not exist $T \in L(\mathbb{R}^5) \setminus \{0\}$ such that $\text{Range}(T) = \text{Ker}(T)$
- c) There exists $T \in L(\mathbb{R}^6) \setminus \{0\}$ such that $\text{Range}(T) = \text{Ker}(T)$
- d) There does not exist $T \in L(\mathbb{R}^6) \setminus \{0\}$ such that $\text{Range}(T) = \text{Ker}(T)$

1.10. Let V be a finite dimensional vector space over \mathbb{R} and $T : V \rightarrow V$ be a linear map. Can you always write $T = T_2 \circ T_1$ for some linear maps

$$T_1 : V \rightarrow W, T : W \rightarrow V, \quad (1.10.1)$$

where W is some finite dimensional vector space such that

- a) both T_1 and T_2 are onto
- b) both T_1 and T_2 are one to one
- c) T_1 is onto, T_2 is one to one
- d) T_1 is one to one, T_2 is onto

1.11. Let $A = [a_{ij}]$ be a 3×3 complex matrix. Identify the correct statements

- a) $\det \left[(-1)^{i+j} a_{ij} \right] = \det(A)$
- b) $\det \left[(-1)^{i+j} a_{ij} \right] = -\det(A)$
- c) $\det \left[(\sqrt{-1})^{i+j} a_{ij} \right] = \det(A)$
- d) $\det \left[(\sqrt{-1})^{i+j} a_{ij} \right] = -\det(A)$

1.12. Let

$$p(x) = a_0 + a_1 x + \cdots + a_n x^n \quad (1.12.1)$$

be a non-constant polynomial of degree $n \geq 1$. Consider the polynomial

$$q(x) = \int_0^x p(t) dt, r(x) = \frac{d}{dx} p(x) \quad (1.12.2)$$

Let V denote the real vector space of all polynomials in x . Then which of the following are true?

- a) q and r are linearly independent in V
- b) q and r are linearly dependent in V
- c) x^n belongs to the linear span of q and r
- d) x^{n+1} belongs to the linear span of q and r .

1.13. Let $M_n(\mathbb{R})$ be the ring of $n \times n$ matrices over \mathbb{R} . Which of the following are true for every $n \geq 2$?

- a) there exist matrices $A, B \in M_n(\mathbb{R})$ such that $AB - BA = I_n$, where I_n denotes the identity matrix.

- b) If $A, B \in M_n(\mathbb{R})$ and $AB = BA$, then A is diagonalisable over \mathbb{R} if and only if B is diagonalisable over \mathbb{R} .
- c) If $A, B \in M_n(\mathbb{R})$, then AB and BA have the same minimal polynomial.
- d) If $A, B \in M_n(\mathbb{R})$, then AB and BA have the same eigenvalues in \mathbb{R} .

1.14. Consider a matrix

$$A = [a_{ij}], 1 \leq i, j \leq 5 \quad (1.14.1)$$

such that

$$a_{ij} = \frac{1}{n_i + n_j + 1}, \quad n_i, n_j \in \mathbb{N} \quad (1.14.2)$$

Then in which of the following cases A is a positive definite matrix?

- a) $n_i = 1 \forall i = 1, 2, 3, 4, 5$.
- b) $n_1 < n_2 < \dots < n_5$.
- c) $n_1 = n_2 = \dots = n_5$.
- d) $n_1 > n_2 > \dots > n_5$.

1.15. For a nonzero $w \in \mathbb{R}^n$, define

$$T_w : \mathbb{R}^n \rightarrow \mathbb{R}^n \quad (1.15.1)$$

by

$$T_w v = v - \frac{2v^T w}{w^T w} w, \quad v \in \mathbb{R}^n \quad (1.15.2)$$

Which of the following are true?

- a) $\det(T_w) = 1$
- b) $T_w(v_1)_w^T(v_2) = v_1^T v_2 \forall v_1, v_2 \in \mathbb{R}^n$
- c) $T_w = T_w^{-1}$
- d) $T_{2w} = 2T_w$

1.16. Consider the matrix

$$A = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \quad (1.16.1)$$

over the field \mathbb{Q} of rationals. Which of the following matrices are of the form $P^T A P$ for suitable 2×2 invertible matrix P over \mathbb{Q} ?

- a) $\begin{pmatrix} 2 & 0 \\ 0 & -2 \end{pmatrix}$
- b) $\begin{pmatrix} 2 & 0 \\ 0 & 2 \end{pmatrix}$
- c) $\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$
- d) $\begin{pmatrix} 3 & 4 \\ 4 & 5 \end{pmatrix}$

1.17. Consider a Markov Chain with state space

$\{0, 1, 2\}$ and transition matrix

$$P = \begin{pmatrix} 0 & 1 & 2 \\ 1 & \frac{1}{4} & 0 \\ 2 & \frac{1}{2} & \frac{3}{8} \end{pmatrix} \quad (1.17.1)$$

Then which of the following are true?

- a) $\lim_{n \rightarrow \infty} p_{12}^{(n)} = 0$
- b) $\lim_{n \rightarrow \infty} p_{12}^{(n)} = \lim_{n \rightarrow \infty} p_{21}^{(n)}$
- c) $\lim_{n \rightarrow \infty} p_{22}^{(n)} = \frac{1}{8}$
- d) $\lim_{n \rightarrow \infty} p_{21}^{(n)} = \frac{1}{3}$

2 DECEMBER 2018

2.1. Consider the subspaces W_1 and W_2 of \mathbb{R}^3 given by

$$W_1 = \{x \in \mathbb{R}^3 : \begin{pmatrix} 1 & 1 & 1 \end{pmatrix} x = 0\} \quad (2.1.1)$$

$$W_2 = \{x \in \mathbb{R}^3 : \begin{pmatrix} 1 & -1 & 1 \end{pmatrix} x = 0\}. \quad (2.1.2)$$

If $W \subseteq \mathbb{R}^3$, such that

- a) $W \cap W_2 = \text{span} \left\{ \begin{pmatrix} 0 \\ 1 \\ 1 \end{pmatrix} \right\}$
- b) $\{W \cap W_1\} \perp \{W \cap W_2\}$,
then

- a) $W = \text{span} \left\{ \begin{pmatrix} 0 \\ 1 \\ -1 \end{pmatrix}, \begin{pmatrix} 0 \\ 1 \\ 1 \end{pmatrix} \right\}$
- b) $W = \text{span} \left\{ \begin{pmatrix} 1 \\ 0 \\ -1 \end{pmatrix}, \begin{pmatrix} 0 \\ 1 \\ -1 \end{pmatrix} \right\}$
- c) $W = \text{span} \left\{ \begin{pmatrix} 1 \\ 0 \\ -1 \end{pmatrix}, \begin{pmatrix} 0 \\ 1 \\ 1 \end{pmatrix} \right\}$
- d) $W = \text{span} \left\{ \begin{pmatrix} 1 \\ 0 \\ -1 \end{pmatrix}, \begin{pmatrix} 1 \\ 0 \\ 1 \end{pmatrix} \right\}$

2.2. Let

$$C = \left\{ \begin{pmatrix} 1 \\ 2 \end{pmatrix}, \begin{pmatrix} 2 \\ 1 \end{pmatrix} \right\} \quad (2.2.1)$$

be a basis of \mathbb{R}^2 and

$$T \begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} x + y \\ x - 2y \end{pmatrix}. \quad (2.2.2)$$

If $T[C]$ represents the matrix of T with respect to the basis C then which among the following is true?

- a) $T[C] = \begin{pmatrix} -3 & -2 \\ 3 & 1 \end{pmatrix}$
 b) $T[C] = \begin{pmatrix} 3 & -2 \\ -3 & 1 \end{pmatrix}$
 c) $T[C] = \begin{pmatrix} -3 & -1 \\ 3 & 2 \end{pmatrix}$
 d) $T[C] = \begin{pmatrix} 3 & -1 \\ -3 & 2 \end{pmatrix}$

2.3. Let $W_1 = \{\mathbf{x} \in \mathbb{R}^4 : \}$

$$\begin{pmatrix} 1 & 1 & 1 & 0 \end{pmatrix} \mathbf{x} = 0 \quad (2.3.1)$$

$$\begin{pmatrix} 0 & 2 & 0 & 1 \end{pmatrix} \mathbf{x} = 0 \quad (2.3.2)$$

$$\begin{pmatrix} 2 & 0 & 2 & -1 \end{pmatrix} \mathbf{x} = 0 \quad (2.3.3)$$

and $W_2 = \{\mathbf{x} \in \mathbb{R}^4 : \}$

$$\begin{pmatrix} 1 & 1 & 0 & 1 \end{pmatrix} \mathbf{x} = 0 \quad (2.3.4)$$

$$\begin{pmatrix} 1 & 0 & 1 & -2 \end{pmatrix} \mathbf{x} = 0 \quad (2.3.5)$$

$$\begin{pmatrix} 0 & 1 & 0 & -1 \end{pmatrix} \mathbf{x} = 0. \quad (2.3.6)$$

Then which among the following is true?

- a) $\dim(W_1) = 1$
 b) $\dim(W_2) = 2$
 c) $\dim(W_1 \cap W_2) = 1$
 d) $\dim(W_1 + W_2) = 3$

2.4. Let A be an $n \times n$ complex matrix. Assume that A is self-adjoint and let B denote the inverse of $A + jI$. Then all eigenvalues of $(A - jI)B$ are

- a) purely imaginary
 b) of modulus one
 c) real
 d) of modulus less than one

2.5. Let $\{u_1, u_2, \dots, u_n\}$ be an orthonormal basis of \mathbb{C}^n as column vectors. Let

$$\mathbf{M} = (\mathbf{u}_1 \quad \mathbf{u}_2 \quad \dots \quad \mathbf{u}_k), \quad (2.5.1)$$

$$\mathbf{N} = (\mathbf{u}_{k+1} \quad \mathbf{u}_{k+2} \quad \dots \quad \mathbf{u}_n) \quad (2.5.2)$$

and \mathbf{P} be the diagonal $k \times k$ matrix with diagonal entries $\alpha_1, \alpha_2, \dots, \alpha_k \in \mathbb{R}$. Then which of the following is true?

- a) $\text{rank}(\mathbf{M}\mathbf{P}\mathbf{M}^*) = k$ whenever $\alpha_i \neq \alpha_j, 1 \leq i, j \leq k$.
 b) $\text{tr}(\mathbf{M}\mathbf{P}\mathbf{M}^*) = \sum_{i=1}^k \alpha_i$
 c) $\text{rank}(\mathbf{M}^*\mathbf{N}) = \min(k, n - k)$
 d) $\text{rank}(\mathbf{M}\mathbf{M}^* + \mathbf{N}\mathbf{N}^*) < n$.

2.6. Let $B : \mathbb{R} \times \mathbb{R} \rightarrow \mathbb{R}$ be the function

$$B(a, b) = ab \quad (2.6.1)$$

Which of the following is true?

- a) B is a linear transformation
 b) B is a positive definite bilinear form
 c) B is symmetric but not positive definite
 d) B is neither linear nor bilinear

2.7. Let \mathbf{A} be an invertible real $n \times n$ matrix. Define a function

$$F : \mathbb{R}^n \times \mathbb{R}^n \rightarrow \mathbb{R} \quad (2.7.1)$$

by

$$F(\mathbf{x}, \mathbf{y}) = (F\mathbf{x})^T \mathbf{y} \quad (2.7.2)$$

Let $DF(\mathbf{x}, \mathbf{y})$ denote the derivate of F at (\mathbf{x}, \mathbf{y}) which is a linear transformation from

$$\mathbb{R}^n \times \mathbb{R}^n \rightarrow \mathbb{R} \quad (2.7.3)$$

Then, if

- a) $\mathbf{x} \neq 0, DF(\mathbf{x}, \mathbf{0}) \neq 0$
 b) $\mathbf{y} \neq 0, DF(\mathbf{0}, \mathbf{y}) \neq 0$
 c) $(\mathbf{x}, \mathbf{y}) \neq (\mathbf{0}, \mathbf{0}), DF(\mathbf{x}, \mathbf{0}) \neq 0$
 d) $\mathbf{x} = 0$ or $\mathbf{y} = 0, DF(\mathbf{x}, \mathbf{y}) = 0$

2.8. Let

$$T : \mathbb{R}^n \rightarrow \mathbb{R}^n \quad (2.8.1)$$

be a linear map that satisfies

$$T^2 = T - I. \quad (2.8.2)$$

Then which of the following is true?

- a) T is invertible.
 b) $T - I$ is not invertible.
 c) T has a real eigenvalue.
 d) $T^3 = -I$.

2.9. Let

$$\mathbf{M} = \begin{pmatrix} 2 & 0 & 3 & 2 & 0 & -2 \\ 0 & 1 & 0 & -1 & 3 & 4 \\ 0 & 0 & 1 & 0 & 4 & 4 \\ 1 & 1 & 1 & 0 & 1 & 1 \end{pmatrix} \quad (2.9.1)$$

$$\mathbf{b}_1 = \begin{pmatrix} 5 \\ 1 \\ 1 \\ 4 \end{pmatrix}, \mathbf{b}_2 = \begin{pmatrix} 5 \\ 1 \\ 3 \\ 3 \end{pmatrix}. \quad (2.9.2)$$

Then which of the following are true?

- a) both systems $\mathbf{M}\mathbf{x} = \mathbf{b}_1$ and $\mathbf{M}\mathbf{x} = \mathbf{b}_2$ are

inconsistent.

- b) both systems $\mathbf{M}\mathbf{x} = \mathbf{b}_1$ and $\mathbf{M}\mathbf{x} = \mathbf{b}_2$ are consistent.
- c) the system $\mathbf{M}\mathbf{x} = \mathbf{b}_1 - \mathbf{b}_2$ is consistent.
- d) the system $\mathbf{M}\mathbf{x} = \mathbf{b}_1 - \mathbf{b}_2$ is inconsistent.

2.10. Let

$$\mathbf{M} = \begin{pmatrix} 1 & -1 & 1 \\ 2 & 1 & 4 \\ -2 & 1 & -4 \end{pmatrix}. \quad (2.10.1)$$

Given that 1 is an eigenvalue of \mathbf{M} , then which among the following are correct?

- a) The minimal polynomial of \mathbf{M} is $(x-1)(x+4)$
- b) The minimal polynomial of \mathbf{M} is $(x-1)^2(x+4)$
- c) \mathbf{M} is not diagonalizable.
- d) $\mathbf{M}^{-1} = \frac{1}{4}(\mathbf{M} + 3\mathbf{I})$.

2.11. Let \mathbf{A} be a real matrix with characteristic polynomial $(x-1)^3$. Pick the correct statements from below:

- a) \mathbf{A} is necessarily diagonalizable.
- b) If the minimal polynomial of \mathbf{A} is $(x-1)^3$, then \mathbf{A} is diagonalizable.
- c) The characteristic polynomial of \mathbf{A}^2 is $(x-1)^3$
- d) If \mathbf{A} has exactly two Jordan blocks, then $(\mathbf{A} - \mathbf{I})^2$ is diagonalizable.

2.12. Let P_3 be the vector space of polynomials with real coefficients and of degree at most 3. Consider the linear map

$$T : P_3 \rightarrow P_3 \quad (2.12.1)$$

defined by

$$T(p(x)) = p(x-1) + p(x+1) \quad (2.12.2)$$

Which of the following properties does the matrix of T with respect to the standard basis $B = \{1, x, x^2, x^3\}$ of P_3 satisfy?

- a) $\det T = 0$.
- b) $(T - 2I)^4 = 0$ but $(T - 2I)^3 \neq 0$.
- c) $(T - 2I)^3 = 0$ but $(T - 2I)^2 \neq 0$.
- d) 2 is an eigenvalue with multiplicity 4.

2.13. Let \mathbf{M} be an $n \times n$ Hermitian matrix of rank $k, k \neq n$. If $\lambda \neq 0$ is an eigenvalue of \mathbf{M} with corresponding unit column vector \mathbf{u} , then which of the following are true?

- a) $\text{rank}(\mathbf{M} - \lambda \mathbf{u} \mathbf{u}^*) = k - 1$.

b) $\text{rank}(\mathbf{M} - \lambda \mathbf{u} \mathbf{u}^*) = k$.

c) $\text{rank}(\mathbf{M} - \lambda \mathbf{u} \mathbf{u}^*) = k + 1$.

d) $(\mathbf{M} - \lambda \mathbf{u} \mathbf{u}^*)^n = \mathbf{M}^n - \lambda^n \mathbf{u} \mathbf{u}^*$.

2.14. Define a real valued function B on $\mathbb{R}^2 \times \mathbb{R}^2$ as

$$B(\mathbf{x}, \mathbf{y}) = x_1 y_1 - x_1 y_2 - x_2 y_1 + 4x_2 y_2 \quad (2.14.1)$$

Let $\mathbf{v}_0 = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$ and

$$W = \left\{ \mathbf{v} \in \mathbb{R}^2 : B(\mathbf{v}_0, \mathbf{v}) = 0 \right\} \quad (2.14.2)$$

Then W

a) is not a subspace of \mathbb{R}^2 .

b) equals $\mathbf{0}$.

c) is the y axis

d) is the line passing through $\begin{pmatrix} 0 \\ 0 \end{pmatrix}$ and $\begin{pmatrix} 1 \\ 1 \end{pmatrix}$.

