

MAS242 선형대수학 Notes

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CONTENTS

CHAPTER	LINEAR EQUATIONS	PAGE 3
CHAPTER	VECTOR SPACES	PAGE 4
	2.1 Bases and Dimension	4
CHAPTER	LINEAR TRANSFORMATIONS	PAGE 7
	3.1 Linear Transformations	7
	3.2 The Algebra of Linear Transformations	8
	3.3 Isomorphism	10
	3.4 Representation of Transformation by Matrices	10
	3.5 Linear Functionals	11
	3.6 The Double Dual	13
	3.7 The Transpose of a Linear Transformation	14
CHAPTER	POLYNOMIALS	PAGE 15
	4.1 Algebras	15
CHAPTER	DETERMINANTS	PAGE 19
	5.1 Determinant Functions	19
CHAPTER	ELEMENTARY CANONICAL FORMS	PAGE 23
	6.1 Eigenvalues	23
	6.2 Annihilating Polynomials	25
	6.3 Invariant Subspaces	26
	6.4 Simultaneous Triangulation and Diagonalization	28
	6.5 Direct-Sum Decompositions	30
	6.6 Invariant Direct Sums	31
	6.7 The Primary Decomposition Theorem	31

CHAPTER	THE RATIONAL AND JORDAN FORMS	PAGE 34
	7.1 Cyclic Subspaces and Annihilators	34
	7.2 Cyclic Decompositions and the Rational Form	35
	7.3 The Jordan Form	40

CHAPTER	INNER PRODUCT SPACES	PAGE 43
	8.1 Inner Products	43
	8.2 Inner Product Space	44
	8.3 Linear Functionals and Adjoint	48
	8.4 Normal Operators	51

Chapter 1

Linear Equations

Chapter 2

Vector Spaces

2.1 Bases and Dimension

Theorem 2.1.1

Any subset that is linearly independent can be extended to a basis of V .

Lemma 2.1.1

If W is a subspace of V and $W \subsetneq V$, then $\dim W < \dim V$ provided that V is finite-dimensional.

Proof. Let S_0 be a basis of W . S_0 is linearly independent, so we can enlarge it to get a basis of V . $S' \triangleq S_0 \cup \{v_1, v_2, \dots, v_r\}$ is a basis of V . $|S'| \geq |S_0| + 1$; otherwise $\text{span } S_0 = V$. \square

Theorem 2.1.2 Inclusion/Exclusion Principle for Vector Spaces

If W_1 and W_2 are finite-dimensional subspaces of V , then $W_1 + W_2$ is a finite-dimensional vector space and $\dim W_1 + \dim W_2 = \dim(W_1 + W_2) + \dim(W_1 \cap W_2)$.

Proof. Let $a \triangleq \dim W_1$, $b \triangleq \dim W_2$, $c \triangleq \dim(W_1 + W_2)$, and $d \triangleq \dim(W_1 \cap W_2)$. Choose $\{\alpha_1, \alpha_2, \dots, \alpha_d\}$ as a basis for $W_1 \cap W_2$. We may extend this into bases of W_1 and W_2 . Let $\{\alpha_1, \dots, \alpha_d, \beta_{d+1}, \beta_{d+2}, \dots, \beta_a\}$ and $\{\alpha_1, \dots, \alpha_d, \gamma_{d+1}, \gamma_{d+2}, \dots, \gamma_b\}$ be bases for W_1 and W_2 respectively.

We now claim that

$$B \triangleq \{\alpha_1, \dots, \alpha_d, \beta_{d+1}, \dots, \beta_a, \gamma_{d+1}, \dots, \gamma_b\}$$

is a basis of $W_1 + W_2$.

- Let $x \in W_1 + W_2$. Then, $x = w_1 + w_2$ where $w_i \in W_i$. Since $w_1 \in \text{span}\{\alpha_1, \dots, \alpha_d, \beta_{d+1}, \dots, \beta_a\}$ and $w_2 \in \text{span}\{\alpha_1, \dots, \alpha_d, \gamma_{d+1}, \dots, \gamma_b\}$, On the other hand, $B \subseteq W_1 + W_2$. Hence, $\text{span } B = W_1 + W_2$.
- Suppose we have $\sum a_i \alpha_i + \sum b_j \beta_j + \sum c_k \gamma_k = 0$ for some $a_i, b_j, c_k \in F$. Rearranging the terms, we get $\sum a_i \alpha_i + \sum b_j \beta_j = -\sum c_k \gamma_k$, which implies that $\sum c_k \gamma_k \in W_1 \cap W_2$. The fact that γ_k 's are linearly independent from $\{\alpha_i\}$ implies that $c_k = 0$ for all k . Similarly, $b_j = 0$ for all j . Hence, we are left with $\sum a_i \alpha_i = 0$, in which α_i 's are linearly independent; $a_i = 0$. Hence, B is linearly independent.

Therefore, $\dim(W_1 + W_2) = a + b - d$. \square

Definition 2.1.1: Ordered Basis

Let V be a finite-dimensional vector space over F . An *ordered basis* of V is a sequence of vectors that forms a basis.

Note:-

Usually, we emphasize the ordered basis with semicolons like $\{\beta_1; \beta_2\}$.

Lemma 2.1.2

Let V be a finite-dimensional vector space over F . Suppose $B = \{v_1; v_2; \dots; v_n\}$ is an ordered basis of V . Then, for each $x \in V$, there uniquely exists an expression of the form

$$x = x_1 v_1 + x_2 v_2 + \dots + x_n v_n$$

for some $x_i \in F$.

Proof. The existence of the form is obvious since $x \in V = \text{span } B$.

(Uniqueness) Suppose we have two such expressions:

$$x = \sum x_i v_i = \sum y_i v_i$$

where $x_i, y_i \in F$. Then, we have $\sum (x_i - y_i) v_i = 0$. The linear independence of B gives that $x_i - y_i = 0$ for all i . Hence, $x_i = y_i$. \square

Definition 2.1.2: Coordinate Matrix

Let V be a finite-dimensional vector space over F . Let B be an ordered basis of V . Let $x \in V$ and write it as $x = \sum_{i=1}^n x_i v_i$ with $x_i \in F$, $v_i \in B$. Define

$$[x]_B \triangleq \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix}$$

be the *coordinate matrix* of x with respect to the basis B

Theorem 2.1.3

Let V be a finite-dimensional vector space over F . Let B and B' be two ordered bases of V . Then, there uniquely exists an invertible matrix P such that $\forall x \in V$, $[x]_B = P[x]_{B'}$ and $[x]_{B'} = P^{-1}[x]_B$.

Proof. Let $B \triangleq \{\alpha_1; \dots; \alpha_n\}$ and $B' \triangleq \{\alpha'_1; \dots; \alpha'_n\}$. For $\alpha'_j \in B'$, since B is a basis, there are unique $P_{ij} \in F$ ($i \in [n]$) such that $\alpha'_j = \sum_{i=1}^n P_{ij} \alpha_i$.

Let $x \in V$. Write $[x]_B = \begin{pmatrix} x_1 \\ \vdots \\ x_n \end{pmatrix}$ and $[x]_{B'} = \begin{pmatrix} x'_1 \\ \vdots \\ x'_n \end{pmatrix}$. Then, $x = \sum_{j=1}^n x'_j \alpha'_j = \sum_{j=1}^n (\sum_{i=1}^n x'_j P_{ij}) \alpha_i$.

By the uniqueness, we have $x_i = \sum_{j=1}^n x'_j P_{ij}$ for each i . In other words, we have

$$\begin{bmatrix} x_1 \\ \vdots \\ x_n \end{bmatrix} = \begin{bmatrix} P_{11} & \dots & P_{1n} \\ \vdots & \dots & \vdots \\ P_{n1} & \dots & P_{nn} \end{bmatrix} \begin{bmatrix} x'_1 \\ \vdots \\ x'_n \end{bmatrix}$$

Since B and B' are linearly independent, $x = 0 \iff [x]_B = 0 \iff [x]_{B'} = 0$. Hence, P is invertible. \square

Chapter 3

Linear Transformations

3.1 Linear Transformations

Definition 3.1.1: Linear Transformation

Let V_1 and V_2 be vector spaces over F . $T: V_1 \rightarrow V_2$ is said to be a *linear transformation* if

- $\forall x_1, x_2 \in V_1, T(x_1 + x_2) = T(x_1) + T(x_2)$
- $\forall x \in V_1, \forall c \in F, T(cx) = cT(x)$.

Theorem 3.1.1

Let V and W be finite-dimensional vector spaces over F . where $\{\alpha_1, \dots, \alpha_n\}$ is a basis of V . Let $\{\beta_1, \dots, \beta_n\}$ be any given set of vectors of W . Then, there exists a unique transformation $T: V \rightarrow W$ such that $T(\alpha_i) = \beta_i$.

Proof. Let $T_0: V \rightarrow W$ be defined by

$$T_0\left(\sum_{i=1}^n x_i \alpha_i\right) = \sum_{i=1}^n x_i \beta_i.$$

This is a linear transformation indeed.

(Uniqueness) If there is another such $U: V \rightarrow W$, Then, $U\left(\sum_{i=1}^n x_i \alpha_i\right) = \sum_{i=1}^n x_i U(\alpha_i)$. Hence, $U = T_0$. \square

Definition 3.1.2: Null Space and Range Space

Let $T: V \rightarrow W$ be a linear transformation between vector spaces over F .

- $\text{null } T \triangleq \ker T \triangleq \{v \in V \mid T(v) = 0\}$
- $\text{range } T \triangleq \text{Im } T \triangleq \{w \in W \mid \exists v \in V, w = T(v)\}$

Note:-

$\ker T$ and $\text{Im } T$ are subspaces of V and W respectively.

Definition 3.1.3

Let $T: V \rightarrow W$ be a linear transformation between vector spaces over F .

$$\text{nullity}(T) \triangleq \dim \ker(T) \quad \text{and} \quad \text{rank}(T) \triangleq \dim \text{Im}(T)$$

Theorem 3.1.2 Rank-Nullity Theorem

Let $T: V \rightarrow W$ be a linear transformation between vector spaces over F . Then, $\text{rank}(T) + \text{nullity}(T) = \dim V$.

Proof. Let $\{v_1, \dots, v_k\}$ be a basis for $\ker T$ where $k = \text{nullity } T$. Choose $v_{k+1}, \dots, v_n \in V$ such that $\{v_i\}_{i=1}^n$ is a basis of V . We claim that $\{T(v_{k+1}), \dots, T(v_n)\}$ is a basis of $\text{Im } T$.

Suppose $\sum_{i=k+1}^n c_i T(v_i) = 0$ for some $c_i \in F$. Then, we have $T(\sum_{i=k+1}^n c_i v_i) = 0$; hence $\sum_{i=k+1}^n c_i v_i \in \ker T$. Since $\{v_1, \dots, v_k\}$ is a basis of $\ker T$, we have $\sum_{i=k+1}^n c_i v_i = \sum_{i=1}^k a_i v_i$ for some a_i 's. Therefore, since $\{v_1, \dots, v_n\}$ is linearly independent, all c_i 's and a_i 's are zero. This implies that $\{T(v_i)\}_{i=k+1}^n$ is linearly independent.

Take any $T(v) \in \text{Im } T$. Then, $v = \sum_{i=1}^n c_i v_i$ for some $c_i \in F$. Then, $T(v) = \sum_{i=k+1}^n c_i T(v_i)$. Hence, $\text{Im } T \subseteq \text{span}\{T(v_{k+1}), \dots, T(v_n)\}$

The two paragraphs imply that $\text{rank } T = n - k$. \square

Theorem 3.1.3

Let A be a $m \times n$ matrix. Then $\dim \text{span}(\text{rows}) = \dim \text{span}(\text{columns})$.

Proof. $V = F^n$, $W = F^m$. Then, $\dim \text{span}(\text{columns}) = \dim \text{Im } T = \text{rank } T$, so $\text{nullity } T = n - \text{rank } T = n - \text{colrank } T$.

The number of rows with leading one's in $\text{rref } A$ equals the dimension of the row space of A , which is simply the number of columns with the leading ones. It is equal to the dimension of the column space. Hence, $\text{nullity } T = n - \text{colrank } T$ \square

3.2 The Algebra of Linear Transformations

Definition 3.2.1

Let $T: V \rightarrow W$ be a linear transformation between vector spaces over F . $L(V, W) \triangleq \{T: V \rightarrow W \mid T \text{ is a linear transformation}\}$

Theorem 3.2.1

Let $T: V \rightarrow W$ be a linear transformation between vector spaces over F . Then, $L(V, W)$ is a vector space over F under usual addition and multiplication.

Theorem 3.2.2

Let V and W be n - and m -dimensional vector spaces over F , respectively. Then, $\dim L(V, W) = mn$.

Proof. Let $\mathcal{B} = \{\alpha_1, \dots, \alpha_n\}$ and $\mathcal{B}' = \{\beta_1, \dots, \beta_m\}$ be bases for V and W , respectively. For each $p \in [n]$ and $q \in [m]$, Define

$$E^{p,q}(\alpha_i) = \begin{cases} 0 & \text{if } i \neq p \\ \beta_q & \text{if } i = p \end{cases}.$$

Then,

- These $E^{p,q}$ are linear transformations
- These are linearly independent.

- They span $L(V, W)$.

□

Lemma 3.2.1

Let $T: V \rightarrow W$ and $U: W \rightarrow Z$ be linear transformations between vector spaces over F . Then, $U \circ T \in L(V, Z)$.