2.15. Consider the Quadratic forms

$$Q_1(x, y) = xy \quad (2.15.1)$$

$$Q_2(x, y) = x^2 + 2xy + y^2 \quad (2.15.2)$$

$$Q_3(x, y) = x^2 + 3xy + 2y^2 \quad (2.15.3)$$

on \mathbb{R}^2 . Choose the correct statements from below

- a) Q_1 and Q_2 are equivalent.
- b) Q_1 and Q_3 are equivalent.
- c) Q_2 and Q_3 are equivalent.
- d) all are equivalent.

2.16. Consider a Markov Chain with state space $\{0, 1, 2\}$ and transition matrix

$$P = \begin{pmatrix} 0 & 1 & 2 \\ 0 & \frac{1}{2} & \frac{1}{2} \\ 1 & 0 & \frac{1}{3} \\ 2 & \frac{1}{3} & \frac{2}{3} \end{pmatrix} \quad (2.16.1)$$

For any two states i and j , let $p_{ij}^{(n)}$ denote the n -step transition probability of going from i to j . Identify correct statements.

- a) $\lim_{n \rightarrow \infty} p_{11}^{(n)} = \frac{2}{9}$
- b) $\lim_{n \rightarrow \infty} p_{21}^{(n)} = 0$
- c) $\lim_{n \rightarrow \infty} p_{32}^{(n)} = \frac{1}{3}$
- d) $\lim_{n \rightarrow \infty} p_{13}^{(n)} = \frac{1}{3}$

3 JUNE 2018

3.1. Let \mathbf{A} be a $(m \times n)$ matrix and \mathbf{B} be a $(n \times m)$ matrix over real numbers with $m < n$. Then

- a) \mathbf{AB} is always nonsingular.

- b) \mathbf{AB} is always singular.
 c) \mathbf{BA} is always nonsingular.
 d) \mathbf{BA} is always singular.

- a) $\mathbf{A} = \mathbf{A}^{-1}$
 b) $\mathbf{A} = \mathbf{A}^\top$
 c) $\mathbf{A}^{-1} = \mathbf{A}^\top$
 d) $\det(\mathbf{A}) = 1$

3.2. If \mathbf{A} is a (2×2) matrix over \mathbb{R} with $\det(\mathbf{A} + \mathbf{I}) = 1 + \det(\mathbf{A})$. Then we can conclude that

- a) $\det(\mathbf{A}) = 0$.
 b) $\mathbf{A} = 0$.
 c) $\text{tr}(\mathbf{A}) = 0$.
 d) \mathbf{A} is nonsingular.

3.3. The system of equations

$$x + 2x^2 + 3xy = 6 \quad (3.3.1)$$

$$x + x^2 + 3xy + y = 5 \quad (3.3.2)$$

$$x - x^2 + y = 7 \quad (3.3.3)$$

- a) has solutions in rational numbers.
 b) has solutions in real numbers.
 c) has solutions in complex numbers.
 d) has no solutions.

3.4. The trace of the matrix

$$\begin{pmatrix} 2 & 1 & 0 \\ 0 & 2 & 0 \\ 0 & 0 & 3 \end{pmatrix}^{20} \quad (3.4.1)$$

is

- a) 7^{20} .
 b) $2^{20} + 3^{20}$.
 c) $2^{21} + 3^{20}$.
 d) $2^{20} + 3^{20} + 1$.

3.5. Given that there are real constants a, b, c, d such that the identity

$$\lambda x^2 + 2xy + y^2 = (ax + by)^2 + (cx + dy)^2, \quad \forall x, y \in \mathbb{R} \quad (3.5.1)$$

This implies that

- a) $\lambda = -5$
 b) $\lambda \geq 1$
 c) $0 < \lambda < 1$
 d) There is no such $\lambda \in \mathbb{R}$

3.6. Let $\mathbb{R}, n \geq 2$, be equipped with the standard inner product. Let $\mathbf{v}_1, \mathbf{v}_2, \dots, \mathbf{v}_n$ be n column vectors forming an orthonormal basis of \mathbb{R}^n . Let \mathbf{A} be the $n \times n$ matrix formed by the column vectors $\mathbf{v}_1, \mathbf{v}_2, \dots, \mathbf{v}_n$. Then

3.7. Consider a Markov Chain with state space $\{1, 2, 3, 4\}$ and transition matrix

$$P = \begin{pmatrix} 1 & 2 & 3 & 4 \\ 1 & \frac{1}{2} & 0 & \frac{1}{2} & 0 \\ 2 & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} & \frac{1}{4} \\ 3 & \frac{1}{3} & 0 & \frac{1}{3} & \frac{1}{3} \\ 4 & \frac{1}{2} & 0 & \frac{1}{2} & 0 \end{pmatrix} \quad (3.7.1)$$

Then,

- a) $\lim_{n \rightarrow \infty} p_{22}^{(n)} = 0, \sum_{n=0}^{\infty} p_{22}^{(n)} = \infty$
 b) $\lim_{n \rightarrow \infty} p_{22}^{(n)} = 0, \sum_{n=0}^{\infty} p_{22}^{(n)} < \infty$
 c) $\lim_{n \rightarrow \infty} p_{22}^{(n)} = 1, \sum_{n=0}^{\infty} p_{22}^{(n)} = \infty$
 d) $\lim_{n \rightarrow \infty} p_{22}^{(n)} = 1, \sum_{n=0}^{\infty} p_{22}^{(n)} < \infty$

3.8. Let V denote the vector space of all sequences $\mathbf{a} = (a_1, a_2, \dots)$ of real numbers such that

$$\sum_n 2^n |a_n| \quad (3.8.1)$$

converges. Define

$$\|\cdot\| : V \rightarrow \mathbb{R} \quad (3.8.2)$$

by

$$\|\mathbf{a}\| = \sum_n 2^n |a_n|. \quad (3.8.3)$$

Which of the following are true?

- a) V contains only the sequence $(0, 0, \dots)$
 b) V is finite dimensional
 c) V has a countable linear basis
 d) V is a complete normed space

3.9. Let V be a vector space over \mathbb{C} with dimension n . Let $T : V \rightarrow V$ be a linear transformation with only 1 as eigenvalue. Then which of the following must be true?

- a) $T - I = 0$
 b) $(T - I)^{n-1} = 0$
 c) $(T - I)^n = 0$
 d) $(T - I)^{2n} = 0$

3.10. If \mathbf{A} is a 5×5 matrix and the dimension of the solution space of $\mathbf{Ax} = 0$ is at least two, then

- a) $\text{rank}(\mathbf{A}^2) \leq 3$
 b) $\text{rank}(\mathbf{A}^2) \geq 3$
 c) $\text{rank}(\mathbf{A}^2) = 3$
 d) $\det(\mathbf{A}^2) = 0$

- 3.11. Let $\mathbf{A} \in M_3(\mathbb{R})$ be such that $\mathbf{A}^3 = \mathbf{I}_{3 \times 3}$. Then
- minimal polynomial of \mathbf{A} can only be of degree 2
 - minimal polynomial of \mathbf{A} can only be of degree 3
 - either $\mathbf{A} = \mathbf{I}$ or $\mathbf{A} = -\mathbf{I}$
 - there can be uncountably many \mathbf{A} satisfying the above.
- 3.12. Let \mathbf{A} be an $n \times n, n > 1$ matrix satisfying

$$\mathbf{A}^2 - 7\mathbf{A} + 12\mathbf{I} = \mathbf{0} \quad (3.12.1)$$

Then which of the following statements is true?

- \mathbf{A} is invertible
 - $t^2 - 7t + 12n = 0$ where $t = \text{tr}(\mathbf{A})$
 - $d^2 - 7d + 12 = 0$ where $d = \det(\mathbf{A})$
 - $\lambda^2 - 7\lambda + 12 = 0$ where λ is an eigenvalue of \mathbf{A}
- 3.13. Let \mathbf{A} be a 6×6 matrix over \mathbb{R} with characteristic polynomial

$$(x-3)^2(x-2)^4 \quad (3.13.1)$$

and minimal polynomial

$$(x-3)(x-2)^2 \quad (3.13.2)$$

Then the Jordan canonical form of \mathbf{A} can be

- $$\begin{pmatrix} 3 & 0 & 0 & 0 & 0 & 0 \\ 0 & 3 & 0 & 0 & 0 & 0 \\ 0 & 0 & 2 & 1 & 0 & 0 \\ 0 & 0 & 0 & 2 & 1 & 0 \\ 0 & 0 & 0 & 0 & 2 & 1 \\ 0 & 0 & 0 & 0 & 0 & 2 \end{pmatrix}$$
- $$\begin{pmatrix} 3 & 0 & 0 & 0 & 0 & 0 \\ 0 & 3 & 0 & 0 & 0 & 0 \\ 0 & 0 & 2 & 1 & 0 & 0 \\ 0 & 0 & 0 & 2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 2 \end{pmatrix}$$
- $$\begin{pmatrix} 3 & 0 & 0 & 0 & 0 & 0 \\ 0 & 3 & 0 & 0 & 0 & 0 \\ 0 & 0 & 2 & 1 & 0 & 0 \\ 0 & 0 & 0 & 2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 2 & 1 \\ 0 & 0 & 0 & 0 & 0 & 2 \end{pmatrix}$$
- $$\begin{pmatrix} 3 & 1 & 0 & 0 & 0 & 0 \\ 0 & 3 & 0 & 0 & 0 & 0 \\ 0 & 0 & 2 & 1 & 0 & 0 \\ 0 & 0 & 0 & 2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 2 & 1 \\ 0 & 0 & 0 & 0 & 0 & 2 \end{pmatrix}$$

- 3.14. Let V be an inner product space and S be a subset of V . Let \bar{S} denote the closure of S in V with respect to the topology induced by the metric given by the inner product. Which of the following statements is true?

- $S = (S^\perp)^\perp$
- $\bar{S} = (S^\perp)^\perp$
- $\text{span}(S) = (S^\perp)^\perp$
- $S^\perp = ((S^\perp)^\perp)^\perp$

- 3.15. Let

$$\mathbf{A} = \begin{pmatrix} 1 & 2 & 0 \\ 0 & 0 & -2 \\ 0 & 0 & 1 \end{pmatrix} \quad (3.15.1)$$

and

$$Q(\mathbf{x}) = \mathbf{x}^T \mathbf{A} \mathbf{x} \quad (3.15.2)$$

Which of the following statements is true?

- The matrix of second order partial derivatives of the quadratic form Q is $2\mathbf{A}$
- The rank of the quadratic form Q is 2
- The signature of the quadratic form Q is $++0$
- The quadratic form Q take the value 0 for some non-zero vector \mathbf{x}

- 3.16. Assume that a non-singular matrix

$$\mathbf{A} = \mathbf{L} + \mathbf{D} + \mathbf{U} \quad (3.16.1)$$

where \mathbf{L} and \mathbf{U} are lower and upper triangular matrices respectively with all diagonal entries are zero, and \mathbf{D} is a diagonal matrix. Let \mathbf{x}^* be the solution of $\mathbf{A}\mathbf{x} = \mathbf{b}$. Then the Gauss-Seidel iteration method

$$\mathbf{x}_{k+1} = \mathbf{H}\mathbf{x}_k + \mathbf{c}, k = 0, 1, 2, \dots \quad (3.16.2)$$

with $\|\mathbf{H}\| < 1$ converges to \mathbf{x}^* provided \mathbf{H} is equal to

- $-\mathbf{D}^{-1}(\mathbf{L} + \mathbf{U})$
- $-(\mathbf{D} + \mathbf{L})^{-1}\mathbf{U}$
- $-\mathbf{D}(\mathbf{L} + \mathbf{U})^{-1}$
- $-(\mathbf{L} - \mathbf{D})^{-1}\mathbf{U}$

- 3.17. Consider a Markov Chain with state space $S =$

$\{1, 2, 3\}$ and transition matrix

$$P = \begin{matrix} & \begin{matrix} 1 & 2 & 3 \end{matrix} \\ \begin{matrix} 1 \\ 2 \\ 3 \end{matrix} & \begin{pmatrix} 0 & \frac{1}{2} & \frac{1}{2} \\ \frac{1}{2} & 0 & \frac{1}{2} \\ \frac{1}{2} & \frac{1}{2} & 0 \end{pmatrix} \end{matrix} \quad (3.17.1)$$

Let π be a stationary distribution of the Markov chain and $d(1)$ denote the period of state 1. Which of the following statements are correct?

- a) $d(1) = 1$
- b) $d(1) = 2$
- c) $\pi_1 = \frac{1}{2}$
- d) $\pi_1 = \frac{1}{3}$

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4.1. Let \mathbf{A} be a real symmetric matrix and $\mathbf{B} = \mathbf{I} + i\mathbf{A}$, where $i^2 = -1$. Then choose the correct option.

- a) \mathbf{B} is invertible if and only if \mathbf{A} is invertible.
- b) All Eigenvalues of \mathbf{B} are necessarily real.
- c) $\mathbf{B} - \mathbf{I}$ is necessarily invertible.
- d) \mathbf{B} is necessarily invertible.

Solution: See Table 4.1.1.

Statement 1.	B is invertible if and only if A is invertible.
False statement	Matrix B is invertible even if A is non invertible.
Example:	<p>Consider a matrix</p> $\mathbf{A} = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \quad (4.1.1)$ <p>a real non invertible,symmetric matrix.</p> $\Rightarrow \mathbf{B} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + i \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} = \begin{pmatrix} 1+i & 0 \\ 0 & 1 \end{pmatrix} \quad (4.1.2)$ <p>is invertible even if A is non invertible.</p>
Statement 2.	All Eigenvalues of B are necessarily real.
False statement	Matrix B can have complex Eigenvalues.
Proof :	<p>Eigen values of B = Eigen values of (I) + i (Eigen values of A).</p> <p>Clearly from (4.1.2) above Eigen values of B are 1 and $1 + i$ respectively.</p> <p>Hence B can also have complex Eigen value.</p>
Statement 3.	B – I is necessarily invertible.
False statement	B – I = $i\mathbf{A}$ will be invertible if A , is invertible.
Proof:	<p>We have B – I = $i\mathbf{A}$</p> $\Rightarrow \mathbf{B} - \mathbf{I} = i\mathbf{A} = \begin{pmatrix} i & 0 \\ 0 & 0 \end{pmatrix}, \text{from (4.1.1)}$ <p>Hence B – I is not invertible,unless A is invertible.</p>
Statement 4.	B is necessarily invertible.
Correct Statement:	Matrix B has non zero Eigen values corresponding to Eigenvector X .
Proof:	<p>Let X be an Eigen vector of A corresponding to Eigen value λ</p> <p>also, $\lambda \in \mathbb{R}$</p> $\Rightarrow \mathbf{A}X = \lambda X$ $\therefore \mathbf{B}X = (\mathbf{I} + i\mathbf{A})X = \mathbf{I}X + i\mathbf{A}X = X + i\lambda X$ $\Rightarrow \mathbf{B}X = (1 + i\lambda)X$ <p>Therefore, $1 + i\lambda$ is an Eigen value of B, corresponding to Eigen vector X,which are non zero.</p> <p>Hence, B is necessarily invertible.</p>

TABLE 4.1.1: Solution summary

4.2. Let $\mathbf{A} = \begin{pmatrix} 0 & 1 \\ -1 & 1 \end{pmatrix}$. Then the smallest positive integer n such that $\mathbf{A}^n = \mathbf{I}$ is

Solution: *Property of eigen values of A:* Let \mathbf{A} be an arbitrary $n \times n$ matrix of complex numbers with eigen values $\lambda_1, \lambda_2, \dots, \lambda_n$. Then the eigen values of k^{th} power of \mathbf{A} , that is the eigen values of \mathbf{A}^k , for any positive integer k are $\lambda_1^k, \lambda_2^k, \dots, \lambda_n^k$. Let us calculate the eigen values of \mathbf{A} .

$$\mathbf{A} = \begin{pmatrix} 0 & 1 \\ -1 & 1 \end{pmatrix} \quad (4.2.1)$$

$$\det(\mathbf{A} - \lambda \mathbf{I}) = 0 \quad (4.2.2)$$

$$\begin{vmatrix} -\lambda & 1 \\ -1 & 1 - \lambda \end{vmatrix} = 0 \quad (4.2.3)$$

$$-\lambda(1 - \lambda) + 1 = 0 \quad (4.2.4)$$

$$\lambda^2 - \lambda + 1 = 0 \quad (4.2.5)$$

$$\Rightarrow \lambda = \frac{-1 \pm \sqrt{3}i}{2} \quad (4.2.6)$$

From the above property, the eigen values of \mathbf{A}^n are λ^n . Also as it is given that $\mathbf{A}^n = \mathbf{I}$,

$$\Rightarrow \lambda^n = 1 \quad (4.2.7)$$

$$\Rightarrow \left(\frac{-1 \pm \sqrt{3}i}{2} \right)^n = 1 \quad (4.2.8)$$

Clearly $n \neq 1$. For $n = 2$,

$$\left(\frac{-1 \pm \sqrt{3}i}{2} \right)^2 = \frac{-1 \mp \sqrt{3}i}{2} \quad (4.2.9)$$

For $n = 4$,

$$\left(\frac{-1 \pm \sqrt{3}i}{2} \right)^4 = \frac{-1 \pm \sqrt{3}i}{2} \quad (4.2.10)$$

For $n = 6$,

$$\left(\frac{-1 \pm \sqrt{3}i}{2} \right)^6 = 1 \quad (4.2.11)$$

Hence $n = 6$ is the smallest positive integer.