Definition 3.2.2: Linear Operator (Endomorphism)

Let $T: V \rightarrow V$ be a linear transformation from a vector space V to itself. Then, T is called a *linear operator*. (Or an *endomorphism*.)

Note:-

For each $T, U \in L(V, V)$, $T \circ U \in L(V, V)$. $(T_1 + T_2) \circ U = T_1 \circ U + T_2 \circ U$. And many more... $(L(V, V), +, \circ)$ is a non-commutative ring.

Definition 3.2.3: Injectivity and Surjectivity

A linear transform $T: V \rightarrow W$ is

- *injective* (or, nonsingular) if $T(v) = 0 \implies v = 0$.
- *surjective* if $T(V) = W$.
- *invertible* if \exists linear transform $U: W \rightarrow V$, $U \circ T = \text{id}_V \wedge T \circ U = \text{id}_W$.

Exercise 3.2.1

$T: V \rightarrow W$ is injective and surjective if and only if T is invertible.

Exercise 3.2.2

If $T: V \rightarrow W$ is a nonsingular linear transformation, then, for any linearly independent subset $S \subseteq V$, $T(S)$ is linearly independent.

Exercise 3.2.3

Suppose V and W are finite-dimensional vector spaces. If $T: V \rightarrow W$ is invertible, then $\dim V = \dim W$.

Theorem 3.2.3

Let V and W be finite-dimensional vector spaces over F with $\dim V = \dim W$. Let $T: V \rightarrow W$ be a linear transform. TFAE

- T is invertible.
- T is injective.
- T is surjective.

Proof. T is injective \iff nullity $T = 0 \iff$ rank $T = n \iff \text{Im } T = W \iff T$ is onto □

Definition 3.2.4: General Linear Group

Let $\text{GL}(V) \triangleq \{ T \in L(V, V) \mid T \text{ is invertible} \}$. Then, $(\text{GL}(V), \circ)$ is called the *general linear group* of V .

Note:-

The general linear group is actually a group.

3.3 Isomorphism

Definition 3.3.1: Isomorphism

Let V and W be vector spaces over F . We say that a linear transformation $T: V \rightarrow W$ is an *isomorphism* if T is an invertible linear transformation.

We say V and W are *isomorphic* if there exists an isomorphism $T: V \rightarrow W$, if V and W are isomorphic, then we write $V \simeq W$.

Theorem 3.3.1

Let V be a vector spaces over F of dimension n . Then, $V \simeq F^n$.

Proof. Let $B = \{\alpha_1; \dots; \alpha_n\}$ be a basis of V . Define $T: V \rightarrow F^n$ by $v \mapsto [v]_B$.

Suppose $T(v) = 0$. Then, $v = 0 \cdot \alpha_1 + \dots + 0 \cdot \alpha_n = 0$. Hence, T is injective. By Theorem 3.2.3, T is isomorphism. \square

3.4 Representation of Transformation by Matrices

Theorem 3.4.1

Let V and W be vector spaces over F with $\dim V = n$ and $\dim W = m$. Let B and B' be bases of V and W , respectively. If $T: V \rightarrow W$ is a linear transformation, then there uniquely exists $m \times n$ matrix A such that $[T(v)]_{B'} = A[v]_B$. We write $[T]_{B,B'} \triangleq A$.

Proof. $A = \begin{bmatrix} [T(v_1)]_{B'} & [T(v_2)]_{B'} & \dots & [T(v_n)]_{B'} \end{bmatrix}$ where v_i is the i^{th} basis vector of B . \square

Theorem 3.4.2

Let $V \xrightarrow{T} W \xrightarrow{U} Z$ be linear transformations. Let $A_1 = [T]_{B,B'}$ and $A_2 = [U]_{B'',B'}$. Then, $[U \circ T]_{B,B''} = A_2 A_1$.

Theorem 3.4.3

Let V be finite-dimensional vector space over F with two (possibly different) bases B_1 and B_2 . Let $T \in L(V, V)$. Let P be the matrix such that $[v]_{B_1} = P[v]_{B_2}$. Then, $[T]_{B_1} \triangleq [T]_{B_1, B_1}$ are related by

$$[T]_{B_2} = P^{-1}[T]_{B_1}P.$$

Definition 3.4.1: Similar Matrices

Suppose M and N are $n \times n$ matrices. M and N are *similar* if there exists an invertible P such that $N = P^{-1}MP$.

Proof. $[T(v)]_{B_1} = [T]_{B_1}[v]_{B_1} = [T]_{B_1}P[v]_{B_2}$. $[T(v)]_{B_1} = P[T(v)]_{B_2} = P[T]_{B_2}[v]_{B_2}$.

Since v was arbitrary, $P[T]_{B_2} = [T]_{B_1}P$. \square

Note:-

- A linear transformation $T: V \rightarrow V$ gives varying matrices $[T]_B$ that are all similar when the basis B is changed.
- On linear operators, we will have various definitions.
- Characteristic (eigen) polynomial has $(-1)^{\deg}(\text{constant term})$ as $\det T$ and $-(n - 1 \text{ deg term})$ as $\text{tr } T$.

3.5 Linear Functionals

Definition 3.5.1: Linear Functional

Let V be a vector space over F . A linear transformation $T: V \rightarrow F$ is called a *(linear) functional*.

Definition 3.5.2: Dual Vector Space

Let V be a vector space over F . We normally write $V^* \triangleq L(V, F)$ and call it the *dual vector space* of V .

Note:-

By Theorem 3.2.2, we know that $\dim V^* = \dim V$ if V is a finite-dimensional vector space.

Lemma 3.5.1

Let V be a finite-dimensional vector space over F and let $n = \dim V$. Let $\{\alpha_1, \alpha_2, \dots, \alpha_n\}$ be a basis for V . Define $f_i \in V^*$ by declaring $f_i(\alpha_j) = \delta_{ij}$. Then, $\{f_1, \dots, f_n\}$ is a basis for V^* .

Proof. Since $\dim V^* = \dim V = n$, we only need to show that the set is linearly independent.

Suppose $\sum_{i=1}^n c_i f_i = 0$ for some $c_i \in F$. Then, for each $j \in [n]$, as $f_i(\alpha_j) = \delta_{ij}$, $0 = (\sum_{i=1}^n c_i f_i)(\alpha_j) = c_j f_j(\alpha_j) = c_j$. Hence, they are linearly independent. \square

Definition 3.5.3: Dual Basis

The set $\{f_1, f_2, \dots, f_n\} \subseteq V^*$ in Lemma 3.5.1 is called the *dual basis* of the basis $\{\alpha_1, \dots, \alpha_n\}$ for V .

Lemma 3.5.2

Let V be a finite-dimensional vector space over F and let $n = \dim V$. Let $\{\alpha_1, \alpha_2, \dots, \alpha_n\}$ be a basis for V . Let $\{f_1, \dots, f_n\} \subseteq V^*$ be the dual basis of it.

- For each $f \in V^*$, $f = \sum_{i=1}^n f(\alpha_i) f_i$.
- For each $v \in V$, $v = \sum_{i=1}^n f_i(v) \alpha_i$.

Proof.

- There exists $x_i \in F$ such that $f = \sum_{i=1}^n x_i f_i$. Evaluating at α_j for each $j \in [n]$, we get $f(\alpha_j) = x_j$.
- There exists $y_i \in F$ such that $v = \sum_{i=1}^n y_i \alpha_i$. Applying f_j for each $j \in [n]$, we get $f_j(v) = y_j$.

\square

Definition 3.5.4: Hyperspace

Let V be a finite-dimensional vector space over F and let $n = \dim V$. A subspace W of V which has the dimension $n - 1$ is called a *hyperspace* in V .

Example 3.5.1

If $f : V \rightarrow F$ is a nonzero functional, then $\ker f$ is an example of a hyperspace in V .

Definition 3.5.5: Annihilator

Let V be a finite-dimensional vector space over F with dimension n . Let $\emptyset \subsetneq S \subseteq V$. The *annihilator* of S , $S^\circ = \text{Ann } S$ is defined to be

$$S^\circ = \{f \in V^* \mid \forall \alpha \in S, f(\alpha) = 0\}.$$

Note:-

- S° is a subspace of V^*
- $\text{Ann } \{0\} = V^*$.
- $\text{Ann } V = \{0\}$.

Theorem 3.5.1

Let V be a finite-dimensional vector space over F with dimension n . Let W be a subspace of V . Then,

$$\dim W + \dim W^\circ = \dim V.$$

Proof. Let $k \triangleq \dim W$ and $\{\alpha_1, \dots, \alpha_k\} \subseteq W$ be a basis for W . We may extend it to the basis for V so that $\{\alpha_1, \dots, \alpha_k, \alpha_{k+1}, \dots, \alpha_n\}$ is a basis for V . Let $\{f_1, \dots, f_k, f_{k+1}, \dots, f_n\}$ be the dual basis of $\{\alpha_1, \dots, \alpha_n\}$.

For each $i \in \{k+1, \dots, n\}$, by the construction of the dual basis, $f_i(\alpha_j) = 0$ for each $j \in [k]$. Hence, $f_{k+1}, \dots, f_n \in W^\circ$.

Take any $f \in W^\circ$. Then, $f = \sum_{i=1}^n f(\alpha_i)f_i$. For each $i \in [k]$, $f(\alpha_i) = 0$. Hence, $f = \sum_{i=k+1}^n f(\alpha_i)f_i$; $\{f_{k+1}, \dots, f_n\}$ spans W° . Therefore, $\{f_{k+1}, \dots, f_n\}$ is a basis for W° . \square

Corollary 3.5.1

Let V be a finite-dimensional vector space over F with dimension n . Let W be a k -dimensional subspace of V . Then, W is the intersection of $n - k$ hyperspaces in V of the form $\ker f_i$ for some $f_i \in V^* \setminus \{0\}$.

Proof. Let $\{\alpha_1, \dots, \alpha_k\}$ be a basis for W and extend it to $\{\alpha_1, \dots, \alpha_n\}$ so that it becomes a basis for V . Let $\{f_1, \dots, f_n\} \subseteq V^*$ be the dual basis of $\{\alpha_1, \dots, \alpha_n\}$. Then, $W = \bigcap_{i=k+1}^n \ker f_i$. \square

Corollary 3.5.2

Let V be a finite-dimensional vector space over F with dimension n . Let W be a hyperspace in V . Then, $W = \ker f$ for some $f \in V^* \setminus \{0\}$.

3.6 The Double Dual

Note:-

Take $\alpha \in V$. Let us define $L_\alpha \in V^{**}$ as follows:

$$\begin{aligned} L_\alpha : V^* &\longrightarrow F \\ f &\longmapsto f(\alpha). \end{aligned}$$

Then, define \mathcal{L} by

$$\begin{aligned} \mathcal{L} : V &\longrightarrow V^{**} \\ \alpha &\longmapsto L_\alpha. \end{aligned}$$

Then, \mathcal{L} is an injective linear transformation.

Theorem 3.6.1

Let V be a finite-dimensional vector space over F with dimension n . Then, $\mathcal{L} : V \rightarrow V^{**}$ is an isomorphism of vector spaces.

Proof. We have $\dim V = \dim V^* = \dim V^{**} = n$ by Theorem 3.2.2. The result follows from Theorem 3.2.3. \square

Definition 3.6.1: Proper Subspace

Let V be a vector space over F . Then, a subspace W of V is a *proper subspace* of V if $W \subsetneq V$.

Definition 3.6.2: Maximal Subspace

A proper subspace W of V is said to be *maximal* if, there exists no subspace Z of V such that $W \subsetneq Z \subsetneq V$.

Definition 3.6.3: Hyperspace

Let V be a vector space over F . A maximal proper subspace W of V is called a *hyperspace* in V .

Note:-

In case of $\dim V = n$, a proper maximal subspace of V is of dimension $n - 1$.

Theorem 3.6.2

Let V be a vector space over F . Let $f \in V^* \setminus \{0\}$. Then, $\ker f$ is a hyperspace in V .

Proof. $\ker f$ is proper, since, otherwise, $f = 0$.

It is enough to show that, for each $\alpha \in V \setminus \ker f$, $\text{span}\{\ker f, \alpha\} = V$. Take any $\beta \in V$. Let $\alpha \in V \setminus \ker f$. Define $c \triangleq f(\alpha)^{-1}f(\beta)$ and $\gamma \triangleq \beta - c\alpha$. Then, $f(\gamma) = f(\beta) - cf(\alpha) = 0$; $\gamma \in \ker f$. Hence, $\beta = \gamma + c\alpha \in \text{span}[\ker f, \alpha]$. \square

Theorem 3.6.3

Let V be a vector space over F . Let W be a hyperspace in V . Then, there exists $f \in$

$V^* \setminus \{0\}$ such that $W = \ker f$.

Proof. There exists $\alpha \in V \setminus W$ such that $\text{span}\{W, \alpha\} = V$. Hence, every $\beta \in V$ can be written as $\beta = \gamma + c\alpha$ where $\gamma \in W$ and $c \in F$. Note that γ and c are uniquely determined by β .

Define $g: V \rightarrow F$ by $g(\beta) = c$. Then, g is a linear functional, and $\ker g = W$ by definition. \square

Note:-

Theorem 3.6.2 and Theorem 3.6.3 together imply that the set of hyperspaces in V and the set of null spaces of functionals have a one-to-one correspondence.

3.7 The Transpose of a Linear Transformation

Definition 3.7.1: Transpose

Let $T: V \rightarrow W$ be a linear transformation. The map $T^t: W^* \rightarrow V^*$ defined by $g \mapsto g \circ T$ is called the *transpose* of T .