4.3. Let $\mathbf{A} = \begin{pmatrix} 1 & -1 & 1 \\ 1 & 1 & 1 \\ 2 & 3 & \alpha \end{pmatrix}$ and $\mathbf{b} = \begin{pmatrix} 1 \\ 3 \\ \beta \end{pmatrix}$. Then the system $\mathbf{AX} = \mathbf{b}$ over the real numbers has

- No solution when $\beta \neq 7$
- Infinite number of solutions when $\alpha \neq 2$
- Infinite number of solutions when $\alpha = 2$ and $\beta \neq$

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d) A unique solution if $\alpha \neq 2$

Solution: First we derive the Row Reduced Echelon Form (RREF) of the augmented matrix of the system $\mathbf{AX} = \mathbf{b}$ as follows,

$$\begin{pmatrix} 1 & -1 & 1 & 1 \\ 1 & 1 & 1 & 3 \\ 2 & 3 & \alpha & \beta \end{pmatrix} \xrightarrow[R_3=R_3-2R_1]{R_2=R_2-R_1} \begin{pmatrix} 1 & -1 & 1 & 1 \\ 0 & 2 & 0 & 2 \\ 0 & 5 & \alpha-2 & \beta-2 \end{pmatrix} \quad (4.3.1)$$

$$\xrightarrow{R_2=\frac{1}{2}R_2} \begin{pmatrix} 1 & -1 & 1 & 1 \\ 0 & 1 & 0 & 1 \\ 0 & 5 & \alpha-2 & \beta-2 \end{pmatrix} \quad (4.3.2)$$

$$\xrightarrow{R_1=R_1+R_2} \begin{pmatrix} 1 & 0 & 1 & 2 \\ 0 & 1 & 0 & 1 \\ 0 & 5 & \alpha-2 & \beta-2 \end{pmatrix} \quad (4.3.3)$$

$$\xrightarrow{R_3=R_3-5R_2} \begin{pmatrix} 1 & 0 & 1 & 2 \\ 0 & 1 & 0 & 1 \\ 0 & 0 & \alpha-2 & \beta-7 \end{pmatrix} \quad (4.3.4)$$

From the RREF of the augmented matrix of the system $\mathbf{AX} = \mathbf{b}$ in (4.3.4) we make the following observations for different values of α and β in Table 4.3.1. ,

Values	Observations
$\beta \neq 7$	Then the existence of solution and the number of solutions will entirely depend on value of α
$\alpha = 2$ $\beta \neq 7$	Then RREF in (4.3.4) will contain Zero Row in R_3 . Moreover solvability condition will not satisfy. \Rightarrow system will have Zero solutions
$\alpha \neq 2$	RREF in (4.3.4) will have all pivots \Rightarrow RREF in (4.3.4) will be fullrank $\Rightarrow \mathbf{AX} = \mathbf{b}$ have unique solution.

TABLE 4.3.1

Hence, if $\alpha \neq 2$ then the system $\mathbf{AX} = \mathbf{b}$ has unique solution.

4.4. Consider a Markov chain $\{X_n | n \geq 0\}$ with state space $\{1, 2, 3\}$ and transition matrix

$$\mathbf{P} = \begin{pmatrix} 0 & \frac{1}{2} & \frac{1}{2} \\ \frac{1}{2} & 0 & \frac{1}{2} \\ \frac{1}{2} & \frac{1}{2} & 0 \end{pmatrix}$$

Then, $P(X_3 = 1 | X_0 = 1)$ equals

Solution: The three step transitional probabilities are given as,

$$P(X_3 = j | X_0 = i) = P(X_{n+3} = j | X_n = i) = (\mathbf{P}^3)_{ij} \text{ for any } n \quad (4.4.1)$$

$$\mathbf{P}^3 = \begin{pmatrix} 0 & \frac{1}{2} & \frac{1}{2} \\ \frac{1}{2} & 0 & \frac{1}{2} \\ \frac{1}{2} & \frac{1}{2} & 0 \end{pmatrix}^3 = \begin{pmatrix} \frac{1}{8} & \frac{3}{8} & \frac{3}{8} \\ \frac{3}{8} & \frac{1}{8} & \frac{3}{8} \\ \frac{3}{8} & \frac{3}{8} & \frac{1}{8} \end{pmatrix} \quad (4.4.2)$$

From (4.4.2),

$$P(X_3 = 1 | X_0 = 1) = (\mathbf{P}^3)_{11} = \frac{1}{4} \quad (4.4.3)$$

4.5. Let \mathbf{A} be an $m \times n$ matrix with rank r . If the linear system $\mathbf{A}\mathbf{X} = \mathbf{b}$ has a solution for each $\mathbf{b} \in \mathbf{R}^m$, then

- $m = r$
- the column space of \mathbf{A} is a proper subspace of \mathbf{R}^m
- the null space of \mathbf{A} is a non-trivial subspace of \mathbf{R}^n whenever $m = n$
- $m \geq n$ implies $m = n$

Solution: Theorem

Theorem 4.1. Consider the $m \times n$ system $Ax = b$, with either $b \neq 0$ or $b = 0$. We distinguish the following cases:

- Unique Solution:** If $\text{rank}[A, b] = \text{rank}(A) = n \leq m$, then and only then the system has a unique solution. In this case, indeed as many as $m - n$ equations are redundant. And the solution $\mathbf{X} = \mathbf{A}^{-1}\mathbf{b}$. This is called as **Exactly Determined**.
- No Solution:** If $\text{rank}[A, b] > \text{rank}(A)$ which necessarily implies $\mathbf{b} \neq 0$ and $m > \text{rank}(A)$, then and only then the system has no solution. This is called as **Overdetermined**.

See Table 4.5.1 If the columns of an $m \times n$ matrix \mathbf{A} span \mathbf{R}^m then the equation $\mathbf{A}\mathbf{x} = \mathbf{b}$ is consistent for each \mathbf{b} in \mathbf{R}^m .

The **null space** of \mathbf{A} is defined to be

$$\text{Null}(\mathbf{A}) = \{\mathbf{x} \in \mathbf{R}^n | \mathbf{A}\mathbf{x} = 0\} \quad (4.5.1)$$

$$\mathbf{A} = \begin{pmatrix} -3 & -2 & 4 \\ 14 & 8 & -18 \\ 4 & 2 & -4 \end{pmatrix} \quad (4.5.2)$$

Reduced Row Echelon form is

$$\text{RREF}(\mathbf{A}) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (4.5.3)$$

\therefore the only possible nullspace of the matrix \mathbf{A} is $\begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix}$.

Let \mathbf{B} be given as

$$\mathbf{B} = \begin{pmatrix} -3 & -2 & 4 \\ 14 & 8 & -18 \\ 4 & 2 & -4 \\ 28 & 16 & -36 \\ 8 & 4 & -8 \end{pmatrix} \quad (4.5.4)$$

Reduced Row Echelon form is

$$\text{RREF}(\mathbf{B}) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad (4.5.5)$$

\therefore the rank of matrix $\mathbf{B} = 3$.

4.6. Let $\mathbf{M} = \left\{ \begin{pmatrix} a & b \\ c & d \end{pmatrix} : a, b, c, d \in \mathbb{Z} \text{ and eigen values of } \mathbf{A} \in \mathbb{Q} \right\}$

- \mathbf{M} is empty
- $\mathbf{M} = \left\{ \begin{pmatrix} a & b \\ c & d \end{pmatrix} : a, b, c, d \in \mathbb{Z} \right\}$
- If $\mathbf{A} \in \mathbf{M}$ then the eigen values of $\mathbf{A} \in \mathbb{Z}$
- If $\mathbf{A}, \mathbf{B} \in \mathbf{M}$ such that $\mathbf{AB} = \mathbf{I}$ then $|\mathbf{A}| \in \{+1, -1\}$

Solution: See Table 4.6.1.

Options	Observations
$m = r$	<p>The rank of any matrix \mathbf{A} is the dimension of its column space. When the number of rows (m) is equal to the rank (r) of the matrix, then their linear combination gives us span of \mathbf{R}^m.</p> <p>\therefore This statement is True.</p>
the column space of \mathbf{A} is a proper subspace of \mathbf{R}^m	<p>Any subspace of a vector space \mathbf{V} other than \mathbf{V} itself is considered a proper subspace of \mathbf{V}. Which means that linear combination of \mathbf{A} will span less than m. That will make the resultant \mathbf{b} span strictly less than m. But it is given that $\mathbf{b} \in \mathbf{R}^m$, which is contradicting.</p> <p>\therefore This statement is False.</p>
the null space of \mathbf{A} is a non-trivial subspace of \mathbf{R}^n whenever $m = n$	<p>From (4.5.2) we see that even when $m = n$ then also we are getting a trivial nullspace.</p> <p>\therefore This statement is False.</p>
$m \geq n$ implies $m = n$	<p>It is given that the number of rows are greater than the column, and it is given that there exists a solution. If we refer to theorem (4.1) we see that the corresponding system will be Exactly Determined system.</p> <p>As an example, it will look like (4.5.4).</p> <p>\therefore This statement is True.</p>

TABLE 4.5.1: Solution

\mathbf{M} is empty	Consider $\mathbf{A}=\mathbf{I}=\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$. The elements of $\mathbf{A} \in \mathbb{Z}$ and its eigen values $1 \in \mathbb{Q}$. So, \mathbf{M} is not empty.
$\mathbf{M} = \left\{ \begin{pmatrix} a & b \\ c & d \end{pmatrix} : a, b, c, d \in \mathbb{Z} \right\}$	<p>Let $\mathbf{A}=\begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$ where elements of $\mathbf{A} \in \mathbb{Z}$. The characteristic equation can be written as :</p> $\lambda^2 + 1 = 0 \implies \lambda = \pm i$

	We see that $\lambda \in \mathbb{C}$ which is contradicting the main definition of \mathbf{M} . So, this is not correct.
Eigen values of $\mathbf{A} \in \mathbb{Z}$	<p>Given $\mathbf{A} \in \mathbf{M}$. Let λ_1, λ_2 be the eigen values of \mathbf{A}. The characteristic polynomial can be written as:</p> $\lambda^2 - \text{tr}(\mathbf{A})\lambda + \det \mathbf{A} = 0 \text{ where } \text{tr}(\mathbf{A}) = \lambda_1 + \lambda_2, \det \mathbf{A} = \lambda_1 \lambda_2$ <p>Given the eigen values $\lambda_1, \lambda_2 \in \mathbb{Q}$, For this to be possible the discriminant of above equation should $\in \mathbb{Z}$</p> $\sqrt{(\lambda_1 + \lambda_2)^2 - 4\lambda_1 \lambda_2} \in \mathbb{Z}$ $\Rightarrow \sqrt{(\lambda_1 - \lambda_2)^2} \in \mathbb{Z}$ $\Rightarrow \lambda_1 - \lambda_2 \in \mathbb{Z} \text{ This is possible when both } \lambda_1, \lambda_2 \in \mathbb{Z}.$
If $\mathbf{AB}=\mathbf{I}$ then $ \mathbf{A} \in \{+1, -1\}$	<p>As $\mathbf{A}, \mathbf{B} \in \mathbf{M} \Rightarrow \mathbf{A} , \mathbf{B} \in \mathbb{Z}$</p> <p>Given $\mathbf{AB}=\mathbf{I} \Rightarrow \mathbf{A} \mathbf{B} =1$</p> <p>This is possible only when $\mathbf{A} = \mathbf{B} = \pm 1$</p>
Conclusion	options 3) and 4) are correct.

TABLE 4.6.1: Solution

4.7. Let \mathbf{A} be a 3×3 matrix with real entries. Identify the correct statements.

- a) \mathbf{A} is necessarily diagonalizable over \mathbf{R}
- b) If \mathbf{A} has distinct real eigen values then it is diagonalizable over \mathbf{R}
- c) If \mathbf{A} has distinct eigen values then it is diagonalizable over \mathbf{C}
- d) If all eigen values are non zero then it is diagonalizable over \mathbf{C}

Solution: See Table 4.7.1.

Statement 1.	A is necessarily diagonalizable over \mathbf{R}
False statement Example:	<p>Matrix A is diagonalizable if and only if there is a basis of \mathbf{R}^3 consisting of eigenvectors of A. Consider a matrix</p> $\begin{pmatrix} 1 & 1 & 0 \\ 0 & 1 & 1 \\ 0 & 0 & 4 \end{pmatrix} \quad (4.7.1)$ <p>Eigen values are:</p> $\begin{pmatrix} 1-\lambda & 1 & 0 \\ 0 & 1-\lambda & 1 \\ 0 & 0 & 4-\lambda \end{pmatrix} = 0. \implies \lambda_1 = 1, \lambda_2 = 4 \quad (4.7.2)$ <p>$\lambda_1 = 1$ has eigen vector $\begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}$ and $\lambda_2 = 4$ has eigen vector $\begin{pmatrix} 1 \\ 3 \\ 9 \end{pmatrix}$ (4.7.3)</p> <p>We have found only two linearly independent eigenvectors for A, not diagonalisable</p>
Statement 2.	If A has distinct real eigen values than it is diagonalizable over \mathbf{R}
True statement	Distinct real eigenvalues implies linearly independent eigenvectors . and if a matrix has n linearly independent vectors than it is diagonalizable.
Proof 1:	<p>Distinct eigen values implies linearly independent vectors that spans entire space. Consider 2 eigen vectors \mathbf{v}, \mathbf{w} with eigen values λ, μ respectively. such that $\lambda \neq \mu$</p> $\alpha(\mathbf{v}) + \beta(\mathbf{w}) = 0 \quad (4.7.4)$ $\alpha A(\mathbf{v}) + \beta A(\mathbf{w}) = 0 \quad (4.7.5)$ $\alpha \lambda \mathbf{v} + \beta \mu \mathbf{w} = 0 \quad (4.7.6)$ <p>Multiplying (4.7.4) with $-\lambda$ and subtracting from (4.7.6) we have,</p> $\beta(\mu - \lambda)\mathbf{w} = 0 \quad (4.7.7)$ <p>eigen values are distinct $(\mu - \lambda) \neq 0$. From equation (4.7.7) we have, $\beta = 0$ substituting $\beta = 0$ in equation (4.7.4) we have, $\alpha = 0$. As, $\mathbf{v} \neq 0$ which proves that vectors are linearly independent.</p> <p>If a matrix has n linearly independent vectors than it is diagonalizable If $(\mathbf{p}_1 \ \mathbf{p}_2 \ \cdots \ \mathbf{p}_n)$ are n independent eigen vectors then, $A\mathbf{p}_1 = \lambda\mathbf{p}_1, \dots, A\mathbf{p}_n = \lambda\mathbf{p}_n$</p> $D = \begin{pmatrix} \lambda_1 & 0 & \cdots & 0 \\ 0 & \lambda_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \lambda_n \end{pmatrix} P = (\mathbf{p}_1 \ \mathbf{p}_2 \ \cdots \ \mathbf{p}_n) \quad (4.7.8)$ <p>Now, $A\mathbf{p}_i = \lambda_i\mathbf{p}_i \implies AP = PD$</p>
Proof 2:	

	so, $P^{-1}AP = D$ is a diagonal matrix.
Statement 3.	If A has distinct real eigen values than it is diagonalizable over \mathbb{C}
True statement	If A is an $N \times N$ complex matrix with n distinct eigenvalues, then any set of n corresponding eigenvectors form a basis for \mathbb{C}^n
Proof:	It is sufficient to prove that the set of eigenvectors is linearly independent which is proved in statement 2.
Example:	$A = \begin{pmatrix} 4 & 0 & -2 \\ 2 & 5 & 4 \\ 0 & 0 & 5 \end{pmatrix} \quad (4.7.9)$ <p>Eigen values of A are:</p> $\lambda_1 = 2, \lambda_2 = 3, \lambda_3 = 6 \quad (4.7.10)$
	<p>Eigen vectors are:</p> $x_1 = \begin{pmatrix} -1 \\ 1 \\ 0 \end{pmatrix}, x_2 = \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}, x_3 = \begin{pmatrix} -1 \\ -1 \\ 2 \end{pmatrix} \quad (4.7.11)$ <p>Matrix A is diagonalizable because there is a basis of \mathbb{C}^3 consisting of eigenvectors of A.</p>
Statement 4.	If all eigen values are non zero than it is diagonalizable over \mathbb{C}
False Statement:	Matrix would be diagonalizable if and only if it has linearly independent eigenvectors .
Example:	<p>Consider a matrix</p> $\begin{pmatrix} 1 & 1 & 0 \\ 0 & 1 & 1 \\ 0 & 0 & 4 \end{pmatrix} \quad (4.7.12)$ <p>Eigen values are:</p> $\begin{pmatrix} 1-\lambda & 1 & 0 \\ 0 & 1-\lambda & 1 \\ 0 & 0 & 4-\lambda \end{pmatrix} = 0. \implies \lambda_1 = 1, \lambda_2 = 4 \neq 0 \quad (4.7.13)$ <p>$\lambda_1 = 1$ has eigen vector $\begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}$ and $\lambda_2 = 4$ has eigen vector $\begin{pmatrix} 1 \\ 3 \\ 9 \end{pmatrix}$ (4.7.14)</p> <p>We have found only two linearly independent eigenvectors for A, not diagonalisable.</p>

TABLE 4.7.1: Solution summary

Given	<p>V be a vector space over C of all the polynomials in a variable X of degree atmost 3</p> $D : P_3 \rightarrow P_3$ <p>$D : V \rightarrow V$ be the linear operator given by differentiation wrt X</p> $D(P(x)) \rightarrow P'(x)$ <p>A be the matrix of D wrt some basis for V</p> <p>Assume basis for V be $\{1, x, x^2, x^3\}$</p>
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TABLE 4.8.1

4.8. Let V be a vector space over C of all the polynomials in a variable X of degree atmost 3. Let $D : V \rightarrow V$ be the linear operator given by differentiation with respect to X . Let A be the matrix of D with respect to some basis for V . Which of the following are true?