Lemma 3.7.1

Let $T: V \rightarrow W$ be a linear transformation. Then, T^t is a linear transformation.

Theorem 3.7.1

Let $T: V \rightarrow W$ be a linear transformation between finite-dimensional vector spaces over F . Fix ordered bases \mathcal{B} and \mathcal{B}' for V and W , respectively. Let \mathcal{B}^* and \mathcal{B}'^* be their dual bases. Let $A \triangleq [T]_{\mathcal{B}, \mathcal{B}'}$ and $A' \triangleq [T^t]_{\mathcal{B}'^*, \mathcal{B}^*}$. Then, $a_{ij} = a'_{ji}$.

Proof. Let $\mathcal{B} = \{\alpha_1, \dots, \alpha_n\}$, $\mathcal{B}' = \{\beta_1, \dots, \beta_m\}$, $\mathcal{B}^* = \{f_1, \dots, f_n\}$, and $\mathcal{B}'^* = \{g_1, \dots, g_m\}$. Then, we have $T\alpha_j = \sum_{i=1}^m a_{ij}\beta_i$ for each $j \in [n]$ and $T^tg_j = \sum_{i=1}^n b_{ij}f_i$ for each $j \in [m]$.

For each $i \in [n]$ and $j \in [m]$, $(T^tg_j)(\alpha_i) = g_j(T\alpha_i) = g_j\left(\sum_{k=1}^m a_{ki}\beta_k\right) = \sum_{k=1}^m a_{ki}g_j(\beta_k) = a_{ji}$. Hence, since T^tg_j is a linear functional on V , $T^tg_j = \sum_{i=1}^n (T^tg_j)(\alpha_i)f_i = \sum_{i=1}^n a_{ji}f_i$. Therefore, $a_{ij} = b_{ji}$ for each $i \in [n]$ and $j \in [m]$. \square

Theorem 3.7.2

Let $T: V \rightarrow W$ be a linear transformation.

- (i) $\ker T^t = (\text{Im } T)^\circ$.
- (ii) If V and W are finite-dimensional, then $\text{rank } T^t = \text{rank } T$.
- (iii) If V and W are finite-dimensional, then $\text{Im } T^t = (\ker T)^\circ$.

Proof.

- (i) $g \in \ker T^t \iff T^t(g) = 0 \iff g \circ T = 0 \iff g \in (\text{Im } T)^\circ$
- (ii) Let $n \triangleq \dim V$ and $m \triangleq \dim W$. Let $r = \text{rank } T$. Then, by Theorem 3.5.1, $\dim(\text{Im } T)^\circ = m - r$. By (i), $(\text{Im } T)^\circ = \ker T^t$; hence $\text{nullity } T^t = m - r$. By the rank-nullity theorem, $\text{rank } T^t = r = \text{rank } T$.
- (iii) Take any $f \in \text{Im } T^t$. Then, there exists $g \in W^*$ such that $f = g \circ T$. Then, for any $\alpha \in \ker T$, $f(\alpha) = g(T(\alpha)) = 0$. Hence, $f \in (\ker T)^\circ$; $\text{Im } T^t \subseteq (\ker T)^\circ$. But since the two spaces have the same dimension, it must be the equality to hold. \square

Chapter 4

Polynomials

4.1 Algebras

Definition 4.1.1: F -algebra

Let F be a field. A vector space \mathcal{A} with a map $\mathcal{A} \times \mathcal{A} \rightarrow \mathcal{A}$ such that

- (i) $\forall \alpha, \beta, \gamma \in \mathcal{A}, \alpha(\beta\gamma) = (\alpha\beta)\gamma$
- (ii) $\forall \alpha, \beta, \gamma \in \mathcal{A}, \alpha(\beta + \gamma) = \alpha\beta + \alpha\gamma$ and $(\alpha + \beta)\gamma = \alpha\gamma + \beta\gamma$
- (iii) $\forall c \in F, \forall \alpha, \beta \in \mathcal{A}, c(\alpha\beta) = (c\alpha)\beta = \alpha(c\beta)$

is called a F -algebra or a linear algebra over F .

- If there is an element 1 in \mathcal{A} such that $1\alpha = \alpha 1 = \alpha$ for each $\alpha \in \mathcal{A}$, then we call \mathcal{A} a F -algebra with identity.
- The algebra \mathcal{A} is called *commutative* if $\alpha\beta = \beta\alpha$ for all $\alpha, \beta \in \mathcal{A}$.

Definition 4.1.2: Polynomial

Let $F[x]$ be the subspace of F^ω spanned by the vectors $1, x, x^2, \dots$. An element of $F[x]$ is called a *polynomial over F* .

Definition 4.1.3: Degree

For each $f \in F[x] \setminus \{0\}$, $\deg f \triangleq \max\{k \in \mathbb{N} \cup \{0\} \mid f_k \neq 0\}$.

Theorem 4.1.1

Let $f, g \in F[x] \setminus \{0\}$.

- (i) $fg \neq 0$
- (ii) $\deg(fg) = \deg f + \deg g$
- (iii) fg is monic if f and g are monic.
- (iv) fg is scalar polynomial if f and g are scalar polynomials.
- (v) If $f + g \neq 0$, then $\deg(f + g) \leq \max\{\deg f, \deg g\}$.

Theorem 4.1.2 Euclidean Algorithm

Let $f, g \in F[x]$ and $g \neq 0$. Then, there uniquely exists $q, r \in F[x]$ such that

- $f = gq + r$ and
- either $r = 0$ or $\deg r < \deg g$.

Definition 4.1.4: Divisibility

Let $f, g \in F[x]$. If $f = gq$ for some $q \in F[x]$, then we write $g \mid f$.

Lemma 4.1.1

Let $f \in F[x] \setminus \{0\}$ and $c \in F$. Then, $(x - c) \mid f \iff f(c) = 0$.

Proof. There exists $q, r \in F[x]$ such that $f = (x - c)q + r$ with either $r = 0$ or $\deg r = 0$. Note that $f(c) = r$. Hence, $f(c) = 0 \iff (x - c) \mid f$. \square

Definition 4.1.5: Evaluation

Let F be a field. Let $\alpha \in F$ be fixed. Then, the function $\text{ev}_\alpha: F[x] \rightarrow F$ defined by $f \mapsto f(\alpha)$ is called the *evaluation of α in $f(x)$* .

Definition 4.1.6: Ideal

An ideal $M \subseteq F[x]$ is an F -subspace if for every $f \in F[x]$ and $g \in M$, we have $fg \in M$.

Definition 4.1.7: Principal Ideal

An ideal of the form

$$M = \{g_0 h \mid h \in F[x]\} = (g_0)$$

for a fixed g_0 is called a *principal ideal*.

Theorem 4.1.3

Let F be a field. Let $M \subseteq F[x]$ be a nonzero ideal. Then, M is a principal ideal given by a monic polynomial in $F[x]$.

Proof. M does contain nonzero polynomials. Hence, we may let $g_0 \in \arg\min_{g \in M \setminus \{0\}} \deg g$ by the well-orderedness of natural numbers. WLOG, g_0 is monic.

We shall claim that $M = (g_0)$. Take any $f \in M$. By the Euclidean algorithm, $\exists q, r \in F[x]$, $f = g_0 q + r$ with either $r = 0$ or $\deg r < \deg g_0$. If $r \neq 0$, then $r = f - g_0 q \in M$ but $\deg r < \deg g_0$, which contradicts the minimality of $\deg g_0$. Hence, $r = 0$, and thus $f = g_0 q \in (g_0)$. \square

Note:-

By putting “monic” assumption, such g_0 is unique as well.

Corollary 4.1.1

Let $p_1, \dots, p_n \in F[x]$ be a finite number of polynomials where not all of them are zero. Then, there uniquely exists monic $g_0 \in F[x]$ such that

(i) $p_1 F[x] + p_2 F[x] + \dots + p_n F[x] = (g_0)$

(ii) $\forall i \in [n], g_0 \mid p_i$

(iii) $(\forall i \in [n], f \mid p_i) \implies f \mid g_0$

Such g_0 is called the *greatest common divisor* of p_1, \dots, p_n . Sometimes this is denoted by $(p_1, \dots, p_n) = (g_0)$.

Proof. $p_1F[x] + p_2F[x] + \cdots + p_nF[x]$ is an ideal. By Theorem 4.1.3, there uniquely exists monic g_0 that generates it. (ii) directly follows from (i). $g_0 = \sum_{j=1}^n p_j g_j = f \sum_{j=1}^n h_j g_j$. \square

Definition 4.1.8: Relatively Prime

Let p_1, \dots, p_n be nonzero polynomials. We say that they are *relatively prime* if $(p_1, \dots, p_n) = (1)$.

Definition 4.1.9: Reducibility

Let F be a field. We say $f \in F[x] \setminus \{0\}$ is *reducible* if $f = gh$ for some $g, h \in F[x]$ with $\deg g, \deg h \geq 1$. If f is not reducible, we say f is *irreducible*.

Definition 4.1.10: Prime Element

Let F be a field. We say that $f \in F[x]$ is a *prime element* if, for every $g, h \in F[x]$, $f \mid gh \implies (f \mid g \vee f \mid h)$.

Example 4.1.1

- Let F be a field. Then any polynomial over F with degree one is irreducible.
- $F = \mathbb{R}$. $f(x) = x^2 + ax + b$ is irreducible iff $D < 0$.
- $F = \mathbb{F}_p = \mathbb{Z}/p$. There are quite many irreducible polynomial of degree d .

Theorem 4.1.4

Let $p \in F[x] \setminus \{0\}$ be a polynomial. Then, p is irreducible if and only if p is prime.

Proof.

(\implies) Suppose $p \mid gh$ for some $g, h \in F[x]$. If g or h is zero, then it is done. Hence, WMA that $g, h \neq 0$. Let $(p, g) = (d)$. $d \mid p$ implies that $d = 1$ or $d = p$ since p is irreducible. If $d = p$, then $d \mid g$, i.e., $p \mid g$. If $d = 1$, then there exists p_0, g_0 such that $pp_0 + gg_0 = 1$. Hence, $php_0 + ghg_0 = h$. Hence, $p \mid h$.

(\impliedby) Suppose p is reducible. Then, $p = gh$ for some g, h with nonzero degrees. Since p is prime, $p \mid g$ or $p \mid h$. This implies $\deg p \leq \deg g$ or $\deg p \leq \deg h$. This is a contradiction since $\deg p = \deg g + \deg h \leq 2 \deg p$ arises. \square

Theorem 4.1.5 Unique Factorization of Polynomials

Let F be a field. Every non-constant polynomial $f \in F[x]$ factors into a product of irreducible polynomials $f = p_1 p_2 \cdots p_r$. Moreover, the representation is unique up to multiplying nonzero constants and relabeling.

Proof. WLOG, f is monic.

(existence) If $\deg f = 1$, then $f(x) = x - a$ for some $a \in F$, which is itself irreducible.

Suppose $\deg f > 1$. Suppose the theorem holds for all $g \in F[x]$ with $\deg g < \deg f$. If f is itself irreducible, then done. Otherwise, there are $g_1, g_2 \in F[x]$ with $\deg g_i \geq 1$ such that $f = g_1 g_2$. Then, $\deg g_1$ and $\deg g_2$ are less than f . Hence, $g_1 = p_1 p_2 \cdots p_r$ and $g_2 = q_1 q_2 \cdots q_s$ where p_j and q_j are irreducible, yielding $f = p_1 \cdots p_r q_1 \cdots q_s$.

(uniqueness) Suppose we have two factorization $f = p_1 \cdots p_r = q_1 \cdots q_s$. $p_1 \mid q_1 \cdots q_s$. Hence, $p_1 \mid q_j$ for some $j \in [s]$. Since q_j is irreducible, this means p_1 is a nonzero constant

multiple of q_j . Relabeling, $p_1 = q_1$, we have $p_2 \cdots p_r = q_2 \cdots q_s$. Proceeding in this way, we get $r = s$ and $p_j = q_j$ for each j . \square

Definition 4.1.11: (Formal) Derivative

For $f(x) = a_0 + a_1x + \cdots + a_nx^n \in F[x]$, we define

$$f'(x) \triangleq a_1 + 2a_2x + \cdots + na_nx^{n-1}.$$

Note:-

- $(f + g)' = f' + g'$
- $(fg)' = f'g + fg'$

Theorem 4.1.6

f is a product of distinct irreducible polynomials if and only if f and f' are relatively prime.

Proof. (\Leftarrow) Suppose f and f' are relatively prime but $f = p^2h$ for some irreducible polynomial p for the sake of contradiction. Then, $f' = p(2p'h + ph')$, which contradicts $(f, f') = (1)$.
 (\Rightarrow) \square

Definition 4.1.12: Algebraically Closed

A field F is said to be *algebraically closed* if every irreducible polynomial in $F[x]$ is of degree 1.

Note:-

F is algebraically closed.

- \Leftrightarrow Every $f \in F[x]$ with $\deg f \geq 1$ has precisely n roots counting multiplicity.
- \Leftrightarrow Every non-constant $f \in F[x]$ factors into linear polynomials.

Note:-

\mathbb{C} is algebraically closed while \mathbb{R} is not.

Chapter 5

Determinants

5.1 Determinant Functions

Definition 5.1.1: n -linear and Iterating

Let K be a ring. Let $\mathcal{D} \rightarrow K^{n \times n} \rightarrow K$ be a function. This is considered as a function on n row vectors.

- (i) We say \mathcal{D} is n -linear if \mathcal{D} is a linear function on the i^{th} row while fixing all other rows.

$$\mathcal{D} \begin{bmatrix} \cdots & a_1 + a'_1 & \cdots \\ \cdots & a_2 & \cdots \\ & \vdots & \\ \cdots & a_n & \cdots \end{bmatrix} = \mathcal{D} \begin{bmatrix} \cdots & a_1 & \cdots \\ \cdots & a_2 & \cdots \\ & \vdots & \\ \cdots & a_n & \cdots \end{bmatrix} + \mathcal{D} \begin{bmatrix} \cdots & a'_1 & \cdots \\ \cdots & a_2 & \cdots \\ & \vdots & \\ \cdots & a_n & \cdots \end{bmatrix}$$

- (ii) An n -linear function \mathcal{D} is called *iterating* if $\mathcal{D}(A) = 0$ when two rows are equal.

Note:-

If \mathcal{D} is iterating, and if A' is obtained by switching i^{th} and j^{th} rows of A , then $\mathcal{D}(A') = -\mathcal{D}(A)$.

Definition 5.1.2: Determinant

Let K be a commutative ring with unity. Let $\mathcal{D}: K^{n \times n} \rightarrow K$ be a function. We say \mathcal{D} is a determinant function if

- (i) \mathcal{D} is n -linear,
- (ii) \mathcal{D} is alternating, and
- (iii) $\mathcal{D}(I_n) = 1$.

Definition 5.1.3: Minor Matrix

Let K be a commutative ring with unity. Let $A \in K^{n \times n}$ where $n > 1$. For each $i, j \in [n]$, define $A(i | j)$ be the $(n-1) \times (n-1)$ matrix with the i^{th} row and the j^{th} column are removed. $A(i | j)$ is called (i, j) -minor of A .

Theorem 5.1.1

There exists a determinant function $\mathcal{D}: K^{n \times n} \rightarrow K$.

Proof. We shall prove by exploiting mathematical induction. If $n = 1$, the identity function is a determinant function.

Suppose we have found a function $\mathcal{D}: K^{(n-1) \times (n-1)}$ which is $(n-1)$ -linear and alternating. We shall denote $\mathcal{D}(A(i | j)) = D_{ij}(A)$. Define $E_i(A) \triangleq \sum_{j=1}^n (-1)^{i+j} A_{ij} D_{ij}(A)$ for each $j \in [n]$.

Claim. E_j is an n -linear function on $K^{n \times n}$.

$D_{ij}(A)$ is independent from the entries of the i -th row and the j -th column. Hence, D_{ij} is n -linear as \mathcal{D} is $(n-1)$ -linear. Furthermore, $A \mapsto A_{ij} D_{ij}(A)$ is also n -linear; thus E_j is linear combination of n -linear functions.

Claim. E_j is an alternating function on $K^{n \times n}$.

For the sake of simplicity, suppose A has two equal rows at α_k and α_{k+1} . Hence, when $i \neq k$ and $i \neq k+1$, $A(i | j)$ has two identical rows; thus $D_{ij}(A) = \mathcal{D}(A(i | j)) = 0$. Thus, $E_j(A) = (-1)^{k+j} A_{kj} D_{kj}(A) + (-1)^{k+j+1} A_{(k+1),j} D_{(k+1),j}(A)$.

$$\begin{aligned} E_j(A) &= (-1)^{k+j} A_{kj} D_{kj}(A) + (-1)^{k+j+1} A_{(k+1),j} D_{(k+1),j}(A) \\ &= (-1)^{k+j} (A_{kj} D_{kj}(A) - A_{(k+1),j} D_{(k+1),j}(A)) = 0 \end{aligned}$$

Claim. $E_j(I_n) = 1$.

$$I_n(i | j) = I_{n-1}.$$

□

Corollary 5.1.1

The function defined recursively in the proof of Theorem 5.1.1 is a determinant function.

Definition 5.1.4: Permutation

Let S be a set. A permutation σ of S is a bijective function $\sigma: S \rightarrow S$. S_n is the set of bijective functions from $[n]$ onto $[n]$.

Definition 5.1.5: Transposition

$\tau \in S_n$ is called a *transposition* if it interchanges just the values of two members. A transposition that interchanges i and j is usually written as (i, j) .

Definition 5.1.6: Cycle

A cycle is like:

$$i_1 \mapsto i_2 \mapsto i_3 \mapsto \cdots \mapsto i_n \mapsto i_1.$$

This is written as (i_1, i_2, \dots, i_n) .

Note:-

- Every permutation can be written as a product of disjoint cycles.
- Every cycle can be written as a product of transpositions.
- Every permutation can be written as a product of transpositions.

Theorem 5.1.2

For any permutation $\sigma \in S_n$, the number of transpositions needed to express σ modular 2 is an invariant of σ .

Definition 5.1.7: Sign of Permutation

$$\text{sign}(\sigma) \triangleq \begin{cases} 1 & \text{if } \sigma \text{ is even} \\ -1 & \text{if } \sigma \text{ is odd} \end{cases}$$

Corollary 5.1.2

For $\sigma_1, \sigma_2 \in S_n$, $\text{sign}(\sigma_1 \sigma_2) = \text{sign}(\sigma_1) \text{sign}(\sigma_2)$.

Theorem 5.1.3

There exists a unique determinant function $\mathcal{D}: K^{n \times n} \rightarrow K$, which is equal to

$$\mathcal{D}(A) = \sum_{\sigma \in S_n} \text{sign}(\sigma) \prod_{j \in [n]} A_{j, \sigma(j)}.$$

Proof. Let e_1, \dots, e_n be the rows of I_n . For $A \in K^{n \times n}$, let α_i be the i -th rows of A . Then, $\alpha_i = \sum_{j=1}^n A_{ij} e_j$.

Note that, if $j_i = j_{i'}$, then $\mathcal{D}(e_{j_1}, \dots, e_{j_n}) = 0$. Also, if $\sigma \in S_n$, $\mathcal{D}(e_{\sigma(1)}, \dots, e_{\sigma(n)}) = \text{sign}(\sigma) \mathcal{D}(I_n) = \text{sign}(\sigma)$.

$$\begin{aligned} \mathcal{D}(A) &= \mathcal{D}(\alpha_1, \alpha_2, \dots, \alpha_n) \\ &= \mathcal{D}\left(\sum_{j=1}^n A_{1j} e_j, \alpha_2, \dots, \alpha_n\right) \\ &= \sum_{j=1}^n A_{1j} \mathcal{D}(e_j, \alpha_2, \dots, \alpha_n) \\ &= \dots = \sum_{j_1=1}^n \sum_{j_2=1}^n \dots \sum_{j_n=1}^n A_{1j_1} A_{2j_2} \dots A_{nj_n} \mathcal{D}(e_{j_1}, \dots, e_{j_n}) \\ &= \sum_{\sigma \in S_n} \text{sign}(\sigma) \prod_{j \in [n]} A_{j, \sigma(j)} \end{aligned}$$

Note that, if \mathcal{D} is a n -linear and alternating, then $\mathcal{D}(A) = \det A \cdot \mathcal{D}(I_n)$. □

Corollary 5.1.3

$$\det(AB) = \det A \cdot \det B$$

Corollary 5.1.4

Any cofactor expansion gives the same value.

Corollary 5.1.5

$$\det A^t = \det A$$

Proof. Theorem 3.7.1 and Theorem 5.1.3. □

Exercise 5.1.1

Let A be $r \times r$ matrix and C be an $s \times s$ matrix. Then,

$$\det \begin{bmatrix} A & B \\ 0 & C \end{bmatrix} = \det A \cdot \det C.$$

Hint) Fixing A, B , define $\mathcal{D}(A, B, C)$.

Definition 5.1.8: Adjoint Matrix

Let A be an $n \times n$ matrix. $C_{ij} \triangleq (-1)^{i+j} \det(A(i \mid j))$ for each $i, j \in [n]$ is called the (i, j) -cofactor. Then, $\text{adj}A \triangleq C^t$ where $(C)_{ij} = C_{ij}$ is called the *adjoint* of A .

Corollary 5.1.6

$A \cdot \text{adj}A = (\det A)I_n$. If $\det A \in K$ is invertible, then $A^{-1} = (\det A)^{-1} \text{adj}A$.

Chapter 6

Elementary Canonical Forms

6.1 Eigenvalues

Definition 6.1.1: Eigenvalue

Let V be a vector space over F . Let $T: V \rightarrow V$ be a linear operator.

- $c \in F$ is said to be an *eigenvalue* (or a *characteristic value*) of T if there exists $v \in V \setminus \{0\}$ such that $T(v) = cv$. Such v is called an *eigenvector* (or a *characteristic vector*) of T associated to c .
- For each $c \in F$, $E_c \triangleq \{v \in V \mid T(v) = cv\}$ is called an *eigenspace* (or a *characteristic space*) associated to c .

Theorem 6.1.1

Let V be a vector space over F . Let $T: V \rightarrow V$ be a linear operator. Then, TFAE.

- (i) $c \in F$ is an eigenvalue of T .
- (ii) $T - cI$ is singular.
- (iii) $\det(T - cI) = 0$.

Proof. The equivalence of (i) and (ii) is trivial. The equivalence of (ii) and (iii) is evident from Corollary 5.1.6. \square

Definition 6.1.2: Characteristic Polynomial

Let A be an $n \times n$ matrix over F . Define $f(x) \triangleq \det(xI - A) \in F[x]$. Then, f is a monic polynomial in x of degree $n = \dim V$.

If there exists a basis \mathcal{B} for V and $A = [T]_{\mathcal{B}}$, then we call $f(x) = \det(xI - A)$ the *characteristic polynomial* of T .

Note:-

The choice of basis does not affect the characteristic polynomial. See Theorem 3.4.3.

Note:-

If f is a characteristic polynomial of T , then $f(c) = 0$ if and only if c is an eigenvalue of T .

Corollary 6.1.1

If T is a linear operator on V , then there are at most n eigenvalues of T .

Proof. Every polynomial of degree n has at most n solutions. \square

Definition 6.1.3: Diagonalizability

Let V be a finite-dimensional vector space over F . Let $T \in L(V)$. We say T is *diagonalizable* if there exists a basis \mathcal{B} such that it consists of eigenvectors of T .

Note:-

- If $\mathcal{B} = \{v_1, \dots, v_n\}$ and $Tv_i = c_i v_i$ for each $i \in [n]$, then $[T]_{\mathcal{B}} = \text{diag}(c_1, c_2, \dots, c_n)$.
- If $T \in L(V)$ is diagonalizable, then the characteristic polynomial can be completely decomposed into a product of linear factors.

Lemma 6.1.1

Let V be a finite-dimensional vector space over F . Let $T \in L(V)$. Suppose $c_1, \dots, c_k \in F$ are all the possible distinct characteristic values of T . Let W_i be the eigenspace of c_i , i.e., $W_i = \ker(T - c_i I)$. Then, if \mathcal{B}_i is a basis for W_i for each $i \in [k]$, $\bigcup_{i=1}^k \mathcal{B}_i$ is a basis for $\sum_{i=1}^k W_i$.

Proof. Suppose $\sum \beta_i = 0$ where $\beta_i \in W_i$. Then, applying T, T^2, \dots, T^{k-1} , we get

$$\sum_{i=1}^k c_i^j \beta_i = 0$$

for each $j \in \{0, \dots, k-1\}$. As

$$\begin{bmatrix} 1 & 1 & \dots & 1 \\ c_1 & c_2 & \dots & c_k \\ \vdots & \vdots & \ddots & \vdots \\ c_1^{k-1} & c_2^{k-1} & \dots & c_k^{k-1} \end{bmatrix}$$

is invertible since c_i 's are distinct, we get $\beta_i = 0$ for each i . \square

Note:-

Lemma 6.1.1 also implies that $\dim(\sum_{i=1}^k W_i) = \sum_{i=1}^k \dim W_i$.

Theorem 6.1.2

Let V be a n -dimensional vector space over F . Let $T \in L(V)$. Suppose $c_1, \dots, c_k \in F$ are all the possible distinct characteristic values of T . Let W_i be the eigenspace of c_i , i.e., $W_i = \ker(T - c_i I)$. TFAE.

- T is diagonalizable.
- The characteristic polynomial is $p(x) = \prod_{i=1}^k (x - c_i)^{d_i}$ where $d_i = \dim W_i$.
- $\sum_{i=1}^k d_i = n$.

Proof. ((i) \Rightarrow (ii)) Let \mathcal{B} be the basis for V that consists of eigenvectors of T . If \mathcal{B}_i is the part of \mathcal{B} that only consists of eigenvectors corresponding to c_i , we have $\text{span } \mathcal{B}_i = W_i$. Hence, on

rearranging, $[T]_{\mathcal{B}} = \text{diag}(\overbrace{c_1, \dots, c_1}^{d_1}, \overbrace{c_2, \dots, c_2}^{d_2}, \dots, \overbrace{c_k, \dots, c_k}^{d_k})$.

((ii) \Rightarrow (iii)) A direct consequence of Lemma 6.1.1.

((iii) \Rightarrow (i)) $\dim \sum W_i = \sum \dim W_i = \sum d_i = n$. Hence, $\sum W_i = V$, i.e., V has a basis consisting of characteristic vectors. \square

6.2 Annihilating Polynomials

Note:-

Let V be a n -dimensional vector space over F . Let $T \in L(V)$. $\{f \in F[x] \mid f(T) = 0\}$ is a nonzero ideal as $\{I, T, T^2, \dots, T^{n^2}\}$ is linearly dependent.