- a) A is nilpotent matrix
- b) A is diagonalizable matrix
- c) the rank of A is 2
- d) the Jordan canonical form of A is

$$\begin{pmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

Solution: See Tables 4.8.1, 4.8.2 and 4.8.3

4.9. For every 4×4 real symmetric non-singular matrix A there exists a positive integer p such that

- a) $pI + A$ is positive definite
- b) A^p is positive definite
- c) A^{-p} is positive definite
- d) $\exp(pA) - I$ is positive definite

Solution: A matrix is real symmetric implies its eigen values are real and eigen vectors are orthogonal, that is its eigen value decomposition is

$$A = PDP^T \quad (4.9.1)$$

D is the diagonal matrix containing the real eigen values of A

P has the corresponding eigen vectors

$$PP^T = P^T P = I \quad (4.9.2)$$

A real matrix is positive definite if

$$\mathbf{x}^T A \mathbf{x} > 0 \quad (4.9.3)$$

$$\implies \mathbf{x}^T \lambda \mathbf{x} > 0 \quad (4.9.4)$$

$$\implies \lambda \mathbf{x}^T \mathbf{x} > 0 \quad (4.9.5)$$

$$\implies \lambda > 0 \quad (4.9.6)$$

In other words, all the eigen values of A are positive See Table 4.9.1

Let A be

$$A = PDP^T \quad (4.9.7)$$

$$D = \begin{pmatrix} \lambda_1 & 0 & 0 & 0 \\ 0 & \lambda_2 & 0 & 0 \\ 0 & 0 & \lambda_3 & 0 \\ 0 & 0 & 0 & \lambda_4 \end{pmatrix} \quad (4.9.8)$$

From the table, the choices would be option 1,2,3

4.10. Let A be an $m \times n$ matrix of rank m with $n > m$. If for some non-zero real number α , we have $\mathbf{x}^T A A^T \mathbf{x} = \alpha \mathbf{x}^T \mathbf{x}$, for all $\mathbf{x} \in \mathbf{R}^m$, then $A^T A$ has,

- a) exactly two distinct eigenvalues.
- b) 0 as an eigenvalue with multiplicity $n - m$.
- c) α as a non-zero eigenvalue.
- d) exactly two non-zero distinct eigenvalues.

Solution: Refer Table 4.10.1.

Refer Table 4.10.2.

4.11. Consider a Markov chain with five states

$\{1, 2, 3, 4, 5\}$ and transition matrix

$$P = \begin{pmatrix} \frac{1}{2} & 0 & 0 & \frac{1}{2} & 0 \\ 0 & \frac{1}{7} & 0 & 0 & \frac{6}{7} \\ \frac{1}{5} & \frac{1}{5} & \frac{1}{5} & \frac{1}{5} & \frac{1}{5} \\ \frac{1}{3} & 0 & 0 & \frac{2}{3} & 0 \\ 0 & \frac{5}{8} & 0 & 0 & \frac{3}{8} \end{pmatrix} \quad (4.11.1)$$

Which of the following are true?

- a) 3 and 1 are in the same communicating class
- b) 1 and 4 are in the same communicating class
- c) 4 and 2 are in the same communicating class
- d) 2 and 5 are in the same communicating class

Solution: See Tables 4.11.1 and 4.11.2

Matrix	$D(1) = 0 = 0.1 + 0.x + 0.x^2 + 0.x^3$ $D(1) = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$ $D(x) = 1 = 1.1 + 0.x + 0.x^2 + 0.x^3$ $D(x) = \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix}$ $D(x^2) = 2x = 0.1 + 2.x + 0.x^2 + 0.x^3$ $D(x^2) = \begin{pmatrix} 0 \\ 2 \\ 0 \\ 0 \end{pmatrix}$ $D(x^3) = 3x^2 = 0.1 + 0.x + 3.x^2 + 0.x^3$ $D(x^3) = \begin{pmatrix} 0 \\ 0 \\ 3 \\ 0 \end{pmatrix}$ $\text{Matrix } A = \begin{pmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 2 & 0 \\ 0 & 0 & 0 & 3 \\ 0 & 0 & 0 & 0 \end{pmatrix}$
Inference	<p>An $n \times n$ matrix with λ as diagonal elements, ones on the super diagonal and zeroes in all other entries is nilpotent with minimal polynomial $(A - \lambda I)^n$</p>
Nilpotent	$A = \begin{pmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 2 & 0 \\ 0 & 0 & 0 & 3 \\ 0 & 0 & 0 & 0 \end{pmatrix}$ <p>All eigen values of matrix A is 0</p> <p>Thus, above matrix is nilpotent matrix</p> <p>Thus, above statement is true</p>

TABLE 4.8.2

Diagonalizable	$A = \begin{pmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 2 & 0 \\ 0 & 0 & 0 & 3 \\ 0 & 0 & 0 & 0 \end{pmatrix}$ <p> $Rank(A) + nullity(A) = \text{no of column}$ $Rank(A) = 3, \text{ no of column} = 4$ $nullity(A) = 4 - 3 = 1$ means there exists only one linearly independent eigen vector corresponding to 0 eigen values Thus, matrix A is not Diagonalizable. Thus, above statement is false </p>
Rank	$A = \begin{pmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 2 & 0 \\ 0 & 0 & 0 & 3 \\ 0 & 0 & 0 & 0 \end{pmatrix}$ <p> Rank of matrix A is 3 Thus, above statement is false </p>
Jordan CF	<p> Assume characteristic polynomial of matrix A is $c_A(x)$ $c_A(x) = x^4$ Assume minimal polynomial of A is $m_A(x)$ $m_A(x)$ always divide $c_A(x)$ $m_A(x) = \{x, x^2, x^3, x^4\}$ Minimal polynomial always annihilates its matrix. Thus, we see that $m_A(A) = \{A = 0, A^2 = 0, A^3 = 0, A^4 = 0\}$ But we see that neither A is zero matrix nor A^2 and A^3 equal to zero but A^4 is equal to zero. Thus, x^4 is minimal polynomial. Algebraic Multiplicity = $a_M(\lambda = 0) = 4$ Geometric Multiplicity = $g_M(\lambda = 0) = nullity(A - 0I) = nullity(A) = 1$ Hence, Jordan form of block size 4 Using Inference, $\mathbf{J} = \begin{pmatrix} \lambda & 1 & 0 & 0 \\ 0 & \lambda & 1 & 0 \\ 0 & 0 & \lambda & 1 \\ 0 & 0 & 0 & \lambda \end{pmatrix}$ $\lambda = 0$ $\begin{pmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \end{pmatrix}$ <p> which is same as given in the question. Thus, statement is true </p> </p>

OPTIONS	DERIVATIONS
Choice 1	$p\mathbf{I} + \mathbf{A} = \mathbf{P}(p\mathbf{I})\mathbf{P}^T + \mathbf{P}\mathbf{D}\mathbf{P}^T \quad (4.9.9)$
	$= \mathbf{P}\mathbf{D}_1\mathbf{P}^T \quad (4.9.10)$
	$\mathbf{D}_1 = \begin{pmatrix} \lambda_1 + p & 0 & 0 & 0 \\ 0 & \lambda_2 + p & 0 & 0 \\ 0 & 0 & \lambda_3 + p & 0 \\ 0 & 0 & 0 & \lambda_4 + p \end{pmatrix} \quad (4.9.11)$
	<p>Some of the eigen values of \mathbf{A} may be negative. All the eigen values in \mathbf{D}_1 are positive only if</p> $p > \lambda_i \quad \forall i \in [1, 4] \quad (4.9.12)$
Choice 2	$\mathbf{A}^2 = \mathbf{A}\mathbf{A} \quad (4.9.13)$
	$= (\mathbf{P}\mathbf{D}\mathbf{P}^T)(\mathbf{P}\mathbf{D}\mathbf{P}^T) \quad (4.9.14)$
	$= \mathbf{P}\mathbf{D}^2\mathbf{P}^T \quad (4.9.15)$
	<p>Similarly, $\mathbf{A}^p = \mathbf{P}\mathbf{D}^p\mathbf{P}^T \quad (4.9.16)$</p>
	$\mathbf{D}^p = \begin{pmatrix} \lambda_1^p & 0 & 0 & 0 \\ 0 & \lambda_2^p & 0 & 0 \\ 0 & 0 & \lambda_3^p & 0 \\ 0 & 0 & 0 & \lambda_4^p \end{pmatrix} \quad (4.9.17)$
	<p>\mathbf{A}^p is positive definite only if p is even.</p>
Choice 3	$\mathbf{A}^{-p} = \mathbf{P}\mathbf{D}^{-p}\mathbf{P}^T \quad (4.9.18)$
	$\mathbf{D}^{-p} = \begin{pmatrix} \lambda_1^{-p} & 0 & 0 & 0 \\ 0 & \lambda_2^{-p} & 0 & 0 \\ 0 & 0 & \lambda_3^{-p} & 0 \\ 0 & 0 & 0 & \lambda_4^{-p} \end{pmatrix} \quad (4.9.19)$
	<p>\mathbf{A}^{-p} is positive definite only if p is even.</p>
Choice 4	$\exp(p\mathbf{A}) = \sum_{k=0}^{\infty} \frac{(p\mathbf{A})^k}{k!} \quad (4.9.20)$
	$\Rightarrow \exp(p\mathbf{A}) - \mathbf{I} = \mathbf{P}\exp(p\mathbf{D})\mathbf{P}^T - \mathbf{P}\mathbf{I}\mathbf{P}^T \quad (4.9.21)$
	$= \mathbf{P}(\exp(p\mathbf{D}) - \mathbf{I})\mathbf{P}^T \quad (4.9.22)$
	$\exp(p\mathbf{D}) - \mathbf{I} = \begin{pmatrix} e^{\lambda_1} - 1 & 0 & 0 & 0 \\ 0 & e^{\lambda_2} - 1 & 0 & 0 \\ 0 & 0 & e^{\lambda_3} - 1 & 0 \\ 0 & 0 & 0 & e^{\lambda_4} - 1 \end{pmatrix} \quad (4.9.23)$
	<p>\mathbf{A} is non-singular</p>
	$\Rightarrow \forall i \in [1, 4], \lambda_i \neq 0 \quad (4.9.24)$
	$e^{\lambda_i} < 1 \quad (4.9.25)$
	<p>So, $\exp(p\mathbf{A}) - \mathbf{I}$ is not positive definite.</p>

TABLE 4.9.1: Solution

Given	Derivation
Given	\mathbf{A} is a $m \times n$ matrix of rank m with $n > m$. A non-zero real number α . To find eigenvalues of $\mathbf{A}^T \mathbf{A}$.
Eigenvalues of $\mathbf{A} \mathbf{A}^T$	$\mathbf{A} \mathbf{A}^T$ is a $m \times m$ matrix and $\mathbf{A}^T \mathbf{A}$ is a $n \times n$ matrix. Let, λ be a non-zero eigen value of $\mathbf{A}^T \mathbf{A}$. $\mathbf{A}^T \mathbf{A} \mathbf{v} = \lambda \mathbf{v} \quad \mathbf{v} \in \mathbf{R}^n \quad (4.10.1)$ $\mathbf{A} \mathbf{A}^T \mathbf{A} \mathbf{v} = \lambda \mathbf{A} \mathbf{v} \quad (4.10.2)$ Let, $\mathbf{x} = \mathbf{A} \mathbf{v} \quad \mathbf{x} \in \mathbf{R}^m \quad (4.10.3)$ $\mathbf{A} \mathbf{A}^T \mathbf{x} = \lambda \mathbf{x} \quad (4.10.4)$ $\mathbf{x}^T \mathbf{A} \mathbf{A}^T \mathbf{x} = \lambda \mathbf{x}^T \mathbf{x} \quad (4.10.5)$ Given, $\mathbf{x}^T \mathbf{A} \mathbf{A}^T \mathbf{x} = \alpha \mathbf{x}^T \mathbf{x} \quad (4.10.6)$ $\implies \alpha \mathbf{x}^T \mathbf{x} = \lambda \mathbf{x}^T \mathbf{x} \quad (4.10.7)$ From equation (4.10.7), $\lambda = \alpha$ as $\ \mathbf{x}\ \neq 0$ As $\text{rank}(\mathbf{A}^T \mathbf{A}) = \text{rank}(\mathbf{A}) = m$ and equation (4.10.7) satisfies the condition in question. Therefore the only non-zero eigen value is α $\mathbf{A}^T \mathbf{A}$ has an eigenvalue α with multiplicity m .
Eigenvalues of $\mathbf{A}^T \mathbf{A}$	$\mathbf{A}^T \mathbf{A}$ is a $n \times n$ matrix. Given $n > m$, We know that, $\mathbf{A}^T \mathbf{A}$ and $\mathbf{A} \mathbf{A}^T$ have same number of non-zero eigenvalues and if one of them has more number of eigenvalues than the other then these eigenvalues are zero. 1. From above, as α is non-zero, $\mathbf{A}^T \mathbf{A}$ has α as its eigenvalue with multiplicity m 2. $\mathbf{A}^T \mathbf{A}$ has 0 as its eigenvalue with multiplicity $n - m$ 3. Therefore, the two distinct eigenvalues of $\mathbf{A}^T \mathbf{A}$ are α and 0.

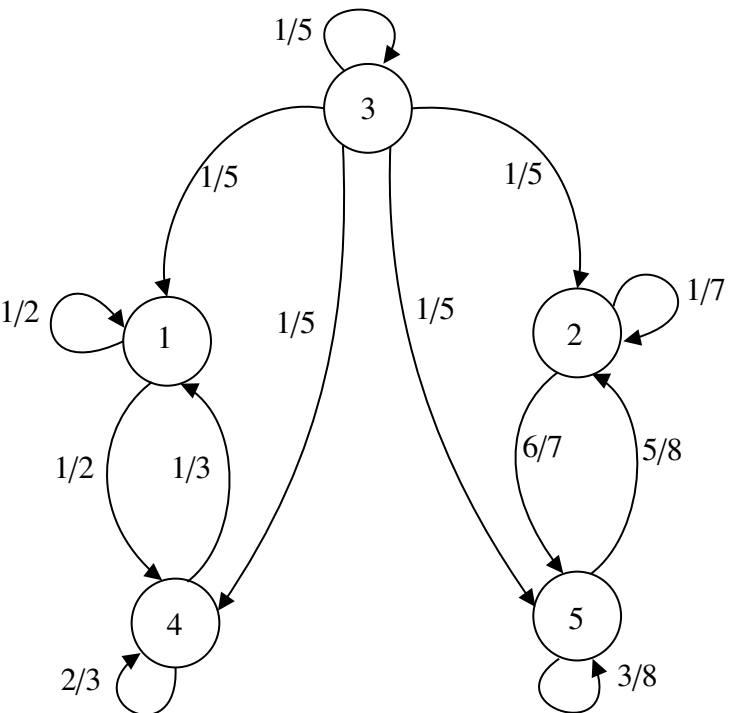
TABLE 4.10.1: Explanation

$\mathbf{A}^T \mathbf{A}$ has exactly two distinct eigenvalues.	True statement
$\mathbf{A}^T \mathbf{A}$ has 0 as an eigenvalue with multiplicity $n - m$	True statement
$\mathbf{A}^T \mathbf{A}$ has α as a non-zero eigenvalue	True statement
$\mathbf{A}^T \mathbf{A}$ has exactly two non-zero distinct eigenvalues.	False statement

TABLE 4.10.2: Solution

Accessibility of states in Markov's chain	We say that state j is accessible from state i , written as $i \rightarrow j$, if $p_{ij}^{(n)} > 0$ for some n . Every state is accessible from itself since $p_{ii}^{(0)} = 1$
Communication between states	Two states i and j are said to communicate, written as $i \leftrightarrow j$, if they are accessible from each other. In other words, $i \leftrightarrow j \text{ means } i \rightarrow j \text{ and } j \rightarrow i.$
Communicating class	For each Markov chain, there exists a unique decomposition of the state space S into a sequence of disjoint subsets C_1, C_2, \dots , $S = \bigcup_{i=1}^{\infty} C_i$ in which each subset has the property that all states within it communicate. Each such subset is called a communication class of the Markov chain.

TABLE 4.11.1: Definition and Result used

Drawing Transition diagram	
Checking whether the states 3 and 1 are in the same communicating class	<p>Here, State 1 is accessible from the state 3. But, State 3 is not accessible from the state 1 i.e. $3 \rightarrow 1, 1 \nrightarrow 3$ $\Rightarrow \boxed{3 \leftrightarrow 1}$</p> <p>Therefore, 3 and 1 are not in the same communicating class.</p>
Checking whether the states 1 and 4 are in the same communicating class	<p>Here, State 1 is accessible from the state 4. Also, State 4 is accessible from the state 1 i.e. $3 \rightarrow 1, 1 \rightarrow 3$ $\Rightarrow \boxed{3 \leftrightarrow 1}$</p> <p>Therefore, 1 and 4 are in the same communicating class.</p>
Checking whether the states 4 and 2 are in the same communicating class	<p>Here, State 2 is not accessible from the state 4. Also, State 4 is not accessible from the state 2 i.e. $4 \nrightarrow 2, 2 \nrightarrow 4$</p>

	$\Rightarrow \boxed{4 \leftrightarrow 2}$ <p>Therefore, 4 and 2 are not in the same communicating class.</p>
Checking whether the states 2 and 5 are in the same communicating class	<p>Here, State 2 is accessible from the state 5. Also, State 5 is accessible from the state 2 i.e. $5 \rightarrow 2, 2 \rightarrow 5$ $\Rightarrow \boxed{2 \leftrightarrow 5}$</p> <p>Therefore, 2 and 5 are in the same communicating class.</p>
Conclusion	<p>Communication classes are:</p> $\boxed{S = \{1, 4\} \cup \{3\} \cup \{2, 5\}}$ <p>Option 2) and 4) are true.</p>

TABLE 4.11.2: Solution

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5.1. Let \mathbf{A} be a 4×4 matrix. Suppose that the null space $N(\mathbf{A})$ of \mathbf{A} is

$$\{(x, y, z, w) \in \mathbf{R}^4 : x + y + z = 0, x + y + w = 0\} \quad (5.1.1)$$

Then which one of the following is correct

- a) $\dim(\text{column space}(\mathbf{A})) = 1$
- b) $\dim(\text{column space}(\mathbf{A})) = 2$
- c) $\text{rank}(\mathbf{A}) = 1$
- d) $\mathbf{S} = \{(1, 1, 1, 0), (1, 1, 0, 1)\}$ is a basis of $N(\mathbf{A})$

Solution: The nullspace is given by

$$\begin{pmatrix} 1 & 1 & 1 & 0 \\ 1 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} x \\ y \\ z \\ w \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \quad (5.1.2)$$

Row reducing the above matrix we get,

$$\begin{pmatrix} 1 & 1 & 1 & 0 \\ 1 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \xleftrightarrow[R_2 \leftarrow R_2 - R_1]{R_2 \leftarrow R_2 \times -1} \begin{pmatrix} 1 & 1 & 1 & 0 \\ 0 & 0 & 1 & -1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \quad (5.1.3)$$

$$\xleftrightarrow{R_1 \leftarrow R_1 - R_2} \begin{pmatrix} 1 & 1 & 0 & 1 \\ 0 & 0 & 1 & -1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \quad (5.1.4)$$

See Table 5.1.1

5.2. Let \mathbf{A} and \mathbf{B} be real invertible matrices such that

$$\mathbf{AB} = -\mathbf{BA}. \quad (5.2.1)$$

Then

- a) $\text{trace} \mathbf{A} = \text{trace}(\mathbf{B}) = 0$
- b) $\text{trace} \mathbf{A} = \text{trace}(\mathbf{B}) = 1$
- c) $\text{trace} \mathbf{A} = 0, \text{trace}(\mathbf{B}) = 1$
- d) $\text{trace}(\mathbf{A}) = 1, \text{trace}(\mathbf{B}) = 0$

Solution: See Tables 5.2.1 and 5.2.2

5.3. Let \mathbf{A} be an $n \times n$ self-adjoint matrix with eigenvalues $\lambda_1, \dots, \lambda_n$. Let,

$$\|\mathbf{X}\|_2 = \sqrt{|\mathbf{X}_1^2| + \dots + |\mathbf{X}_n^2|} \quad (5.3.1)$$

for $\mathbf{X} = (\mathbf{X}_1, \dots, \mathbf{X}_n) \in \mathbb{C}^n$. If

$$p(\mathbf{A}) = a_0 \mathbf{I} + a_1 \mathbf{A} + \dots + a_n \mathbf{A}^n \quad (5.3.2)$$

then $\sup_{\|\mathbf{X}\|_2=1} \|p(\mathbf{A})\mathbf{X}\|_2$ is equal to

Solution: We know that \mathbf{A} is a self adjoint matrix and hence $\mathbf{A} = \mathbf{A}^*$ with eigen values $\lambda_1, \lambda_2, \dots, \lambda_n$. Now as we are given,

$$p(\mathbf{A}) = a_0 \mathbf{I} + a_1 \mathbf{A} + \dots + a_n \mathbf{A}^n \quad (5.3.3)$$

then,

$$(p(\mathbf{A}))^* = a_0 \mathbf{I}^* + a_1 \mathbf{A}^* + \dots + a_n (\mathbf{A}^*)^n \quad (5.3.4)$$

Since, $\mathbf{A} = \mathbf{A}^*$ we can state that,

$$p(\mathbf{A})(p(\mathbf{A}))^* = (p(\mathbf{A}))^* p(\mathbf{A}) \quad (5.3.5)$$

Hence $p(\mathbf{A})$ is a normal matrix. Now using spectral theorem for a normal matrix,

$$\|p(\mathbf{A})\|_2 = \rho(p(\mathbf{A})) \quad (5.3.6)$$

\sup refers to the smallest element that is greater than or equal to every number in the set. Hence, \sup of $\|p(\mathbf{A})\|_2$ will be,

$$= \max \{|\alpha| : \alpha \text{ is the eigen value of } p(\mathbf{A})\} \quad (5.3.7)$$

$$= \max \{|p(\lambda_j)| : j = 1, 2, \dots, n\} \quad (5.3.8)$$

$$= \max \{|a_0 + a_1 \lambda_j + \dots + a_n \lambda_j^n| : j = 1, 2, \dots, n\} \quad (5.3.9)$$

Now, to find $\sup \|p(\mathbf{A})\mathbf{X}\|_2$,

$$= \max \{|a_0 + a_1 \lambda_j + \dots + a_n \lambda_j^n| : j = 1, 2, \dots, n\} \|\mathbf{X}\|_2 \quad (5.3.10)$$

Since, we have to find $\sup_{\|\mathbf{X}\|_2=1}$ i.e.,

$$\|\mathbf{X}\|_2 = \sqrt{|\mathbf{X}_1^2| + \dots + |\mathbf{X}_n^2|} = 1 \quad (5.3.11)$$

Hence the final answer will be,

$$= \max \{|a_0 + a_1 \lambda_j + \dots + a_n \lambda_j^n| : j = 1, 2, \dots, n\} \quad (5.3.12)$$

5.4. Let $p(x) = \alpha x^2 + \beta x + \gamma$ be a polynomial, where $\alpha, \beta, \gamma \in \mathbf{R}$. Fix $X_0 \in \mathbf{R}$. Let $S = \{(a, b, c) \in \mathbf{R}^3 : p(x) = a(x - x_0)^2 + b(x - x_0) + c\}$ for all $x \in \mathbf{R}$. Find the number of elements in S is

- a) 0
- b) 1
- c) Strictly greater than 1 but finite
- d) Infinite

$\dim(C(\mathbf{A})) = 1$	False. Because the number of pivot variables are 2 as obtained in (5.1.4)
$\dim(C(\mathbf{A})) = 2$	True. Since the number of pivot variables are 2, the rank of \mathbf{A} is 2. $\therefore \dim(C(\mathbf{A})) = 2 \quad [\because \dim(C(\mathbf{A})) = \text{rank}(\mathbf{A})]$
$\text{rank}(\mathbf{A}) = 1$	False. Because the $\text{rank}(\mathbf{A}) = 2$, as the number of pivot variables are 2
$\mathbf{S} = \{(1, 1, 1, 0), (1, 1, 0, 1)\}$ is a basis of $N(\mathbf{A})$	False. Let, $\mathbf{u} = \begin{pmatrix} 1 \\ 1 \\ 1 \\ 0 \end{pmatrix}, \mathbf{v} = \begin{pmatrix} 1 \\ 1 \\ 0 \\ 1 \end{pmatrix}$ Consider, $\begin{pmatrix} 1 & 1 & 1 & 0 \\ 1 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} 1 \\ 1 \\ 1 \\ 0 \end{pmatrix} = \begin{pmatrix} 3 \\ 2 \\ 0 \\ 0 \end{pmatrix} \neq \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$ Similarly, $\begin{pmatrix} 1 & 1 & 1 & 0 \\ 1 & 1 & 0 & 1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} 1 \\ 1 \\ 0 \\ 1 \end{pmatrix} = \begin{pmatrix} 2 \\ 3 \\ 0 \\ 0 \end{pmatrix} \neq \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$ Hence, the given vectors do not form the basis.

TABLE 5.1.1

Definition	Matrix \mathbf{A} is said to be similar to matrix \mathbf{B} if there exists matrix \mathbf{P} such that $\mathbf{A} = \mathbf{PBP}^{-1}$
Properties	Similar matrices have same eigenvalues Sum of eigenvalue of a matrix equals its trace From above two properties we can conclude that similar matrices have same trace

TABLE 5.2.1: Similar matrices and Properties

Solution:

$$S = \{(a, b, c) \in \mathbb{R}^3 : p(x) = a(x - x_0)^2 + b(x - x_0) + c\},$$

$$p(x) = \alpha x^2 + \beta x + \gamma \quad (5.4.1)$$

$$\Rightarrow p(x) = (\alpha\beta\gamma) \begin{pmatrix} x^2 & x & 1 \end{pmatrix}^T \quad (5.4.2)$$

$$\forall \mathbf{x} \in R(\text{Fix } X_0) \quad (5.4.3)$$

$$p(x) = (abc) \left((x - x_0)^2 (x - x_0) 1 \right)^T \quad (5.4.4)$$

$$= a(x^2 - 2x_0x + x_0^2) + b(x - x_0) + c \quad (5.4.5)$$

$$= ax^2 + (b - 2ax_0)x + (ax_0^2 - bx_0 + c) \quad (5.4.6)$$

Refer (5.4.2) and (5.4.6) and comparing the coefficients of powers of x,

$$\alpha = a, \beta = b - 2ax_0, \gamma = ax_0^2 - bx_0 + c \quad (5.4.7)$$

$$a = \alpha, b = \beta + 2\alpha x_0, c = \gamma - \alpha x_0^2 + (\beta + 2\alpha x_0)x_0 \quad (5.4.8)$$

Here α, β, γ and x_0 are the real fixed numbers. So a, b, c have unique values.

Hence S contain only 1 element. So option 2 is correct

5.5. Let

$$\mathbf{A} = \begin{pmatrix} 1 & 0 & 2 \\ 1 & -2 & 0 \\ 0 & 0 & -3 \end{pmatrix} \quad (5.5.1)$$

and \mathbf{I} be the 3×3 identity matrix. If

$$6\mathbf{A}^{-1} = a\mathbf{A}^2 + b\mathbf{A} + c\mathbf{I} \quad (5.5.2)$$

for $a, b, c \in \mathbb{R}$ then (a,b,c) equals

a) (1,2,1)

b) (1,-1,2)

c) (4,1,1)

d) (1,4,1)

Solution: Finding the characteristic equation,

$$|\mathbf{A} - \lambda\mathbf{I}| = \begin{vmatrix} 1-\lambda & 0 & 2 \\ 1 & -2-\lambda & 0 \\ 0 & 0 & -3-\lambda \end{vmatrix} \quad (5.5.3)$$

$$\Rightarrow (1-\lambda)(-2-\lambda)(-3-\lambda) = 0 \quad (5.5.4)$$

$$\Rightarrow (\lambda^2 + \lambda - 2)(-3-\lambda) = 0 \quad (5.5.5)$$

$$\Rightarrow \lambda^3 + 4\lambda^2 + \lambda - 6 = 0 \quad (5.5.6)$$

Using Cayley-Hamilton Theorem we get,

$$\mathbf{A}^3 + 4\mathbf{A}^2 + \mathbf{A} - 6\mathbf{I} = 0 \quad (5.5.7)$$

$$\Rightarrow \mathbf{A}^3 + 4\mathbf{A}^2 + \mathbf{A} = 6\mathbf{I} \quad (5.5.8)$$

$$\Rightarrow \mathbf{A}(\mathbf{A}^2 + 4\mathbf{A} + \mathbf{I}) = 6\mathbf{I} \quad (5.5.9)$$

$|\mathbf{A}| = 6 \neq 0$ hence inverse exists. Hence (5.5.9)

we get,

$$6\mathbf{A}^{-1} = \mathbf{A}^2 + 4\mathbf{A} + \mathbf{I} \quad (5.5.10)$$

Comparing (5.5.2) and (5.5.10) we get,

$$a = 1 \quad b = 4 \quad c = 1 \quad (5.5.11)$$

Hence $(a, b, c) = (1, 4, 1)$

5.6. Find the Eigenvalues of the matrix,

$$\mathbf{A} = \begin{pmatrix} 1 & 1 & 2 \\ 1 & -2 & 5 \\ 2 & 5 & -3 \end{pmatrix} \quad (5.6.1)$$

a) -4, 3, -3

b) 4, 3, 1

c) 4, $-4 \pm \sqrt{13}$

d) 4, $-2 \pm \sqrt{7}$

Solution: Using the characteristic equation of the matrix can find the Eigenvalues,

$$|\lambda\mathbf{I} - \mathbf{A}| = 0 \quad (5.6.2)$$

$$\Rightarrow \begin{vmatrix} \lambda-1 & -1 & -2 \\ -1 & \lambda+2 & -5 \\ -2 & -5 & \lambda+3 \end{vmatrix} = 0 \quad (5.6.3)$$

The expression that is obtained after expanding the determinant and simplifying it is,

$$(\lambda-1)(\lambda^2+5\lambda-19) - (5\lambda+31) = 0 \quad (5.6.4)$$

Further simplifying this we obtain the cubic equation,

$$\lambda^3 + 4\lambda^2 - 29\lambda - 12 = 0 \quad (5.6.5)$$

Solving this equation, the Eigenvalues obtained are,

$$\lambda_1 = -7.605, \lambda_2 = -0.394 \text{ and } \lambda_3 = 4 \quad (5.6.6)$$

Therefore, the Eigenvalues of the given matrix are 4, $-4 \pm \sqrt{13}$ (Option 3)

5.7. Consider the vector space V of real polynomials of degree less than or equal to n. Fix distinct real numbers a_0, a_1, \dots, a_k . For $p \in V$

$$\max \{ |p(a_j)| : 0 \leq j \leq k \} \quad (5.7.1)$$

defines a norm on V

a) only if $k < n$

b) only if $k \geq n$

c) if $k+1 \leq n$

d) if $k \geq n + 1$

Solution: Options 2 and 4 are correct as verified in the table 5.7.2

The scalar multiplication and triangle inequality properties holds true for all k .

$$\max \{ |\alpha p(a_j)| \} = |\alpha| \max \{ |p(a_j)| \} \quad (5.7.4)$$

$$\max \{ |p(a_i) + p(a_j)| \} \leq \max \{ |p(a_i)| \} + \max \{ |p(a_j)| \} \quad (5.7.5)$$

The positivity property holds true only if $k \geq n$ as more than n roots are possible when,

$$p(x) = 0 \implies |p(a_j)|_{0 \leq j \leq k} = 0 \quad (5.7.6)$$

$$\implies \max \{ |p(a_j)| : 0 \leq j \leq k \} = 0 \quad (5.7.7)$$

5.8. Let \mathbf{V} be the vector space of polynomials of degree at most 3 in a variable x with coefficients in \mathbb{R} . Let $\mathbf{T} = d/dx$ be the linear transformation of \mathbf{V} to itself given by differentiation.

Which of the following are correct?