Definition 6.2.1: Minimal Polynomial

Let V be a n -dimensional vector space over F . Let $T \in L(V)$. The monic generator of the nonzero ideal $\{f \in F[x] \mid f(T) = 0\}$ is called the *minimal polynomial* of T .

Theorem 6.2.1

Let V be a n -dimensional vector space over F . Let $T \in L(V)$. If $p(x)$ is the characteristic polynomial of T and $m(x)$ is the minimal polynomial of T , then $p(x)$ and $m(x)$ has the same solutions in F .

Proof. (\Rightarrow) Suppose $m(c) = 0$. Then, $m(x) = (x - c)q(x)$ for some $q \in F[x]$. As m is minimal, $q(T) \neq 0$. This means that $q(T)(\beta) \neq 0$ for some $\beta \in V$. However, $m(T)(\beta) = ((T - cI)q(T))(\beta) = 0$; hence $q(T)(\beta) \in \ker(T - cI)$, i.e., c is an eigenvalue. This means that $p(c) = 0$.

(\Leftarrow) Suppose $p(c) = 0$, i.e., $T(\alpha) = c\alpha$ for some nonzero $\alpha \in V$. As $T^k(\alpha) = c^k\alpha$ for all $k \in \mathbb{N} \cup \{0\}$, for any polynomial $f \in F[x]$, we have $f(T)(\alpha) = f(c)\alpha$. In particular, $0 = m(T)\alpha = m(c)\alpha$, i.e., $m(c) = 0$. \square

Theorem 6.2.2 Cayley-Hamilton

Let V be a n -dimensional vector space over F . Let $T \in L(V)$. If $p(x)$ is the characteristic polynomial of T , then $p(T) = 0$.

Proof. Let $K \triangleq \{h(T) \mid h \in F[x]\}$ be a commutative ring. Let $\mathcal{B} = \{\alpha_1, \dots, \alpha_n\}$ be a basis for V . Let $A \triangleq [T]_{\mathcal{B}}$ so that $T(\alpha_i) = \sum_{j=1}^n A_{ji}\alpha_j$. This is equivalent to $\sum_{j=1}^n (\delta_{ij}T - A_{ji}I)\alpha_j = 0$.

Let $B_{ij} \triangleq \delta_{ij}T - A_{ji}I \in K$ and $B \triangleq [B_{ij}]$. Then, $(\text{adj } B)B = B(\text{adj } B) = (\det B)I$. By construction, $\sum_{j=1}^n (\text{adj } B)_{ki}B_{ij}\alpha_j = 0$ for all $k, i \in [n]$.

Taking sum over i , we have

$$\begin{aligned} 0 &= \sum_{i=1}^n \sum_{j=1}^n (\text{adj } B)_{ki}B_{ij}\alpha_j \\ &= \sum_{j=1}^n \left(\sum_{i=1}^n (\text{adj } B)_{ki}B_{ij} \right) \alpha_j \\ &= \sum_{j=1}^n \delta_{kj}(\det B)\alpha_j = (\det B)\alpha_k \end{aligned}$$

for each $k \in [n]$. As $\{\alpha_1, \dots, \alpha_n\}$ is a basis of V , we have $\det B = 0$, i.e., $p(T) = 0$. \square

6.3 Invariant Subspaces

Definition 6.3.1: T -Invariant Subspace

Let V be a finite-dimensional vector space over F and W be a subspace of V . Let $T \in L(V)$. Then, W is said to be a T -invariant subspace if $T(W) \subseteq W$.

Note:-

If W is a T -invariant subspace of V , then $T|_W$ is a naturally induced linear operator on W .

Example 6.3.1

Let V be a finite-dimensional vector space over F and $T \in L(V)$.

- $W = \{0\}$ is a T -invariant subspace.
- For every eigenvalue c of T , $E_c = \ker(T - cI)$ is a T -invariant subspace.

Lemma 6.3.1

Let V be a finite-dimensional vector space over F and $T \in L(V)$. Let W be a T -invariant subspace of V . Then, $m_W \mid m$ and $f_W \mid f$ where m_W and m are minimal polynomials of $T|_W$ and T , and f_W and f are characteristic polynomials of $T|_W$ and T .

Proof. Let $\mathcal{B}' = \{\alpha_1, \dots, \alpha_k\}$ be a basis for W , and extend it to $\mathcal{B} = \{\alpha_1, \dots, \alpha_n\}$ so \mathcal{B} is a basis for V . As W is T -invariant, we have

$$M \triangleq [T]_{\mathcal{B}} = \begin{bmatrix} A & B \\ 0 & C \end{bmatrix}$$

where $A = [T|_W]_{\mathcal{B}'}$. Hence, $f(x) = \det(xI - M) = \det(xI - A) \det(xI - C) = f_W(x) \det(xI - C)$.

Now, noting that $M^r = \begin{bmatrix} A^r & * \\ 0 & C^r \end{bmatrix}$, whenever $p(x) \in F[x]$ satisfies $p(M) = 0$, we always have $p(A) = 0$ as A is invertible; $m(A) = 0$. By the definition of m_W , we have $m_W \mid m$. \square

Definition 6.3.2: T -conductor

Let V be a finite-dimensional vector space over F and $T \in L(V)$. Let W be a T -invariant subspace of V . Then, for each $\alpha \in V$, the set

$$S_T(\alpha; W) \triangleq \{g \in F[x] \mid g(T)\alpha \in W\}$$

is called the T -conductor of α to W .

Lemma 6.3.2

Let V be a finite-dimensional vector space over F and $T \in L(V)$. Let W be a T -invariant subspace of V . Then, for each $\alpha \in V$, $S_T(\alpha; W)$ is a nonzero ideal.

Proof. $S_T(\alpha, W)$ is nonzero as the characteristic polynomial is contained in the set by Theorem 6.2.2.

It is evident that $S_T(\alpha, W)$ is a subspace of $F[x]$. Now, take any $h \in F[x]$ and $g \in S_T(\alpha; W)$. Then, $(hg)(T)\alpha = h(T)g(T)\alpha \in W$ as W is T -invariant and $g(T)\alpha \in W$. \square

Definition 6.3.3: T -conductor

Let V be a finite-dimensional vector space over F and $T \in L(V)$. Let W be a T -invariant subspace of V . Due to Lemma 6.3.2 and Theorem 4.1.3, there uniquely exists the monic generator $g_{T,\alpha,W}$ of $S_T(\alpha, W)$. $g_{T,\alpha,W}$ is also often called the T -conductor of α to W .

Note:-

Since $m(T) = f(T) = 0$ where m and f are minimal and characteristic polynomials of T , they are elements of $S_T(\alpha, W)$ for any α, W . Hence,

$$g_{T,\alpha,W} \mid m \mid f.$$

Definition 6.3.4: Triangulable Matrix

Let V be a finite-dimensional vector space over F and $T \in L(V)$. T is said to be *triangulable* if there exists basis \mathcal{B} for V such that $[T]_{\mathcal{B}}$ is upper triangular matrix.

Note:-

If T is diagonalizable, then T is triangulable.

Lemma 6.3.3

Let V be a finite-dimensional vector space over F . Let $T : V \rightarrow V$ be a linear operator on V such that the minimal polynomial m of T has the form of

$$m(x) = \prod_{i=1}^k (x - c_i)^{r_i}.$$

If W is a proper T -invariant subspace of V , then there exists $\alpha \in V \setminus W$ and an eigenvalue $c \in F$ such that $(T - cI)\alpha \in W$. In other words, $x - c$ is the T -conductor of α on W .

Proof. Take $\beta \in V \setminus W$. Then, $g \triangleq g_{T,\beta,W} \mid m$, i.e.,

$$g(x) = \prod_{i=1}^k (x - c_i)^{e_i}.$$

By the definition of g , and since $\beta \notin W$, there exists $j \in [k]$ such that $e_j \geq 1$. $g(x) = (x - c_j)h(x)$ for some $h \in F[x]$. By the minimality of g , $\alpha \triangleq h(T)\beta \notin V \setminus W$ but $(T - c_jI)\alpha = (T - c_jI)h(T)\beta = g(T)\beta \in W$. \square

Note:-

For $\alpha \notin W$ and $T \in L(V)$, TFAE.

- (i) $(T - cI)\alpha \in W$ for some $c \in F$.
- (ii) $x - c$ is the T -conductor of α on W for some $c \in F$.
- (iii) $T\alpha \in \text{span}\{W, \alpha\}$.

Theorem 6.3.1

Let V be a finite-dimensional vector space over F . Let $T : V \rightarrow V$ be a linear operator on V . Then, T is triangulable if and only if the minimal polynomial of T is a product of linear polynomials over F .

Proof. (\Rightarrow) Since T is triangulable, there exists a basis \mathcal{B} such that $A = [T]_{\mathcal{B}}$ is upper triangular. Hence, the characteristic polynomial is $\det(xI - A) = \prod_{i=1}^n (x - (A)_{ii})$. The result follows due to Theorem 6.2.1.

(\Leftarrow) Suppose $m(x) = \prod_{i=1}^k (x - c_i)^{r_i}$. We shall make use of Lemma 6.3.3 repeatedly over different choices of W . With $W = \{0\}$, we have $\alpha \in V \setminus \{0\}$ such that $(T - d_1 I)\alpha_1 = 0$ for some eigenvalue d_1 . Inductively define α_i by:

- $W_i = \text{span}\{\alpha_1, \dots, \alpha_i\}$.
- Thanks to Lemma 6.3.3, take $\alpha_{i+1} \in V \setminus W_i$ such that $(T - d_{i+1} I)\alpha_{i+1} \in W_i$ where d_{i+1} is an eigenvalue.

Then, by construction, $\mathcal{B} = \{\alpha_1, \dots, \alpha_n\}$ is a basis for V and $[T]_{\mathcal{B}}$ is an upper triangular matrix since $T\alpha_{i+1} \in \text{span}\{\alpha_1, \dots, \alpha_i\} + d_{i+1}\alpha_{i+1}$. \square

Corollary 6.3.1

Let V be a n -dimensional vector space over an algebraically closed field F . Then, every linear operator on V is triangulable.

Theorem 6.3.2

Let V be a n -dimensional vector space over F . Let $T \in L(V)$. Then, T is diagonalizable if and only if the minimal polynomial is $m(x) = \prod_{i=1}^k (x - c_i)$ where c_1, \dots, c_k are all the distinct eigenvalues of T .

Proof. (\Rightarrow) By Theorem 6.1.2 and Theorem 6.2.1, we already have $m(x) = \prod_{i=1}^k (x - c_i)^{e_i}$ where $e_i \geq 1$. Now, we claim that $S \triangleq \prod_{i=1}^k (T - c_i I) = 0$.

From assumption, there exists a basis $\{\alpha_1, \dots, \alpha_n\}$ for V which consists of eigenvectors. Let α_j corresponds to the eigenvalue $c_{i(j)}$. Then, for each $j \in [n]$, $(T - c_{i(j)} I)\alpha_j = 0$, i.e., $S\alpha_j = 0$. Therefore, $S = 0$.

(\Leftarrow) Let W be the subspace spanned by eigenvectors of T . For the sake of contradiction, suppose $W \subsetneq V$. As W is T -invariant, by Lemma 6.3.3, there exists $\alpha \in V \setminus W$ and an eigenvalue $c_j \in F$ such that $\beta \triangleq (T - c_j I)\alpha \in W$.

Write $m(x) = (x - c_j)h(x)$ so h does not have $x - c_j$ as a factor of it. As $h(x) - h(c_j)$ has $x = c_j$ as a root, $h(x) - h(c_j) = (x - c_j)q(x)$ for some q . Then, we have

$$h(T)\alpha - h(c_j)\alpha = q(T)(T - c_j I)\alpha = q(T)\beta \in W$$

since W is T -invariant.

Moreover, $0 = m(T)\alpha = (T - c_j I)h(T)\alpha$ and thus $h(T)\alpha \in E_{c_j} \subseteq W$. This implies that $h(c_j)\alpha \in W$ but $\alpha \notin W$; thus $h(c_j) = 0$, implying the multiplicity of $x - c_j$ in the minimal polynomial. \square

6.4 Simultaneous Triangulation and Diagonalization

Definition 6.4.1: Commuting Family of Linear Operators

Let V be a n -dimensional vector space over F . A set of linear operators \mathcal{F} is said to be a *commuting family* of linear operators if $T_1 T_2 = T_2 T_1$ for each $T_1, T_2 \in \mathcal{F}$.

Definition 6.4.2: \mathcal{F} -invariant

Let V be a n -dimensional vector space over F . A subspace W of V is said to be \mathcal{F} -invariant if it is T -invariant for all $T \in \mathcal{F}$.

Lemma 6.4.1

Let V be a n -dimensional vector space over F . Suppose \mathcal{F} is a commuting family of triangulable linear operators on V . Suppose a proper subspace W of V is \mathcal{F} -invariant. Then, there exists $\alpha \in V \setminus W$ such that $\forall T \in \mathcal{F}, T\alpha \in \text{span}\{W, \alpha\}$.

Proof. Suppose $\{T_1, \dots, T_r\}$ is a basis for the subspace spanned by \mathcal{F} . Note that $\text{span } \mathcal{F}$ is still a commuting family of triangulable linear operators.

Let $V_0 = V$. Construct V_1, \dots, V_r and β_1, \dots, β_r as follows. For each $i \in [r]$,

- (i) Let $U_i = T_i|_{V_{i-1}}$. Then, $U_i \in L(V_{i-1})$ by (iii)-(c).
- (ii) Take $\beta_i \in V_{i-1} \setminus W$ and $c_i \in F$ such that $(U_i - c_i I)\beta_i \in W$. Their existence is guaranteed by Lemma 6.3.3 and (iii)-(b).
- (iii) Let $V_i \triangleq \{\beta \in V_{i-1} \mid (T_i - c_i I)\beta \in W\}$. Then, by construction, the following hold.
 - (a) $\beta_i \in V_i \setminus W$
 - (b) $W \subsetneq V_i \subseteq V_{i-1}$
 - (c) V_i is \mathcal{F} -invariant as, for each $T \in \mathcal{F}$ and $\beta \in V_i$, $(T_i - c_i I)(T\beta) = T(T_i - c_i I)\beta \in W$, i.e., $T\beta \in V_i$.

Then, β_r satisfies $T_i \beta_r \in \text{span}\{W, \beta_r\}$ for each $i \in [r]$. □

Corollary 6.4.1

Let V be a n -dimensional vector space over F . Let \mathcal{F} be a commuting family of triangulable linear operators on V . Then, there exists a basis \mathcal{B} for V such that $[T]_{\mathcal{B}}$ is an upper triangular matrix for all $T \in \mathcal{F}$.

Proof. Take any $\alpha_1 \in V$. Now, construct $\alpha_2, \dots, \alpha_n$ as following. For each $i \in [n-1]$,

- Let $W_i \triangleq \text{span}\{\alpha_1, \dots, \alpha_i\}$.
- Take $\alpha_{i+1} \in V \setminus W_i$ such that $T\alpha_{i+1} \in \text{span}\{\alpha_1, \dots, \alpha_{i+1}\}$ for each $T \in \mathcal{F}$. The existence is guaranteed by Lemma 6.4.1.

Then, $\mathcal{B} = \{\alpha_1; \dots; \alpha_n\}$ is the ordered basis we are looking for. □

Theorem 6.4.1

Let V be a n -dimensional vector space over F . Let \mathcal{F} be a commuting family of diagonalizable linear operators on V . Then, there exists a basis \mathcal{B} for V such that $[T]_{\mathcal{B}}$ is a diagonal matrix for all $T \in \mathcal{F}$.

Proof. We will apply the mathematical induction over $\dim V$. If $\dim V = 1$, there is nothing to prove. Hence, suppose the theorem holds for any finite-dimensional vector space V over F with dimension less than n .

If \mathcal{F} only consists of multiples of identity, it is done. So we may assume the existence of $T \in \mathcal{F}$ which is not a multiple of identity. Let c_1, \dots, c_k be its distinct characteristic values. For each $i \in [k]$, let $\mathcal{F}_i \triangleq \{T|_{W_i} \in L(W_i, V) : T \in \mathcal{F}\}$ where W_i is the eigenspace associated to c_i . Then:

- (i) As T is not a multiple of identity, $k > 1$ and $\dim W_i < n$.
- (ii) As W_i is \mathcal{F} -invariant, $\mathcal{F}_i \subseteq L(W_i)$.

- (iii) For all $T' \in \mathcal{F}$, if m_i and m are minimal polynomials of $T'|_{W_i}$ and T' , $m_i \mid m$ thanks to Lemma 6.3.1.
- (iv) By (iii) and Theorem 6.3.2, every linear operator in \mathcal{F}_i is diagonalizable.
- (v) By (i), (iv), and the induction hypothesis, there exists a basis \mathcal{B}_i for W_i that simultaneously diagonalize all linear operators in \mathcal{F}_i .

Now, $\mathcal{B} = (\mathcal{B}_1, \dots, \mathcal{B}_k)$ is an ordered basis for V due to Lemma 6.1.1, and \mathcal{B} is the basis we are looking for. \square

Corollary 6.4.2

Let V be a n -dimensional vector space over an algebraically closed field F . Let \mathcal{F} be a commuting family of linear operators on V . Then, there exists a basis \mathcal{B} for V such that $[T]_{\mathcal{B}}$ is a diagonal matrix for all $T \in \mathcal{F}$.

6.5 Direct-Sum Decompositions

Definition 6.5.1: Independent Subspaces

Let V be a n -dimensional vector space over F . We say subspaces W_1, \dots, W_k of V are *independent* if, whenever $a_1 + \dots + a_k = 0$ where $a_i \in W_i$, $a_i = 0$ for all $i \in [k]$.

Definition 6.5.2: Direct Sum

Let V be a n -dimensional vector space over F . Let W_1, \dots, W_k be the finite number of subspaces of V . Then, we say that the sum $W = \sum_{i=1}^k W_i$ is *direct* if W_1, \dots, W_k are independent. We write $W = W_1 \oplus \dots \oplus W_k = \bigoplus_{i=1}^k W_i$ if the sum is direct.

Definition 6.5.3: Projection

Let V be a vector space over F . A linear operator $E \in L(V)$ such that $E^2 = E$ is called a *projection*.

Example 6.5.1

Suppose $V = V_1 \oplus V_2$. Then, $P_1 \in L(V)$ defined by $v_1 + v_2 \mapsto v_1$ where $v_1 \in V_1$ and $v_2 \in V_2$ is a projection.

Lemma 6.5.1

Let V be a vector space over F . Let $E \in L(V)$ be a projection. Then, $V = V_1 \oplus V_2$ for some subspaces V_1 and V_2 of V such that E can be represented by $E(v_1 + v_2) = v_1$ where $v_1 \in V_1$ and $v_2 \in V_2$.

Proof. Take $V_1 = \text{Im } E$ and $V_2 = \ker E$. Take any $v \in V$. Then, $v = Ev + (v - Ev)$ while $Ev \in V_1$ and $v - Ev \in \ker E$. Hence, $V = V_1 + V_2$.

Take any $v_1 \in \text{Im } E$ and $v_2 \in \ker E$ and suppose $v_1 + v_2 = 0$. Then, there exists $v'_1 \in V$ such that $v_1 = E(v'_1)$. Then, $0 = E(v_1 + v_2) = E(v_1) = E^2(v'_1) = E(v'_1) = v_1$. Hence, the sum is direct. It is also shown that $E(v_1 + v_2) = E(v_1) = v_1$. \square

Theorem 6.5.1

Let V be a n -dimensional vector space over F . Suppose $V = \bigoplus_{i=1}^k W_i$ for some subspaces W_i of V . Then, for each $i \in [k]$, there exists $E_i \in L(V)$ such that

- (i) E_i is a projection for each $i \in [k]$,
- (ii) $E_i E_j = 0$ if $i \neq j$.
- (iii) $I = \sum_{i=1}^k E_i$.
- (iv) $\text{Im } E_i = W_i$ for each $i \in [k]$.

Proof. All $v \in V$ can be uniquely written as $v = \sum_{i=1}^k v_i$ where $v_i \in W_i$ for each $i \in [k]$. Hence, define $E_i: V \rightarrow V$ by $v \mapsto v_i$. Then, E_i 's satisfy the four constraints. \square

6.6 Invariant Direct Sums

Theorem 6.6.1

Let V be a n -dimensional vector space over F . Let $T \in L(V)$. Suppose $V = \bigoplus_{i=1}^k W_i$ for some subspaces W_i of V . Let E_1, \dots, E_k be the projections in Theorem 6.5.1. Then, W_i is T -invariant for all $i \in [k]$ if and only if T commutes with all E_i 's.

Proof. (\Rightarrow) Suppose W_i is T -invariant for each $i \in [k]$. Take any $\alpha \in V$ and write $\alpha = \sum_{i=1}^k \alpha_i$ where $\alpha_i \in W_i$ for each $i \in [k]$. Then, $E_i T \alpha = \sum_{j=1}^k E_i T \alpha_j = T \alpha_i = T E_i \alpha$.

(\Leftarrow) Suppose $T E_i = E_i T$. Take any $\alpha_i \in W_i$. Then, $T \alpha_i = T E_i \alpha_i = E_i (T \alpha_i) \in W_i$ by the definition of E_i . Hence, W_i is T -invariant. \square

Theorem 6.6.2

Let V be a n -dimensional vector space over F . Let $T \in L(V)$. If T is diagonalizable and c_1, \dots, c_k are all the distinct eigenvalues, we have projections $E_i \in L(V)$ for each $i \in [k]$ on $W_i = E_{c_i}$ such that $T = \sum_{i=1}^k c_i E_i$ and $V = \bigoplus_{i=1}^k W_i$ with $I = \sum_{i=1}^k E_i$ and $E_i E_j = \delta_{ij} E_i$.

Note:-

The converse of Theorem 6.6.2 also holds.

6.7 The Primary Decomposition Theorem

Theorem 6.7.1 Primary Decomposition Theorem

Let V be a n -dimensional vector space over F . Let $T \in L(V)$ and $m \in F[x]$ be its minimal polynomial. Write $m(x) = \prod_{i=1}^k p_i^{r_i}$ where p_i 's are irreducible polynomials in $F[x]$ and $r_i \geq 1$. Let $W_i \triangleq \ker(p_i(T)^{r_i})$. Then, the following hold.

- (i) $V = \bigoplus_{i=1}^k W_i$.
- (ii) Each W_i is T -invariant.
- (iii) The minimal polynomial of $T_i = T|_{W_i}$ is $p_i^{r_i}$ for each $i \in [k]$.

Proof. If $k = 1$, there is nothing to prove. Hence, we may assume $k \geq 2$.

Define for each $i \in [k]$, $f_i \triangleq \prod_{j \in [n] \setminus \{i\}} p_j^{r_j}$ so that $(f_i, p_i^{r_i}) = 1$. Since f_1, \dots, f_k are also relatively prime, there exists $g_1, \dots, g_k \in F[x]$ such that $f_1 g_1 + \dots + f_k g_k = 1$. Define $h_i \triangleq f_i g_i$ so $\sum_{i=1}^k h_i(T) = I$. When $i \neq j$, we have $m \mid f_i f_j$ and $f_i(T) f_j(T) = 0$.

Define $E_i \triangleq h_i(T) \in L(V)$. Then, we have $\sum_{i=1}^k E_i = I$ and $E_i E_j = f_i(T) f_j(T) g_i(T) g_j(T) = 0$ for each $i \neq j$. Moreover, $E_j = E_j \sum_{i=1}^k E_i = E_j^2$, i.e., E_j is a projection for each $j \in [k]$. Then, $V = \bigoplus_{i=1}^k \text{Im } E_i$ and each $\text{Im } E_i$ is T -invariant.

Now, we claim that $\text{Im } E_i = W_i = \ker(p_i(T)^{r_i})$.

- Take any $\alpha \in \text{Im } E_i$. Then, $\alpha = E_i \alpha$. This implies $p_i(T)^{r_i}(\alpha) = p_i(T)^{r_i} f_i(T) g_i(T) \alpha = 0$ as $p_i^{r_i} f_i = m$. Hence, $\text{Im } E_i \subseteq W_i$.
- Take any $\alpha \in \ker(p_i(T)^{r_i})$. If $j \neq i$, then $p_i^{r_i} \mid f_j \mid f_j g_j$. This implies that $f_j(T) g_j(T) \alpha = h_j(T) \alpha = 0$. In other words, $E_j \alpha = 0$ for each $j \neq i$, this restricts to the only left option: $\alpha \in \text{Im } E_i$. Hence, $W_i \subseteq \text{Im } E_i$.

It remains to show that $T_i = T|_{W_i}$ has the minimal polynomial $p_i^{r_i}$. Let m_i be the minimal polynomial of T_i . By the definition of W_i , we have $p_i(T)^{r_i}|_{W_i} = 0$. Hence, $m_i \mid p_i^{r_i}$. Let g be any polynomial in $F[x]$ such that $g(T_i) = 0$. We now claim that $p_i^{r_i} \mid g$. For each $\alpha_j \in W_j = \ker(p_j(T)^{r_j})$ with $i \neq j$, we have $f_i(T) \alpha_j = 0$. Hence, $g(T) f_i(T) = 0$. $m \mid g f_i$. However, as $(p_i^{r_i}, f_i) = (1)$, $m = \prod_{j=1}^k p_j^{r_j} \mid g \prod_{i \neq j} p_j^{r_j}$ directly implies that $p_i^{r_i} \mid g$. \square

Corollary 6.7.1

If E_1, \dots, E_k are projections associated to the primary decomposition of V with respect to T , then each E_i is a polynomial in T .

In particular, if $U \in L(V)$ commutes with T , then U commutes with all E_i so each W_i is U -invariant.

Definition 6.7.1: Nilpotent Linear Operator

Let V be a finite-dimensional vector space over F . $T \in L(V)$ is called a *nilpotent* operator if $T^N = 0$ for some $N \in \mathbb{N}$.

Theorem 6.7.2

Let V be a finite-dimensional vector space over F . Let $T \in L(V)$ be a triangulable linear operator. Then, there *uniquely* exists a diagonalizable $D \in L(V)$ and a nilpotent $N \in L(V)$ such that

- $T = D + N$ and
- $DN = ND$.

Proof. Let $m(x) = \prod_{i=1}^k (x - c_i)^{r_i}$ be the minimal polynomial of T . As in Theorem 6.7.1, take $W_i \triangleq \ker(T - c_i I)^{r_i} = \text{Im } E_i$ where E_i is the projection to W_i .