- a) \mathbf{T} is invertible
- b) 0 is an eigenvalue of \mathbf{T}
- c) There is a basis with respect to which the matrix of \mathbf{T} is nilpotent.
- d) The matrix of \mathbf{T} with respect to the basis $(1, 1 + x, 1 + x + x^2, 1 + x + x^2 + x^3)$ is diagonal.

Solution: See Tables 5.8.1 , 5.8.2 and 5.8.3.

$\text{trace}(\mathbf{A}) = 0$ $\text{trace}(\mathbf{B}) = 0$	<p>From (5.2.1) we have</p> $\mathbf{AB} = -\mathbf{BA}$ $\Rightarrow \mathbf{A} = \mathbf{B}(-\mathbf{A})\mathbf{B}^{-1}$ <p>So, matrix \mathbf{A} and $(-\mathbf{A})$ are similar.∴</p> $\text{trace}(\mathbf{A}) = \text{trace}(-\mathbf{A})$ $\Rightarrow \text{trace}(\mathbf{A}) = 0$ <p>Similarly From (5.2.1) we have</p> $\mathbf{AB} = -\mathbf{BA}$ $\Rightarrow \mathbf{B} = \mathbf{A}^{-1}(-\mathbf{B})\mathbf{A}$ <p>So, matrix \mathbf{B} and $(-\mathbf{B})$ are similar.∴</p> $\text{trace}(\mathbf{B}) = \text{trace}(-\mathbf{B})$ $\Rightarrow \text{trace}(\mathbf{B}) = 0$ <p>So this statement is true</p>
$\text{trace}(\mathbf{A}) = 1$ $\text{trace}(\mathbf{B}) = 1$	<p>From (5.2.1) we have</p> $\mathbf{AB} = -\mathbf{BA}$ $\Rightarrow \mathbf{A} = \mathbf{B}(-\mathbf{A})\mathbf{B}^{-1}$ <p>So, matrix \mathbf{A} and $(-\mathbf{A})$ are similar.∴</p> $\text{trace}(\mathbf{A}) = \text{trace}(-\mathbf{A})$ $\Rightarrow \text{trace}(\mathbf{A}) = 0.$ <p>As $\text{trace}(\mathbf{A}) = 0$ this statement is false</p>
$\text{trace}(\mathbf{A}) = 0$ $\text{trace}(\mathbf{B}) = 1$	<p>From (5.2.1) we have</p> $\mathbf{AB} = -\mathbf{BA}$ $\Rightarrow \mathbf{B} = \mathbf{A}^{-1}(-\mathbf{B})\mathbf{A}$ <p>So, matrix \mathbf{B} and $(-\mathbf{B})$ are similar.∴</p> $\text{trace}(\mathbf{B}) = \text{trace}(-\mathbf{B})$ $\Rightarrow \text{trace}(\mathbf{B}) = 0.$ <p>As $\text{trace}(\mathbf{B}) = 0$ this statement is false</p>
$\text{trace}(\mathbf{A}) = 1$ $\text{trace}(\mathbf{B}) = 0$	<p>From (5.2.1) we have</p> $\mathbf{AB} = -\mathbf{BA}$ $\Rightarrow \mathbf{A} = \mathbf{B}(-\mathbf{A})\mathbf{B}^{-1}$ <p>So, matrix \mathbf{A} and $(-\mathbf{A})$ are similar.∴</p> $\text{trace}(\mathbf{A}) = \text{trace}(-\mathbf{A})$ $\Rightarrow \text{trace}(\mathbf{A}) = 0.$ <p>As $\text{trace}(\mathbf{A}) = 0$ this statement is false</p>

TABLE 5.2.2: Calculation of trace

Properties	Norm $\forall x \in V$
Positivity	$\ x\ \geq 0, \ x\ = 0 \iff x = 0$
Scalar Multiplication	$\ \alpha x\ = \alpha \ x\ , \alpha \in F$
Triangle Inequality	$\ x + y\ \leq \ x\ + \ y\ $

TABLE 5.7.1: Properties of Norm

For $p \in V$ then the norm, $\max \{ p(a_j) : 0 \leq j \leq k \} = 0 \iff p(a_j) _{0 \leq j \leq k} = 0$	
Conditions	Explanation
only if $k < n$ Example:	<p>A polynomial doesn't necessarily have k distinct real roots, i.e., it may have repeated, complex roots.</p> <p>let p be polynomial of degree $n = 2$ and $k = 1$ given by:-</p> $p(x) = x^2 + 4x + 4 \quad (5.7.2)$ $ p(a_j) _{0 \leq j \leq 1} = 0 \implies a_0 = -2, a_1 = -2 \quad (5.7.3)$ <p>but a_0, a_1, \dots, a_k should be distinct real numbers.</p> <p>This contradicts the property of Norm. Thus condition fails.</p>
only if $k \geq n$	<p>p is a polynomial of degree $\leq n$, it can't have more than n roots and is only possible when,</p> $p(x) = 0 \implies p(a_j) _{0 \leq j \leq k} = 0$ <p>hence p is identically zero. Thus condition satisfies.</p>
if $k + 1 \leq n$	Not a norm for $k < n$. Hence incorrect.
if $k \geq n + 1$	Norm for $k \geq n$. Hence correct.

TABLE 5.7.2: Verifying Positivity Property of Norm

Nilpotent Matrix	1. If all the eigen values of matrix is zero then it is said to nilpotent matrix 2. Determinant and trace of nilpotent matrix are always zero.
Invertible Matrix	A matrix is said to be invertible matrix if its determinant is non zero.
Diagonal matrix	diagonal matrix is a matrix in which the entries outside the main diagonal are all zero.

TABLE 5.8.1: Definition

Given	$T : P_3 \rightarrow P_3$ $T : V \rightarrow V$ be the linear operator given by differentiation wrt x $T(P(x)) \rightarrow P'(x)$ A be the matrix of T wrt some basis for V Assume basis for V be $\{1, x, x^2, x^3\}$
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TABLE 5.8.2: Result used

Checking whether matrix of T is nilpotent	$T : V \rightarrow V$ $TP(x) = P'(x)$ Differentiating wrt x to find matrix A ; $T(1) = 0 = a_1x + b_1x + c_1x^2 + d_1x^3$ $T(x) = 1 = a_2 + b_2x + c_2x^2 + d_2x^3$ $T(x^2) = 2x = a_3 + b_3x + c_3x^2 + d_3x^3$ $T(x^3) = 3x^2 = a_4 + b_4x + c_4x^2 + d_4x^3$ Representing A in matrix form ; $A = \begin{pmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 2 & 0 \\ 0 & 0 & 0 & 3 \\ 0 & 0 & 0 & 0 \end{pmatrix}$ from the above matrix of T we can say it is nilpotent matrix.
Checking eigen value of matrix T	$A = \begin{pmatrix} 0 - \lambda & 1 & 0 & 0 \\ 0 & 0 - \lambda & 2 & 0 \\ 0 & 0 & 0 - \lambda & 3 \\ 0 & 0 & 0 & 0 - \lambda \end{pmatrix}$ $\Rightarrow \lambda = 0$
Checking whether matrix of T is invertible	Since $\det A = 0$. Therefore matrix of T is not invertible
Checking whether Matrix of T is diagonal matrix	Let basis be $B' = \{1, 1 + x, 1 + x + x^2, 1 + x + x^2 + x^3\}$ Differentiating wrt x ;

	$T(1) = 0 = a_1x + b_1(1+x) + c_1(1+x+x^2) + d_1(1+x+x^2+x^3)$ $T(1+x) = 1 = a_2 + b_2(1+x) + c_2(1+x+x^2) + d_2(1+x+x^2+x^3)$ $T(1+x+x^2) = 1+2x = a_3 + b_3(1+x) + c_3(1+x+x^2) + d_3(1+x+x^2+x^3)$ $T(1+x+x^2+x^3) = 1+2x+3x^2 = a_4 + b_4(1+x) + c_4(1+x+x^2) + d_4(1+x+x^2+x^3)$ $B = \begin{pmatrix} 0 & 1 & -1 & -1 \\ 0 & 0 & 2 & -1 \\ 0 & 0 & 0 & 3 \\ 0 & 0 & 0 & 0 \end{pmatrix}$ <p>above matrix is not a diagonal matrix</p>
Conclusion	Thus we can conclude Option 2) and 3) are correct.

TABLE 5.8.3: Solution

5.9. Let m, n, r be natural numbers. Let A be an $m \times n$ matrix with real entries such that $(AA^t)^r = I$, where I is the $m \times m$ identity matrix and A^t is the transpose of the matrix A . We can conclude that

- a) $m = n$
- b) AA^t is invertible
- c) A^tA is invertible
- d) if $m = n$, then A is invertible

Solution: Options 2) and 4) are correct. See Table 5.9.1

5.10. Let \mathbf{A} be a $n \times n$ real matrix with $\mathbf{A}^2 = \mathbf{A}$. Then

- a) the eigenvalues of \mathbf{A} are either 0 or 1
- b) \mathbf{A} is a diagonal matrix with diagonal entries 0 or 1
- c) $\text{rank}(\mathbf{A}) = \text{trace}(\mathbf{A})$
- d) if $\text{rank}(\mathbf{I} - \mathbf{A}) = \text{trace}(\mathbf{I} - \mathbf{A})$

Solution: See Table 5.10.1

5.11. For any $n \times n$ matrix B , let $N(B) = \{X \in \mathbb{R}^n : BX = 0\}$ be the null space of B . Let A be a 4×4 matrix with $\dim(N(A - 4I)) = 2$, $\dim(N(A - 2I)) = 1$ and $\text{rank}(A) = 3$ Which of the following are true?

- a) 0, 2 and 4 are eigenvalues of A
- b) $\det(A) = 0$
- c) A is not diagonalizable
- d) $\text{trace}(A) = 8$

Option	Answer
1) $m = n$	<p>Let $\mathbf{A} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix}$ and $r = 1$</p> $(\mathbf{A}\mathbf{A}^T)^r = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} = I$ <p>Since $m \neq n$ Option 1 is False.</p>
2) AA^T is invertible	<p>w.k.t $\det(A^n) = (\det(A))^n$ Since $(AA^T)^r = I$ So $\det((AA^T)^r) = \det(I)$ $(\det(AA^T))^r = 1$ $\implies \det(AA^T) \neq 0$ Hence AA^T is invertible Option 2 is True.</p>
3) $A^T A$ is invertible	<p>Let $\mathbf{A} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix}$ and $r = 1$</p> $(\mathbf{A}^T \mathbf{A})^r = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix}$ <p>But $\det(AA^T) = 0$. $\implies AA^T$ is not invertible. Hence Option 3 is False</p>
4) if $m = n$ then A is invertible	<p>Since $\det(AA^T) \neq 0$ $\det(A) \cdot \det(A^T) \neq 0$ $\det(A) \cdot \det(A) \neq 0$ $\implies A$ is invertible. Hence Option 4 is True</p>

TABLE 5.9.1

Solution: See Table 5.11.1.

Given	<p>A is a 4×4 matrix. $\dim(N(A - 2I)) = 2$, $\dim(N(A - 4I)) = 1$, and $\text{rank}(A) = 3$</p>
Eigenvalues of a matrix	The number λ is an eigenvalue of a matrix A if and only if $A - \lambda I$ is singular,

i.e. $|A - \lambda I| = 0$

For $\lambda = 2$

Given, $\dim(N(A - 2I)) = 2$

$$\implies \text{nullity}(A - 2I) = 2$$

$$\text{rank}(A) + \text{nullity}(A) = n$$

$$\implies \text{rank}(A - 2I) = 4 - 2 = 2$$

$\implies (A - 2I)$ is not a full rank matrix

Therefore $|A - 2I| = 0$

Also,

$$\implies N(A - 2I) = \{X \in \mathbb{R}^4 : (A - 2I)X = 0\}$$

$\implies (A - 2I)X = 0$ gives two eigen vectors

$\implies 2$ is an eigenvalue of A with multiplicity 2.

Similarly, for $\lambda = 4$

Given, $\dim(N(A - 4I)) = 1$

$$\implies \text{rank}(A - 4I) = 4 - 1 = 3$$

$\implies (A - 4I)$ is not a full rank matrix

	<p>Therefore $A - 4I = 0$ $\Rightarrow 4$ is an eigenvalue of A with multiplicity 1.</p> <p>For $\lambda = 0$ Given that $\text{rank}(A) = 3$ $\Rightarrow A$ is not a full rank matrix Therefore $A = 0$ $\Rightarrow 0$ is an eigenvalue of A with multiplicity 1.</p>
Determinant	<p>Given that $\text{rank}(A) = 3$ $\Rightarrow A$ is not a full rank matrix Therefore $A = 0$</p>
Diagonalizability	<p>An $n \times n$ matrix A is diagonalizable if and only if A has n linearly independent eigen vectors. $\text{rank}(A) + \text{nullity}(A) = n$ \Rightarrow for $\lambda = 0$, $\text{nullity}(A - \lambda I) = \text{nullity}(A) = 4 - 3 = 1$ \Rightarrow There exists only one linearly independent eigen vector corresponding to 0 eigen value Thus, matrix A is not diagonalizable.</p>
Trace	<p>$\text{Trace}(A) = \text{sum of eigen values}$ $\Rightarrow \text{Trace}(A) = 0 + 2 + 2 + 4 = 8$</p>
Conclusion	<p>Option (1), (2) and (4) are correct</p>

TABLE 5.11.1: Solution

5.12. Which of the following 3×3 matrices are diagonalizable over \mathbb{R} ?

- a) $\begin{pmatrix} 1 & 2 & 3 \\ 0 & 4 & 5 \\ 0 & 0 & 6 \end{pmatrix}$
- b) $\begin{pmatrix} 0 & 1 & 0 \\ -1 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$
- c) $\begin{pmatrix} 1 & 2 & 3 \\ 2 & 1 & 4 \\ 3 & 4 & 1 \end{pmatrix}$
- d) $\begin{pmatrix} 0 & 1 & 2 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{pmatrix}$

Solution: See Tables 5.12.1 and 5.12.2

Objective	Explanation
Eigenvalues of \mathbf{A}	<p>Since</p> $\mathbf{A}^2 = \mathbf{A} \quad (5.10.1)$ $\implies \mathbf{A}^2 - \mathbf{A} = \mathbf{O} \quad (5.10.2)$ <p>From Cayley-Hamilton Theorem we have,</p> $\lambda^2 - \lambda = 0 \quad (5.10.3)$ $\implies \lambda(\lambda - 1) = 0 \quad (5.10.4)$ $\implies \lambda = 0, 1 \quad (5.10.5)$ <p>A matrix \mathbf{A} satisfying $\mathbf{A}^2 = \mathbf{A}$ is an idempotent matrix with eigen values equal to 0 or 1.</p>
Check if \mathbf{A} is necessary diagonal	<p>Consider</p> $\mathbf{A} = \begin{pmatrix} 1 & -1 \\ 0 & 0 \end{pmatrix} \quad (5.10.6)$ $\quad (5.10.7)$ <p>Then,</p> $\mathbf{A}^2 = \begin{pmatrix} 1 & -1 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} 1 & -1 \\ 0 & 0 \end{pmatrix} \quad (5.10.8)$ $= \begin{pmatrix} 1 & -1 \\ 0 & 0 \end{pmatrix} \quad (5.10.9)$ $= \mathbf{A} \quad (5.10.10)$ <p>Hence \mathbf{A} is idempotent but not diagonal.</p>
Relation between rank and trace of \mathbf{A}	<p>Rank of matrix is defined as the number of non-zero eigenvalues. Since number of non-zero eigenvalues is 1,</p> $rank(\mathbf{A}) = 1 \quad (5.10.11)$ $trace(\mathbf{A}) = \sum_i \lambda_i = 0 + 1 = 1 \quad (5.10.12)$ $\implies rank(\mathbf{A}) = trace(\mathbf{A}) \quad (5.10.13)$
Relation between rank and trace of $\mathbf{I} - \mathbf{A}$	<p>Now for the matrix $\mathbf{I} - \mathbf{A}$ we have,</p> $(\mathbf{I} - \mathbf{A})^2 = (\mathbf{I} - \mathbf{A})(\mathbf{I} - \mathbf{A}) \quad (5.10.14)$ $= \mathbf{I}^2 - \mathbf{IA} - \mathbf{AI} + \mathbf{A}^2 \quad (5.10.15)$ $= \mathbf{I} - \mathbf{A} - \mathbf{A} + \mathbf{A} \quad (5.10.16)$ $= \mathbf{I} - \mathbf{A} \quad (5.10.17)$ <p>Hence $\mathbf{I} - \mathbf{A}$ is an idempotent matrix. Therefore we conclude,</p> $rank(\mathbf{I} - \mathbf{A}) = trace(\mathbf{I} - \mathbf{A}) \quad (5.10.18)$
Answer	(1),(3) and (4)

TABLE 5.10.1

Test for diagonalizability	<p>Let \mathbf{W}_i be the eigenspace corresponding to eigenvalue λ_i of \mathbf{A}</p> <p>1) \mathbf{A} is diagonalizable</p> <p>2) characteristic polynomial of \mathbf{A} is</p> <p>$f = (\mathbf{x} - \lambda_1)^{d_1} \dots (\mathbf{x} - \lambda_k)^{d_k}$ and $\dim(\mathbf{W}_i) = d_i$</p> <p>3) $\sum_{i=1}^k \mathbf{W}_i = n$</p>
Concept for diagonalization	<p>A linear operator \mathbf{A} on a n-dimensional space \mathbb{V} is</p> <p>diagonalizable , if and only if \mathbf{A} has n distinct</p> <p>characteristic vectors or null spaces corresponding to the characteristic values</p>

TABLE 5.12.1: Illustration of theorem.