Take $D = \sum_{i=1}^k c_i E_i$ and $N = T - D$. Then, D is diagonalizable. Now, we claim that N is nilpotent. As $I = \sum_{i=1}^k E_i$, $D = \sum_{i=1}^k (T - c_i I) E_i$. Hence, $N^r = \sum_{i=1}^k (T - c_i I)^r E_i$ as T and E_i commute, and as E_i 's are projections onto independent subspaces. Hence, $N^{\max_{i=1}^k r_i} = 0$; N is nilpotent. Furthermore, D and N are polynomials in T ; hence they commute.

Now, we are left with the proof for uniqueness. Suppose we have another D' and N' that satisfy (i) and (ii). $D + N = T = D' + N'$ implies that $A = D - D' = N' - N$ is both diagonalizable and nilpotent. In other words, $A = 0$, i.e., $D = D'$ and $N = N'$. \square

Note:-

D and N in Theorem 6.7.2 are called *diagonalizable part* and *nilpotent part* of T , respectively.

Chapter 7

The Rational and Jordan Forms

7.1 Cyclic Subspaces and Annihilators

Definition 7.1.1: T -cyclically Generated Subspace

Let V be a finite-dimensional vector space over F and let $T \in L(V)$. For $\alpha \in V$, the subspace

$$Z(\alpha; T) = \{g(T)\alpha \mid g \in F[x]\}$$

of V is called the T -cyclic subspace generated by α . If $Z(\alpha; T) = V$, then we say V is cyclically generated by α , and α is a cyclic vector for T .

Note:-

Some immediate facts:

- $Z(\alpha; T)$ is T -invariant.
- $Z(0; T) = \{0\}$.
- If $\alpha \neq 0$ is an eigenvector, then $Z(\alpha; T) = \text{span}\{\alpha\}$.
- If $\dim Z(\alpha; T) = 1$, then $\alpha \neq 0$ and $Z(\alpha; T) = \text{span}\{\alpha\}$; thus α is an eigenvector.

So, we need α be neither too bad nor too good to utilize $Z(\alpha; T)$.

Definition 7.1.2: T -annihilator

Let V be a finite-dimensional vector space over F and let $T \in L(V)$. For $\alpha \in V$, the T -annihilator of α is the subspace

$$M(\alpha; T) \triangleq \{g \in F[x] \mid g(T)\alpha = 0\}.$$

In other words, $M(\alpha; T) = S_T(\alpha; \{0\})$.

Note:-

T -annihilator of α is the T -conductor of α to $\{0\}$, $M(\alpha; T)$ is a nonzero ideal and thus has a unique monic generator p_α . p_α is also called the T -annihilator of α . Hence, as the minimal polynomial m of T resides in $M(\alpha; T)$, we have $p_\alpha \mid m$.

Theorem 7.1.1

Let V be a finite-dimensional vector space over F and let $T \in L(V)$. Let $\alpha \in V \setminus \{0\}$ be fixed. Let p_α be the T -annihilator of α .

- (i) If $k = \deg p_\alpha$, $\{\alpha, T\alpha, \dots, T^{k-1}\alpha\}$ is a basis for $Z(\alpha; T)$, hence $\deg p_\alpha = \dim Z(\alpha; T)$.

(ii) Let $U \triangleq T|_{Z(\alpha; T)} \in L(Z(\alpha; T))$. Then, the minimal polynomial of U is p_α .

Proof.

- (i) Let $g \in F[x]$ be arbitrary. By Theorem 4.1.2, we have $g = p_\alpha q + r$ where $q, r \in F[x]$ in which either $r = 0$ or $r \neq 0$ and $\deg r < \deg p_\alpha$. As $(p_\alpha) = M(\alpha; T)$, we also have $p_\alpha q \in M(\alpha; T)$, and thus

$$g(T)\alpha = q(T)p_\alpha(T)\alpha + r(T)\alpha = r(T)\alpha.$$

Hence, $Z(\alpha; T) = \text{span}\{\alpha, T\alpha, \dots, T^{k-1}\alpha\}$. We are left with proving that they are linearly independent.

Suppose they are not linearly independent for the sake of contradiction. Then there exist $c_0, \dots, c_{k-1} \in F$ not all zero such that $(\sum_{i=0}^{k-1} c_i T^i)\alpha = 0$, which means $g_0(x) = \sum_{i=0}^{k-1} c_i x^i \in M(\alpha; T)$ with $\deg g_0 < \deg p_\alpha$, violating the minimality of p_α . Hence, they are linearly independent.

- (ii) Let m be the minimal polynomial of U . Then, $m(U)\alpha = 0$ for all $\alpha \in V$, and thus $p_\alpha \mid m$.

Take any $v \in Z(\alpha; T)$. Then, there exists $g \in F[x]$ so $v = g(T)\alpha$. Then, $p_\alpha(U)v = g(T)p_\alpha(T)\alpha = 0$. Hence, $p_\alpha(U) = 0$; thus $m \mid p_\alpha$. \square

Note:-

With respect to the ordered basis $\mathcal{B} = \{\alpha; T\alpha; \dots; T^{k-1}\alpha\}$ for $Z(\alpha; T)$. Then,

$$[U]_{\mathcal{B}} = \begin{bmatrix} 0 & 0 & \cdots & 0 & -c_0 \\ 1 & 0 & \cdots & 0 & -c_1 \\ 0 & 1 & \cdots & 0 & -c_2 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & 1 & -c_{k-1} \end{bmatrix}$$

where $p_\alpha(x) = \sum_{i=0}^{k-1} c_i x^i + x^k$.

Definition 7.1.3: Companion Matrix

The matrix $[U]_{\mathcal{B}}$ above is called the *companion matrix* of p_α .

7.2 Cyclic Decompositions and the Rational Form

Definition 7.2.1: Complementary T -invariant Subspace

Let V be a finite-dimensional vector space over F and let $T \in L(V)$. Let W be a T -invariant subspace of V . If W' is a T -invariant subspace of V such that $V = W \oplus W'$, we call it a *complementary T -invariant subspace* of W .

Definition 7.2.2: T -admissible Subspace

Let V be a finite-dimensional vector space over F and let $T \in L(V)$. We say a subspace W of V is *T -admissible* if

- (i) W is T -invariant and
- (ii) $\forall f \in F[x], \forall \beta \in V, (f(T)\beta \in W \implies \exists \gamma \in W, f(T)\beta = f(T)\gamma)$.

Lemma 7.2.1

Let V be a finite-dimensional vector space over F and let $T \in L(V)$. Suppose W and W' are T -invariant subspaces such that $V = W \oplus W'$. Then, W and W' are T -admissible.

Proof. The condition (i) is already true. Suppose $f(T)\beta \in W$ where $f \in F[x]$ and $\beta \in V$. We can write $\beta = \gamma + \gamma'$ where $\gamma \in W$ and $\gamma' \in W'$. Then, $f(T)\beta = f(T)\gamma + f(T)\gamma'$. As W and W' are T -invariant, we have $f(T)\beta - f(T)\gamma = f(T)\gamma' \in W \cap W'$. Hence, $f(T)\beta = f(T)\gamma$. \square

Notation 7.1

Let V be a finite-dimensional vector space over F and let $T \in L(V)$. If T is the only subjective linear transform, we may write

- $f\alpha$ instead of $f(T)(\alpha)$ for each $f \in F[x]$ and $\alpha \in V$.
- fW instead of $f(T)(W)$ for each $f \in F[x]$ and $W \subseteq V$.

Lemma 7.2.2

Let V be a finite-dimensional vector space over F and let $T \in L(V)$. Then, the following hold.

- $fZ(\alpha; T) = Z(f\alpha; T)$ for each $\alpha \in V$ and $f \in F[x]$.
- If $V = \bigoplus_{i=1}^k W_i$ where each W_i is T -invariant, then $fV = \bigoplus_{i=1}^k fW_i$.
- For $\alpha, \gamma \in V$, if α and γ have the same T -annihilator, then $f\alpha = f\gamma$ has the same T -annihilator. Therefore, $\dim Z(f\alpha; T) = \dim Z(f\gamma; T)$.

Proof.

- $fZ(\alpha; T) = \{fg\alpha \mid g \in F[x]\} = \{gf\alpha \mid g \in F[x]\} = Z(f\alpha; T)$
- It is evident that $fV = \sum_{i=1}^k fW_i$. Suppose $\sum_{i=1}^k f\alpha_i = 0$ for some $\alpha_i \in W_i$. As $f\alpha_i \in V_i$, we have $f\alpha_i = 0$ for all $i \in [k]$. Hence, fW_1, \dots, fW_k are independent.
- We have $M(\alpha; T) = M(\gamma; T)$, i.e., $\forall g \in F[x], (g\alpha = 0 \iff g\gamma = 0)$. Hence, $M(f\alpha; T) = \{g \in F[x] \mid gf\alpha = 0\} = \{g \in F[x] \mid gf\gamma = 0\} = M(f\gamma; T)$. \square

Theorem 7.2.1 Cyclic Decomposition Theorem

Let V be a finite-dimensional vector space over F and let $T \in L(V)$. Let W_0 be a proper T -admissible subspace of V . Then, there exist $\alpha_1, \dots, \alpha_r \in V \setminus \{0\}$ such that

- $V = W_0 \oplus \left(\bigoplus_{i=1}^r Z(\alpha_i; T) \right)$ and
 - $p_{i+1} \mid p_i$ for each $i \in [r-1]$
- where p_i is the T -annihilator of α_i . Furthermore, r and p_1, \dots, p_r are uniquely decided.

Proof. In this proof we denote the monic generator of $S_T(\alpha; W)$ as $s_T(\alpha; W)$ for conciseness.

Claim 0. For $\alpha, \beta \in V$ and a T -invariant subspace W of V , if $\alpha - \beta \in W$, then $S_T(\alpha; W) = S_T(\beta; W)$. Moreover, if W is T -invariant, then $W + Z(\alpha; T) = W + Z(\beta; T)$.

Let $\gamma \triangleq \alpha - \beta \in W$. Then, $g \in S_T(\alpha; W) \iff g\alpha \in W \iff g(\beta + \gamma) \in W \iff g\beta \in W \iff g \in S_T(\beta; W)$.

Assuming W is T -invariant, we have, for each $g\alpha \in Z(\alpha; T)$, $g\alpha = g(\beta + \gamma) \in Z(\beta; T) + W$; hence $Z(\alpha; T) + W \subseteq Z(\beta; T) + W$. \checkmark

Claim 1. For a proper T -admissible subspace W of V , there exists $\alpha \in V \setminus W$ such that $s_T(\alpha; W)\alpha = 0$.

Take any $\beta \in V \setminus W$. Let $f \triangleq s_T(\beta; W)$ so $f\beta \in W$. By T -admissibility, $\exists \gamma \in W, f\beta = f\gamma$. Let $\alpha \triangleq \beta - \gamma$ so that $f\alpha = 0$. Moreover, $S_T(\alpha; W) = S_T(\beta; W) = (f)$ as W is T -invariant.

Hence, $f = s_T(\beta; W) = s_T(\alpha; W)$. and $f \in M(\alpha; T)$, which implies $(f) = S_T(\alpha; W) \subseteq M(\alpha; T)$. Conversely, if $g \in M(\alpha; T)$, then $g\alpha = 0 \in W$ and thus $M(\alpha; T) \subseteq S_T(\alpha; W)$; f is the T -annihilator of α as well.

Claim 2. Let W be a subspace of V . If $s_T(\alpha; W)\alpha = 0$, then $S_T(\alpha; W) \subseteq M(\alpha; T)$ and $W \cap Z(\alpha; T) = \{0\}$.

It is easily shown that $S_T(\alpha; W) \subseteq M(\alpha; T)$. Suppose $g\alpha \in W \cap Z(\alpha; T)$. Then, $g \in S_T(\alpha; W) \subseteq M(\alpha; T)$, and thus $g\alpha = 0$. \checkmark

Claim 3. For a proper T -invariant subspace W of V , $\beta \in \operatorname{argmax}_{\alpha \in V} \deg s_T(\alpha; W)$ exists. Moreover, $W \cap \operatorname{argmax}_{\alpha \in V} \deg s_T(\alpha; W) = \emptyset$. As a corollary, $W + Z(\beta; T)$ is a T -invariant subspace of V which has W as its proper subspace.

If p is the characteristic polynomial of T , then $p\alpha = 0 \in W$ for all $\alpha \in V$ by Theorem 6.2.2, i.e., $p \in S_T(\alpha; T)$. Therefore, $\deg s_T(\alpha; W)$ is bounded above by $\deg p = \dim V$. Hence, $A = \operatorname{argmax}_{\alpha \in V} \deg s_T(\alpha; W) \neq \emptyset$, thus we may take $\beta \in A$.