Option A	<p>Given matrix is</p> $\mathbf{A} = \begin{pmatrix} 1 & 2 & 3 \\ 0 & 4 & 5 \\ 0 & 0 & 6 \end{pmatrix}$
Finding Characteristics polynomial	<p>Characteristics polynomial of the matrix \mathbf{A} is $\det(x\mathbf{I} - \mathbf{A})$</p> $\det(x\mathbf{I} - \mathbf{A}) = \begin{vmatrix} (x-1) & -3 & -2 \\ 0 & (x-4) & -5 \\ 0 & 0 & x-6 \end{vmatrix}$ <p>Characteristic Polynomial = $(x-1)(x-4)(x-6)$</p>
Testing diagonalizability over \mathbb{R}	<p>1) As the characteristics polynomial is product of linear factors over \mathbb{R} .</p> <p>2) To find characteristic values of the operator $\det(xI - A) = 0$ which gives $\lambda_1 = 1, \lambda_2 = 4, \lambda_3 = 6$</p> <p>Thus over \mathbb{R} matrix \mathbf{A} has three distinct characteristic values. There will be atleast one characteristics vector i.e., one dimension with each characteristics value .</p> <p>Thus $\dim \mathbf{W}_i = d_i$</p> <p>3) $\sum_i \mathbf{W}_i = n = 3$, which is equal to \dim of \mathbf{A}.</p>

Conclusion on Option A	Option A satisfy all three condition of Diagonalizability over \mathbb{R} .
Option B	<p>Given matrix is</p> $\mathbf{A} = \begin{pmatrix} 0 & 1 & 0 \\ -1 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$
Finding Characteristics polynomial	<p>Characteristics polynomial of the matrix $\det(x\mathbf{I} - \mathbf{A})$</p> $\det(x\mathbf{I} - \mathbf{A}) = \begin{vmatrix} x & -1 & 0 \\ 1 & x & 0 \\ 0 & 0 & x - 1 \end{vmatrix}$ <p>Characteristic Polynomial = $(x - 1)(x + i)(x - i)$</p>
Testing diagonalizability over \mathbb{R}	<p>1) As the characteristics polynomial is not the product of linear factors over \mathbb{R} beacuse roots of characteristic eq are complex . Thus \mathbf{A} is not diagonalizable over \mathbb{R}.</p>
Conclusion on Option B	Option B does not satisfy condition 1.
Option C	<p>Given matrix is</p> $\mathbf{A} = \begin{pmatrix} 1 & 2 & 3 \\ 2 & 1 & 4 \\ 3 & 4 & 1 \end{pmatrix}$
Finding Characteristics polynomial	<p>Characteristics polynomial of the matrix \mathbf{A} is $\det(x\mathbf{I} - \mathbf{A})$</p> $\det(x\mathbf{I} - \mathbf{A}) = \begin{vmatrix} (x - 1) & -2 & -3 \\ -2 & (x - 1) & -4 \\ -3 & -4 & x - 1 \end{vmatrix}$ <p>Characteristic Polynomial = $(x + 3.19)(x + 0.877)(x - 7.07)$</p>
Testing diagonalizability over \mathbb{R}	<p>1) As the characteristics polynomial are product of linear factors over \mathbb{R} .</p> <p>2) To find characteristic values of the operator $\det(x\mathbf{I} - \mathbf{A}) = 0$ which gives $\lambda_1 = -3.19, \lambda_2 = -0.887, \lambda_3 = 7.07$</p>

	<p>Thus over \mathbb{R} matrix \mathbf{A} has three distinct characteristic values. There will be atleast one characteristics vector i.e., one dimension with each characteristics value .</p> <p>Thus $\dim \mathbf{W}_i = d_i$</p> <p>3) $\sum_i \mathbf{W}_i = n = 3$, which is equal to \dim of \mathbf{A}.</p>
Conclusion on Option C	Option C satisfy all three condition of Diagonalizability over \mathbb{R} .
Option D	<p>Given matrix is</p> $\mathbf{A} = \begin{pmatrix} 0 & 1 & 2 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{pmatrix}$
Finding Characteristics polynomial	<p>Characteristics polynomial of the matrix \mathbf{A} is $\det(x\mathbf{I} - \mathbf{A})$</p> $\det(x\mathbf{I} - \mathbf{A}) = \begin{vmatrix} x & -1 & -2 \\ 0 & x & -1 \\ 0 & 0 & x \end{vmatrix}$ <p>Characteristic Polynomial = $(x)(x)(x) = x^3$</p>
Testing diagonalizability over \mathbb{R}	<p>1) As the characteristics polynomial is product of linear factors over \mathbb{R} .</p> <p>2) To find characteristic values of the operator $\det(x\mathbf{I} - \mathbf{A}) = 0$</p> <p>$\lambda_1 = 0$</p> <p>$d_1 = 3$</p> $\mathbf{W}_1 = \mathbf{A} - \lambda_1 \mathbf{I} \Rightarrow \begin{pmatrix} 0 & 1 & 2 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{pmatrix} - 0 \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} 0 & 1 & 2 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{pmatrix}$ <p>$\dim \mathbf{W}_1 = 2$</p> <p>$\dim \mathbf{W}_i \neq d_i$</p> <p>Algebric Multiplicity is not equal to Geometric Multiplicity.</p>
Conclusion on Option D	Option D does not satisfy second condition of Diagonalizability.
Answer	Option A and Option C are Diagonalizable over \mathbb{R} .

TABLE 5.12.2: Option Checking Table

Positive Semi Definite Matrix	A $n \times n$ symmetric real matrix \mathbf{M} is said to be positive semi definite if $\mathbf{x}^T \mathbf{M} \mathbf{x} \geq 0$ for all non-zero \mathbf{x} in \mathbb{R}^n . Formally \mathbf{M} is positive semi-definite $\Leftrightarrow \mathbf{x}^T \mathbf{M} \mathbf{x} \geq 0 \forall \mathbf{x} \in \mathbb{R}^n \setminus \{0\}$
Theorem	For a symmetric $n \times n$ matrix $\mathbf{M} \in \mathbf{L}(\mathbf{V})$, following are equivalent. 1). $\mathbf{x}^T \mathbf{M} \mathbf{x} \geq 0 \forall \mathbf{x} \in \mathbf{V}$. 2). All the eigenvalues of \mathbf{M} are non-negative.

TABLE 5.13.1: Definition and Result used

Calculating eigen values of \mathbf{A}	Given $\mathbf{A} = \begin{pmatrix} 3 & 1 & 2 \\ 1 & 2 & 3 \\ 2 & 3 & 1 \end{pmatrix}$ Calculating, eigen values of \mathbf{A} , ie $\det(\mathbf{A} - \lambda \mathbf{I}) = 0$ $\Rightarrow \begin{vmatrix} 3-\lambda & 1 & 2 \\ 1 & 2-\lambda & 3 \\ 2 & 3 & 1-\lambda \end{vmatrix} = 0$ $\Rightarrow (3-\lambda)((2-\lambda)(1-\lambda)-9) - 1(1-\lambda-6) + 2(3-2(2-\lambda)) = 0$ $\Rightarrow \lambda^3 - 6\lambda^2 - 3\lambda + 18 = 0$ $\Rightarrow \lambda_1 = 6, \lambda_2 = \sqrt{3} \text{ and } \lambda_3 = -\sqrt{3}$ Hence, \mathbf{A} has exactly two positive eigen values.
Proving $\mathbf{x}^T \mathbf{A} \mathbf{x} < 0$ for some $\mathbf{x} \in \mathbb{R}^3$ using contradiction	Suppose $\mathbf{x}^T \mathbf{A} \mathbf{x} \geq 0$ for all $\mathbf{x} \in \mathbb{R}^3$. Then, by theorem above in definition section, matrix \mathbf{A} is positive semi definite. Hence, all the eigen values of \mathbf{A} non-negative, but this is not the case as one of eigen value is $\lambda_3 = -\sqrt{3}$. So, $\mathbf{x}^T \mathbf{A} \mathbf{x} \geq 0$ is not true for all $\mathbf{x} \in \mathbb{R}^3$. Similarly, as $\lambda_2 \leq 0, \forall i$ is also not true, so $\mathbf{x}^T \mathbf{A} \mathbf{x} \leq 0$ is not true for all $\mathbf{x} \in \mathbb{R}^3$. Thus, $\mathbf{x}^T \mathbf{A} \mathbf{x} < 0$ for some $\mathbf{x} \in \mathbb{R}^3$.
Correct Options	Hence, correct options are (1) and (4).

TABLE 5.13.2: Solution

5.13. Let $\mathbf{A} = \begin{pmatrix} 3 & 1 & 2 \\ 1 & 2 & 3 \\ 2 & 3 & 1 \end{pmatrix}$ and $\mathbf{Q}(\mathbf{X}) = \mathbf{X}^T \mathbf{A} \mathbf{X}$ for $\mathbf{X} \in \mathbb{R}^3$. Then

- \mathbf{A} has exactly two positive eigen values.
- all the eigen values of \mathbf{A} are positive.
- $\mathbf{Q}(\mathbf{X}) \geq 0 \forall \mathbf{X} \in \mathbb{R}^3$
- $\mathbf{Q}(\mathbf{X}) < 0$ for some $\mathbf{X} \in \mathbb{R}^3$

Solution: See Tables 5.13.1 and 5.13.2

5.14. Consider the matrix

$$A(x) = \begin{pmatrix} 1+x^2 & 7 & 11 \\ 3x & 2x & 4 \\ 8x & 17 & 13 \end{pmatrix}; x \in \mathbf{R}. \quad (5.14.1)$$

Then,

- $A(x)$ has eigenvalue 0 for some $x \in \mathbf{R}$.
- 0 is not an eigenvalue of $A(x)$ for any $x \in \mathbf{R}$.
- $A(x)$ has eigenvalue 0 $\forall x \in \mathbf{R}$.
- $A(x)$ is invertible $\forall x \in \mathbf{R}$.

Solution: Let $\lambda = 0$ be an eigenvalue. Hence,

$$|A - \lambda I| = 0 \quad (5.14.2)$$

$$\Rightarrow |A| = 0 \quad (5.14.3)$$

$$\Rightarrow |A| = \begin{vmatrix} 1+x^2 & 7 & 11 \\ 3x & 2x & 4 \\ 8x & 17 & 13 \end{vmatrix} = 0 \quad (5.14.4)$$

Performing row reduction we get,

$$\left| \begin{array}{ccc} 1+x^2 & 7 & 11 \\ 0 & \frac{2x^3-19x}{1+x^2} & \frac{4x^2-33x+4}{1+x^2} \\ 0 & 0 & \frac{26x^3-244x^2+538x-68}{2x^3-19x} \end{array} \right| = 0 \quad (5.14.5)$$

$$\Rightarrow 26x^3 - 244x^2 + 538x - 68 = 0 \quad (5.14.6)$$

$$\Rightarrow x_1 = 6.01, x_2 = 3.23, x_3 = 0.13 \quad (5.14.7)$$

See Table 5.14.1

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6.1. The matrix

$$\mathbf{A} = \begin{pmatrix} 3 & -1 & 0 \\ -1 & 2 & -1 \\ 0 & -1 & 3 \end{pmatrix} \quad (6.1.1)$$

is

- positive definite.
- non-negative definite but not positive definite.
- negative definite.
- neither negative definite nor positive definite.

Solution:

- For a real symmetric matrix to be positive definite the eigen values of the matrix should

OPTIONS	Explanation
Option (b)	At the Values of x given by (5.14.7), eigen value $\lambda = 0$. Hence option (b) can't be correct.
Option (c)	If one of the eigenvalue is 0 for A(x) then, $ A(x) = 0 \forall x \in R$. But from (5.14.7) we have concluded that $ A = 0$ only for, $x_1 = 6.01, x_2 = 3.23, x_3 = 0.13$. Hence, Option (c) is incorrect.
Option (d)	Now for the values of x given by (5.14.7), $ A = 0$. Hence it is not invertible $\forall x \in R$ Hence Option (d) is incorrect.
Option (a)	Now clearly from above arguments A(x) has eigenvalue 0 for some $x \in R$ Hence Option (a) is Correct.

TABLE 5.14.1

be positive.

- b) For a real symmetric matrix to be negative definite the eigen values of the matrix should be negative.

$$\mathbf{A} = \begin{pmatrix} 3 & -1 & 0 \\ -1 & 2 & -1 \\ 0 & -1 & 3 \end{pmatrix}$$

$$1. \text{Rank } \mathbf{A} \leq n - 1 \quad (6.2.1)$$

$$2. \text{Rank } \mathbf{A} = m \quad (6.2.2)$$

$$3. n \leq m \quad (6.2.3)$$

$$4. n - 1 \leq m \quad (6.2.4)$$

Solution: See Table 6.2.1

The characteristic equation of the matrix \mathbf{A} is given by

$$|V - \lambda \mathbf{I}| = \begin{vmatrix} 3 - \lambda & -1 & 0 \\ -1 & 2 - \lambda & -1 \\ 0 & -1 & 3 - \lambda \end{vmatrix} = 0$$

$$\Rightarrow \lambda^3 - 8\lambda^2 + 19\lambda - 12 = 0 \quad (6.1.2)$$

The Eigen values of \mathbf{A} are:

$$\begin{aligned} \lambda_1 &= 5/2 \\ \lambda_2 &= 3/2 \\ \lambda_3 &= 4 \end{aligned} \quad (6.1.3)$$

Since all the eigen values of matrix \mathbf{A} are positive, Therefore the matrix \mathbf{A} is positive definite.

- 6.2. Let \mathbf{A} be an $n \times m$ matrix with each entry equal to +1, -1 or 0 such that every column has exactly one +1 and exactly one -1. We can conclude that

option	Solution
1.	<p>Let us consider \mathbf{A} as follows and let s be the summation of all column entries:</p> $\mathbf{A} = \begin{pmatrix} a_{11} & a_{12} & \dots & a_{1m} \\ a_{21} & a_{22} & \dots & a_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \dots & a_{nm} \end{pmatrix}$ $ \mathbf{A} - \lambda \mathbf{I} = \begin{vmatrix} a_{11} - \lambda & a_{12} & \dots & a_{1m} \\ a_{21} & a_{22} - \lambda & \dots & a_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \dots & a_{nm} - \lambda \end{vmatrix} = 0$ $= \begin{vmatrix} a_{11} + a_{21} + \dots + a_{n1} - \lambda & a_{11} + a_{21} + \dots + a_{n1} - \lambda & \dots & a_{11} + a_{21} + \dots + a_{n1} - \lambda \\ a_{21} & a_{22} - \lambda & \dots & a_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \dots & a_{nm} - \lambda \end{vmatrix}$ $\Rightarrow (s - \lambda) \begin{vmatrix} 1 & 1 & \dots & 1 \\ a_{21} & a_{22} - \lambda & \dots & a_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \dots & a_{nm} - \lambda \end{vmatrix} = 0$
Example	<p>Since $s=0$ according to question, Therefore $\lambda = 0$ is an eigen value of \mathbf{A}. Since $\lambda = 0$, Hence \mathbf{A} is singular. Which means at least two rows are linearly dependent. Therefore,</p> $\text{Rank}(\mathbf{A}) < n$ $\text{Rank}(\mathbf{A}) \leq n - 1$ <p>Let us Consider \mathbf{A} as follows, where $n=4$ and $m=3$</p> $\mathbf{A} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ -1 & -1 & -1 \end{pmatrix}$ <p>Calculating Row Reduced Echelon Form of \mathbf{A} as follows:</p>

	$\begin{array}{l} \xleftrightarrow{R_4 \leftarrow R_1 + R_4} \\ \xleftrightarrow{R_4 \leftarrow R_2 + R_4} \end{array} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & -1 \end{pmatrix}$ $\xleftrightarrow{R_4 \leftarrow R_3 + R_4} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{pmatrix}$
Conclusion	Since the Rank $\mathbf{A}=3$ and $n=4$, Therefore the Rank $\mathbf{A} \leq n - 1$ statement is true.
2.	<p>Let us Consider \mathbf{A} as follows,where $n=2$ and $m=2$</p> $\mathbf{A} = \begin{pmatrix} -1 & 1 \\ 1 & -1 \end{pmatrix}$ <p>Applying elementary transformations on \mathbf{A} as follows:</p> $\xleftrightarrow{R_2 \leftarrow R_1 + R_2} \begin{pmatrix} -1 & 1 \\ 0 & 0 \end{pmatrix}$
Conclusion	Since the Rank $\mathbf{A}=1$ and $m=2$, Therefore the Rank $\mathbf{A} \neq m$, Hence the statement is false.
3.	<p>Let us Consider \mathbf{A} as follows,where $n=3$ and $m=2$</p> $\mathbf{A} = \begin{pmatrix} 1 & 1 \\ -1 & -1 \\ 0 & 0 \end{pmatrix} \quad (6.2.5)$
Conclusion	Since there exists a matrix \mathbf{A} when $n>m$, Therefore the statement is false.
4	<p>Let us Consider \mathbf{A} as follows,where $n=4$ and $m=2$</p> $\mathbf{A} = \begin{pmatrix} 1 & 1 \\ -1 & -1 \\ 0 & 0 \\ 0 & 0 \end{pmatrix} \quad (6.2.6)$
Conclusion	Since there exists a matrix \mathbf{A} when $n-1>m$, Therefore the statement is false.

TABLE 6.2.1: Solution summary

Options	Solutions	True/False
1.	<p>Given</p> $\mathbf{A} = \begin{pmatrix} 1 & 1 \\ 1 & 0 \end{pmatrix}$ <p>Now lets find the eigen values of matrix \mathbf{A}</p> $ \mathbf{A} - \lambda \mathbf{I} = 0$ $\Rightarrow \begin{vmatrix} 1-\lambda & 1 \\ 1 & -\lambda \end{vmatrix} = 0$ $\Rightarrow \lambda^2 - \lambda - 1 = 0$ <p>On solving we get 2 eigen values</p> $\alpha_1 = \frac{1+\sqrt{5}}{2} \quad \beta_1 = \frac{1-\sqrt{5}}{2}$ <p>We know that if eigenvalue of \mathbf{A} is λ then eigenvalue of \mathbf{A}^n is λ^n. In this problem we can say that the eigenvalues α_n and β_n of \mathbf{A}^n are</p> $\alpha_n = \alpha_1^n \quad \beta_n = \beta_1^n$ <p>Since $\alpha_1 > 1$ we can say that $\alpha_n \rightarrow \infty$ as $n \rightarrow \infty$.</p>	True
2.	<p>We got $\beta_1 = \frac{1-\sqrt{5}}{2}$ and $\beta_n = \beta_1^n$. Since $-1 < \beta_1 < 0$, we can say that $\beta_n \rightarrow 0$ as $n \rightarrow \infty$.</p>	True
3.	<p>We got $\beta_1 = \frac{1-\sqrt{5}}{2}$ and $\beta_n = \beta_1^n$. Since β_1 is negative because $-1 < \beta_1 < 0$, if n is even then β_n is positive.</p>	True
4.	<p>We got $\beta_1 = \frac{1-\sqrt{5}}{2}$ and $\beta_n = \beta_1^n$. Since β_1 is negative, if n is odd then β_n is negative.</p>	True

TABLE 6.3.1

6.3. Let $\mathbf{A} = \begin{pmatrix} 1 & 1 \\ 1 & 0 \end{pmatrix}$ and let α_n and β_n denote the two eigenvalues of \mathbf{A}^n such that $|\alpha_n| \geq |\beta_n|$.
Then

Solution: See Table 6.5.1

- a) $\alpha_n \rightarrow \infty$ as $n \rightarrow \infty$
- b) $\beta_n \rightarrow 0$ as $n \rightarrow \infty$
- c) β_n is positive if n is even.
- d) β_n is negative if n is odd.

Solution: See Table 6.3.1.

6.4. Let M_n denote the vector space of all $n \times n$ real matrices. Which of the following is a linear subspaces of M_n :-

- a) $V_1 = \{A \in M_n : A \text{ is nonsingular}\}$
- b) $V_2 = \{A \in M_n : \det(A) = 0\}$
- c) $V_3 = \{A \in M_n : \text{trace}(A) = 0\}$
- d) $V_4 = \{BA : A \in M_n\}$, where B is some fixed matrix in M_n

Solution: See Table 6.4.1

6.5. If \mathbf{P} and \mathbf{Q} are invertible matrices such that $\mathbf{PQ} = -\mathbf{QP}$, then we can conclude that

- a) $\text{Tr}(\mathbf{P}) = \text{Tr}(\mathbf{Q}) = 0$
- b) $\text{Tr}(\mathbf{P}) = \text{Tr}(\mathbf{Q}) = 1$
- c) $\text{Tr}(\mathbf{P}) = -\text{Tr}(\mathbf{Q})$
- d) $\text{Tr}(\mathbf{P}) \neq \text{Tr}(\mathbf{Q})$

Vector space	Is it subspace to M_n ?
1) V_1 : All non-singular matrices of $n \times n$	The matrices $I_{n \times n}$ and $-I_{n \times n}$ are non-singular matrices, but the sum $I_{n \times n} - I_{n \times n}$ is zero matrix and it is singular. $\therefore V_1$ does not form subspace of M_n .
2) V_2 : All singular matrices of $n \times n$	The matrices $\begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$ and $\begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}$ are singular matrices, but the sum is a non-singular matrix. $\therefore V_2$ does not form subspace M_n .
3) V_3 : All matrices of $n \times n$ with trace =0	Let \mathbf{v}_1 and \mathbf{v}_2 be matrices with Trace = 0. $Tr(\mathbf{v}_1 + \alpha\mathbf{v}_2) = Tr(\mathbf{v}_1) + \alpha Tr(\mathbf{v}_2) = 0$. \therefore the vector space V_3 forms linear subspace of M_n .
4) V_4 : $F_A = BA$, where B is some fixed matrix in M_n	Let \mathbf{v}_1 and \mathbf{v}_2 be matrices in the vector space V_4 . $F_{\mathbf{v}_1 + \alpha\mathbf{v}_2} = B(\mathbf{v}_1 + \alpha\mathbf{v}_2)$ $= B\mathbf{v}_1 + \alpha B\mathbf{v}_2 =$ $F_{\mathbf{v}_1} + \alpha F_{\mathbf{v}_2}$. $\therefore V_4$ forms linear subspace of M_n .

TABLE 6.4.1

Given	<p>P and Q are invertible matrices. Therefore \mathbf{P}^{-1} and \mathbf{Q}^{-1} exists.</p> $\mathbf{PQ} = -\mathbf{QP} \quad (6.5.1)$
To Prove	$\text{Tr}(\mathbf{P})=0$
Proof 1	<p>Post multiplying equation (6.5.1) by \mathbf{Q}^{-1} we get,</p> $\mathbf{PQQ}^{-1} = -\mathbf{QPQ}^{-1} \quad (6.5.2)$ $\Rightarrow \mathbf{PI} = -\mathbf{QPQ}^{-1} \quad (6.5.3)$ $\Rightarrow \mathbf{P} = -\mathbf{QPQ}^{-1} \quad (6.5.4)$ <p>Taking trace on both sides for the equation (6.5.4),</p> $\text{Tr}(\mathbf{P}) = \text{Tr}(-\mathbf{QPQ}^{-1}) \quad (6.5.5)$ $\Rightarrow \text{Tr}(\mathbf{P}) = -\text{Tr}(\mathbf{QPQ}^{-1}) \quad (6.5.6)$ <p>We know that $\text{Tr}(\mathbf{AB})=\text{Tr}(\mathbf{BA})$ Let $\mathbf{A}=\mathbf{Q}$ and $\mathbf{B}=\mathbf{PQ}^{-1}$</p> <p>From the above property of trace equation (6.5.6) can be modified as</p> $\text{Tr}(\mathbf{P}) = -\text{Tr}(\mathbf{PQ}^{-1}\mathbf{Q}) \quad (6.5.7)$ $\Rightarrow \text{Tr}(\mathbf{P}) = -\text{Tr}(\mathbf{PI}) \quad (6.5.8)$ $\Rightarrow \text{Tr}(\mathbf{P}) = -\text{Tr}(\mathbf{P}) \quad (6.5.9)$ $\Rightarrow 2\text{Tr}(\mathbf{P}) = 0 \quad (6.5.10)$ $\Rightarrow \text{Tr}(\mathbf{P}) = 0 \quad (6.5.11)$
To Prove	$\text{Tr}(\mathbf{Q})=0$
Proof 2	<p>Post multiplying equation (6.5.1) by \mathbf{P}^{-1} we get,</p> $\mathbf{PQP}^{-1} = -\mathbf{QPP}^{-1} \quad (6.5.12)$ $\Rightarrow \mathbf{PQP}^{-1} = -\mathbf{QI} \quad (6.5.13)$ $\Rightarrow \mathbf{PQP}^{-1} = -\mathbf{Q} \quad (6.5.14)$ <p>Taking trace on both sides for the equation (6.5.14),</p>

	$Tr(\mathbf{PQP}^{-1}) = Tr(-\mathbf{Q}) \quad (6.5.15)$ $\implies Tr(\mathbf{PQP}^{-1}) = -Tr(\mathbf{Q}) \quad (6.5.16)$ <p>We know that $Tr(\mathbf{AB})=Tr(\mathbf{BA})$ Let $\mathbf{A}=\mathbf{P}$ and $\mathbf{B}=\mathbf{QP}^{-1}$ From the above property of trace equation (6.5.16) can be modified as</p> $Tr(\mathbf{QP}^{-1}\mathbf{P}) = -Tr(\mathbf{Q}) \quad (6.5.17)$ $\implies Tr(\mathbf{QI}) = -Tr(\mathbf{Q}) \quad (6.5.18)$ $\implies Tr(\mathbf{Q}) = -Tr(\mathbf{Q}) \quad (6.5.19)$ $\implies 2Tr(\mathbf{Q}) = 0 \quad (6.5.20)$ $\implies Tr(\mathbf{Q}) = 0 \quad (6.5.21)$
Statement 1	$Tr(\mathbf{P})=Tr(\mathbf{Q})=0$
Explanation	<p>From equation (6.5.11) and (6.5.21) we could say that,</p> $Tr(\mathbf{P}) = Tr(\mathbf{Q}) = 0 \quad (6.5.22)$ <p>Valid Conclusion</p>
Statement 2	$Tr(\mathbf{P}) = Tr(\mathbf{Q}) = 1$
Explanation	<p>From equation (6.5.11) and (6.5.21) we could say that,</p> $Tr(\mathbf{P}) = Tr(\mathbf{Q}) \neq 1 \quad (6.5.23)$ <p>Invalid Conclusion</p>
Statement 3	$Tr(\mathbf{P}) = -Tr(\mathbf{Q})$
Explanation	<p>Substituting the conclusion 1 result equation (6.5.22) in equation (6.5.9) we get,</p> $Tr(\mathbf{P}) = -Tr(\mathbf{Q}) \quad (6.5.24)$ <p>Valid Conclusion</p>
Statement 4	$Tr(\mathbf{P}) \neq Tr(\mathbf{Q})$
Explanation	<p>From equation (6.5.11) and (6.5.21) we could say that,</p> $Tr(\mathbf{P}) = Tr(\mathbf{Q}) \quad (6.5.25)$ <p>Invalid Conclusion</p>

TABLE 6.5.1: Explanation with Proofs

6.6. Let $\mathbf{W}_1, \mathbf{W}_2, \mathbf{W}_3$ be 3 distinct subspaces of \mathbf{R}^{10} such that each \mathbf{W}_i has dimension of 9. Let $\mathbf{W} = \mathbf{W}_1 \cap \mathbf{W}_2 \cap \mathbf{W}_3$. Then we can conclude that

- a) \mathbf{W} may not be a subspace of \mathbf{R}^{10}
- b) $\dim \mathbf{W} \leq 8$
- c) $\dim \mathbf{W} \geq 7$
- d) $\dim \mathbf{W} \leq 3$

Solution: See Table 6.6.1

Given	<p>$\mathbf{W}_1, \mathbf{W}_2, \mathbf{W}_3$ are 3 distinct subspaces of \mathbf{R}^{10}</p> <p>Each \mathbf{W}_i has dimension 9</p> <p>$\mathbf{W} = \mathbf{W}_1 \cap \mathbf{W}_2 \cap \mathbf{W}_3$</p>
Statement1	\mathbf{W} may not be a subspace of \mathbf{R}^{10}
Explanation	<p>As $\mathbf{W} = \mathbf{W}_1 \cap \mathbf{W}_2 \cap \mathbf{W}_3$ and $\mathbf{W}_1, \mathbf{W}_2, \mathbf{W}_3$ are subspaces of \mathbf{W}, then \mathbf{W} must be a subspace of \mathbf{R}^{10}. So the first option is false.</p>
Statement2	$\dim \mathbf{W} \leq 8$
Explanation	<p>As \mathbf{W} be a subspace of a finite dimension vector space \mathbf{R}^{10} and $\dim \mathbf{R}^{10} = 10$, so \mathbf{W} is finite dimension and $\dim \mathbf{W} \leq 10$</p>
Theorem	<p>$\dim(\mathbf{W}_1 \cap \mathbf{W}_2)$ $= \dim(\mathbf{W}_1) + \dim(\mathbf{W}_2) - \dim(\mathbf{W}_1 + \mathbf{W}_2)$ and $\mathbf{W}_1 \cap \mathbf{W}_2$ is also a subspace of \mathbf{R}^{10}</p>
Proof	The minimum dimension of $\mathbf{W} = \mathbf{W}_1 \cap \mathbf{W}_2 \cap \mathbf{W}_3$
Explanation	<p>Let us consider $\mathbf{V} = \mathbf{R}^{10}$ and $\dim(\mathbf{V}) = 10$ and $\mathbf{U} = \mathbf{W}_1 \cap \mathbf{W}_2$ So, $\dim(\mathbf{W}_1 \cap \mathbf{W}_2 \cap \mathbf{W}_3) = \dim(\mathbf{U})$ $+ \dim(\mathbf{W}_3) - \dim(\mathbf{U} + \mathbf{W}_3)$</p> <p>or, $\dim(\mathbf{W}_1 \cap \mathbf{W}_2 \cap \mathbf{W}_3) = \dim(\mathbf{W}_1)$ $+ \dim(\mathbf{W}_2) + \dim(\mathbf{W}_3) - \dim(\mathbf{W}_1 + \mathbf{W}_2)$ $- \dim((\mathbf{W}_1 \cap \mathbf{W}_2) + \mathbf{W}_3)$</p>
	<p>Now, $(\mathbf{W}_1 \cap \mathbf{W}_2) + \mathbf{W}_3 \subseteq \mathbf{V}$ $\Rightarrow \dim((\mathbf{W}_1 \cap \mathbf{W}_2) + \mathbf{W}_3) \leq \dim(\mathbf{V})$ $\Rightarrow -\dim((\mathbf{W}_1 \cap \mathbf{W}_2) + \mathbf{W}_3) \geq -\dim(\mathbf{V})$</p> <p>Similarly, $(\mathbf{W}_1 + \mathbf{W}_2) \subseteq \mathbf{V}$ $\Rightarrow \dim(\mathbf{W}_1 + \mathbf{W}_2) \leq \dim(\mathbf{V})$</p>

	$\Rightarrow -\dim(\mathbf{W}_1 + \mathbf{W}_2) \geq -\dim(\mathbf{V})$
	<p>Considering these two inequations, $-\dim((\mathbf{W}_1 \cap \mathbf{W}_2) + \mathbf{W}_3) - \dim(\mathbf{W}_1 + \mathbf{W}_2) \geq -2\dim(\mathbf{V})$</p> <p>or, $\dim(\mathbf{W}_1) + \dim(\mathbf{W}_2) + \dim(\mathbf{W}_3) - \dim((\mathbf{W}_1 \cap \mathbf{W}_2) + \mathbf{W}_3) - \dim(\mathbf{W}_1 + \mathbf{W}_2) \geq \dim(\mathbf{W}_1) + \dim(\mathbf{W}_2) + \dim(\mathbf{W}_3) - 2\dim(\mathbf{V})$</p> <p>or, $\dim(\mathbf{W}_1 \cap \mathbf{W}_2 \cap \mathbf{W}_3) \geq \dim(\mathbf{W}_1) + \dim(\mathbf{W}_2) + \dim(\mathbf{W}_3) - 2\dim(\mathbf{V})$</p> <p>$\Rightarrow \dim(\mathbf{W}) \geq \dim(\mathbf{W}_1) + \dim(\mathbf{W}_2) + \dim(\mathbf{W}_3) - 2\dim(\mathbf{V})$</p>
Statement 3	$\dim \mathbf{W} \geq 7$
Explanation	<p>As $\dim(\mathbf{W}) \geq \dim(\mathbf{W}_1) + \dim(\mathbf{W}_2) + \dim(\mathbf{W}_3) - 2\dim(\mathbf{V})$</p> <p>$\Rightarrow \dim(\mathbf{W}) \geq (9+9+9) - (2 \times 10)$</p> <p>$\Rightarrow \dim(\mathbf{W}) \geq 7$</p>
Answer	$7 \leq \dim(\mathbf{W}) \leq 10$

TABLE 6.6.1: Solution summary

Hence, we can conclude that $\dim(\mathbf{W}) \geq 7$.