If $\beta \in W$, we will have $s_T(\alpha; W) = 1$ for all $\alpha \in V$ and thus $\alpha = s_T(\alpha; W)\alpha \in W$, contradicting $W \subsetneq V$. \checkmark

Algorithm: Construct β_1, \dots, β_r and W_1, \dots, W_r

$i \leftarrow 0$;

while $W_i \neq V$ **do**

 Take any $\beta_{i+1} \in \operatorname{argmax}_{\alpha \in V} \deg s_T(\alpha; W_i)$;

\triangleright well-defined by **Claim 3**

$W_{i+1} \leftarrow W_i + Z(\beta_{i+1}, W_i)$;

$i \leftarrow i + 1$;

This algorithm above eventually ends in at most $\dim V$ loops until we have $V = W_0 + \sum_{i=1}^r Z(\beta_i, W_{i-1})$ by **Claim 3**. Also, by the construction, $W_k = W_{k-1} + Z(\beta_k, W_{k-1})$ for each $k \in [r]$, and each W_k is T -invariant.

$$W_k = W_0 + \sum_{i=1}^{k-1} Z(\beta_i; W_{i-1})$$

Claim 4. For each $k \in [r]$ and $\beta \in V$, write $f\beta = \beta_0 + \sum_{i=1}^{k-1} g_i\beta_i$ where $f = s_T(\beta; W_{k-1})$, $g_i \in F[x]$, $\beta_0 \in W_0$, and $\beta_i \in W_i$ for each $i \in [k-1]$. Then, $f \mid g_i$ for each $i \in [k-1]$, and $\beta_0 = f\gamma_0$ for some $\gamma_0 \in W_0$.

Fix $k \in [r]$ for now. By Theorem 4.1.2, $g_i = f q_i + r_i$ for some $q_i, r_i \in F[x]$ such that it is either $r_i = 0$ or $\deg r_i < \deg f$. Let $\gamma \triangleq \beta - \sum_{i=1}^{k-1} q_i\beta_i$. Then, we have:

$$\begin{aligned} f\gamma &= f\beta - \sum_{i=1}^{k-1} f q_i\beta_i \\ &= (\beta_0 + \sum_{i=1}^{k-1} g_i\beta_i) - \sum_{i=1}^{k-1} (g_i - r_i)\beta_i \\ &= \beta_0 + \sum_{i=1}^{k-1} r_i\beta_i. \end{aligned}$$

Note that, by **Claim 0**, $S_T(\gamma; W_{k-1}) = S_T(\beta; W_{k-1}) = (f)$.

For the sake of contradiction, suppose $r_i \neq 0$ for some $i \in [k-1]$ and let j be the maximum among such i so $f\gamma = \beta_0 + \sum_{i=1}^j r_i\beta_i$. Let $p \triangleq s_T(\gamma; W_{j-1})$. As $W_j \subseteq W_{k-1}$, we have $p \in S_T(\gamma; W_{k-1}) = (f)$, i.e., $p = fg$ for some $g \in F[x]$. Then,

$$p\gamma = gf\gamma = g\beta_0 + \sum_{i=1}^{j-1} g r_i\beta_i + g r_j\beta_j.$$

Then, $p\gamma \in W_{j-1}$ by the definition of p and $g(\beta_0 + \sum_{i=1}^{j-1} r_i\beta_i) \in W_{j-1}$ as W_{j-1} is T -invariant. Hence, we have $g r_j\beta_j \in W_{j-1}$, i.e., $g r_j \in S_T(\beta_j; W_{j-1})$. Hence, by the construction of β_j ,

$$\deg(g r_j) \underbrace{\geq}_{\text{by definition}} \deg s_T(\beta_j; W_{j-1}) \underbrace{\geq}_{\text{by construction of } \beta_j} \deg s_T(\gamma; W_{j-1}) = \deg p = \deg(fg).$$

Therefore, $\deg r_j \geq \deg f$, which is a contradiction. Hence, $r_i = 0$ for all $i \in [k-1]$; $f \mid g_i$.

Now, we are left with $\beta_0 = f\gamma$. By T -admissibility of W_0 , there exists $\gamma_0 \in W_0$ such that $f\gamma_0 = f\gamma = \beta_0$. ✓

Fix any $k \in [r]$. Let $p_k \triangleq s_T(\beta_k; W_{k-1})$. Then, by **Claim 4**, $p_k\beta_k = p_k\gamma_0 + \sum_{i=1}^{k-1} p_k h_i \beta_i$ for some $\gamma_0 \in W_0$ and $h_i \in F[x]$. Let $\alpha_k \triangleq \beta_k - \gamma_0 - \sum_{i=1}^{k-1} h_i \beta_i$ so that $p_k\alpha_k = 0$ and $\alpha_k - \beta_k \in W_{k-1}$. Then, by **Claim 0** and **Claim 2**, we have:

- $(p_k) = S_T(\beta; W_{k-1}) = S_T(\alpha_k; W_{k-1}) \subseteq M(\alpha_k; T)$
- $W_{k-1} \cap Z(\alpha_k; T) = \{0\}$
- $W_{k-1} + Z(\alpha_k; T) = W_{k-1} + Z(\beta_k; T)$

As k is arbitrary, we have

$$W_k = W_0 \oplus \left(\oplus_{i=1}^k Z(\alpha_i; T) \right).$$

Moreover, note that $\alpha_1, \dots, \alpha_r$ retains the defining property of β_1, \dots, β_r , i.e., $\alpha_k \in \operatorname{argmax}_{\alpha \in V} \deg s_T(\alpha; W_{k-1})$. **Claim 4** holds when β_1, \dots, β_r are replaced with $\alpha_1, \dots, \alpha_r$. Hence, applying the alternative version of **Claim 4** to the trivial equation

$$p_k\alpha_k = 0 \cdot 0 + \sum_{i=1}^{k-1} p_i\alpha_i,$$

we have $p_k \mid p_i$ for each $i \in [k-1]$. The existence part of the theorem is now proven. ✓

Now, we shall show the uniqueness of such decomposition. Suppose $V = W_0 \oplus \left(\oplus_{i=1}^s Z(\gamma_i; T) \right)$ is another cyclic decomposition where $q_{k+1} \mid q_k$ for each $k \in [s-1]$. (q_i is the T -annihilator of γ_i .) Let $S_T(V; W_0) \triangleq \{f \in F[x] \mid fV \subseteq W_0\}$ so $S_T(V; W_0)$ is an ideal as W_0 is T -invariant.

Claim 5. p_1 and q_1 are the monic generator of $S_T(V; W_0)$. Thus, $p_1 = q_1$.

As it is already $S_T(V; W_0) \subseteq S_T(\alpha_1; W_0)$, it is enough to show that $p_1 \in S_T(V; W_0)$. Take any $\beta \in V$ and write $\beta = \beta_0 + \sum_{i=1}^r f_i \alpha_i$ where $\beta_0 \in W_0$ and $f_i \in F[x]$. Then, $p_1\beta = p_1\beta_0 + \sum_{i=1}^r p_1 f_i \alpha_i$. As $p_i \mid p_1$ for each $i \in [r]$, we have $p_1\alpha_i = 0$. Hence, $p_1\beta \in W_0$; $p_1 \in S_T(V; W_0)$. Similarly, $q_1 \in S_T(V; W_0)$. ✓

Now, we will prove the main question by induction.

Claim 6. Fix any $1 \leq k < r$. If $s \geq k$ and $p_i = q_i$ for each $i \in [k]$, then $s > k$ and $p_{k+1} = q_{k+1}$.

As $k < r$, we have $\dim W_0 + \sum_{i=1}^k \dim Z(\alpha_i; T) < \dim V$. By (i) of Theorem 7.1.1, $\dim W_0 + \sum_{i=1}^k \dim Z(\gamma_i; T) < \dim V$ as $p_i = q_i$. Hence, $s > k$. Now, we may discuss facts about q_{k+1} . The two decompositions give

$$\begin{aligned} p_{k+1}V &= p_{k+1}W_0 \oplus \left(\oplus_{i=1}^k Z(p_{k+1}\alpha_i; T) \right) \quad \text{and} \\ p_{k+1}V &= p_{k+1}W_0 \oplus \left(\oplus_{i=1}^s Z(p_{k+1}\gamma_i; T) \right) \end{aligned}$$

together with (i) and (ii) of Lemma 7.2.2. (For the first representation, we only add up to k since $p_{k+1}\alpha_i$ for all $i \in \{k+1, \dots, r\}$.) Now, we have

$$\begin{aligned} \dim(p_{k+1}V) &= \dim(p_{k+1}W_0) + \sum_{i=1}^k \dim Z(p_{k+1}\alpha_i; T) \\ &= \dim(p_{k+1}W_0) + \sum_{i=1}^s \dim Z(p_{k+1}\gamma_i; T) \\ &= \dim(p_{k+1}W_0) + \sum_{i=1}^k \dim Z(p_{k+1}\alpha_i; T) + \sum_{i=k+1}^s \dim Z(p_{k+1}\gamma_i; T), \end{aligned}$$

by (iii) of Lemma 7.2.2, and thus $\dim Z(p_{k+1}\gamma_{k+1}; T) = 0$, i.e., $p_{k+1}\gamma_{k+1} = 0$. Thus, $q_{k+1} \mid p_{k+1}$. Similarly, we also have $p_{k+1} \mid q_{k+1}$, and thus $p_{k+1} = q_{k+1}$. ✓

Using **Claim 6**, we reach $r \leq s$ and $p_i = q_i$ for each $i \in [r]$ by mathematical induction. By symmetry, we also have $s \leq r$ and thus the theorem is proven. \square

Corollary 7.2.1

Let V be a finite-dimensional vector space over F and let $T \in L(V)$. Let W be a T -invariant subspace of V . Then, W is T -admissible if and only if there exists another T -invariant subspace W' of V such that $V = W \oplus W'$.

Proof. (\Rightarrow) Theorem 7.2.1 (\Leftarrow) Lemma 7.2.1 □

Note:-

- Every $T \in L(V)$ has $\alpha \in V$ such that T -annihilator of α equals the minimal polynomial of T . (α_1 when $W_0 = \{0\}$. T -conductor of α_1 to W_0 is T -annihilator of α_1 and it is the minimal polynomial.)
- If $T \in L(V)$ has a cyclic vector, then characteristic polynomial of T equals the minimal polynomial of T .

Corollary 7.2.2

Let V be a finite-dimensional vector space over F and let $T \in L(V)$. Let $V = \bigoplus_{i=1}^r Z(\alpha_i; T)$ be the cyclic decomposition obtained by applying Theorem 7.2.1 to $W_0 = \{0\}$.

- p_1 , the T -annihilator of α_1 , is the minimal polynomial of T .
- The characteristic polynomial of T equals $\prod_{i=1}^r p_i$.
- T has a cyclic vector if and only if the characteristic polynomial and the minimal polynomial are identical.

Proof.

- p_1 is the monic generator of $S_T(V; \{0\}) = \{g \in F[x] \mid \forall \alpha \in V, g\alpha = 0\}$ by **Claim 6** in the proof of Theorem 7.2.1. In other words, p_1 is the minimal polynomial of T .
- Let $T_i \triangleq T|_{Z(\alpha_i; T)}$ be a linear operator on $Z(\alpha_i; T)$. By Theorem 7.1.1, p_i is the characteristic polynomial of T_i . Hence, $\prod_{i=1}^r p_i$ is the characteristic polynomial of T .
- $\exists \alpha \in V, T = Z(\alpha; T) \iff r = 1 \iff p_1 = (\text{the characteristic polynomial of } T)$ □

$\underbrace{\iff}_{\text{uniqueness}}$

$\underbrace{\iff}_{(ii)}$

Theorem 7.2.2 Generalized Cayley-Hamilton Theorem

Let V be a finite-dimensional vector space over F and let $T \in L(V)$. Let m and f be the minimal and the characteristic polynomial, respectively. Then,

- $m \mid f$.
- m and f have the same prime factors except possibly for multiplicities.
- Suppose $m = \prod_{i=1}^k f_i^{r_i}$ and $f = \prod_{i=1}^k f_i^{d_i}$ are the prime factorizations. Then, $d_i = (\text{nullity } f_i(T)^{r_i}) / (\deg f_i)$.

Proof.

- Theorem 6.2.2
- Apply Theorem 7.2.1 to $W_0 = \{0\}$. Then, we have $V = \bigoplus_{i=1}^r Z(\alpha_i; T)$. and $p_{i+1} \mid p_i$ for each $i \in [r-1]$ where p_i is the T -annihilator of α_i . (ii) of Corollary 7.2.2 says $f = \prod_{i=1}^r p_i$. If a prime factor divides f , then it divides one of p_i , which divides $p_1 = m$. Hence, f and m has the same prime factors.
- Apply Theorem 6.7.1 with respect to V and T . Then, we have $V = \bigoplus_{i=1}^k W_i$ where $W_i = \ker f_i(T)^{r_i}$. Take $T_i = T|_{W_i}$ so $f_i^{r_i}$ is the minimal polynomial of T_i . By (ii) and the supposition, the characteristic polynomial g_i of T_i is $f_i^{d_i}$ where $r_i \leq d_i$. Hence, $\dim W_i = \deg g_i = d_i \cdot \deg f_i$. Therefore, $d_i = (\dim W_i) / (\deg f_i) = (\text{nullity } f_i(T)^{r_i}) / (\deg f_i)$.

□

Corollary 7.2.3

Let V be an n -dimensional vector space over F and let $N \in L(V)$ be nilpotent. Then, the characteristic polynomial of N is x^n .

Proof. As $N^k = 0$ for some $k \in \mathbb{N}$, the minimal polynomial is x^r for some r . Hence, by (ii) of Theorem 7.2.2, we have x^n as the characteristic polynomial of N . □

Definition 7.2.3: Rational Form

Let F be a field. A matrix $A \in F^{n \times n}$ is said to be in a *rational form* if

$$A = \begin{bmatrix} A_1 & \mathbf{0}_{k_1 \times k_2} & \cdots & \mathbf{0}_{k_1 \times k_r} \\ \mathbf{0}_{k_2 \times k_1} & A_2 & \cdots & \mathbf{0}_{k_2 \times k_r} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{0}_{k_r \times k_1} & \mathbf{0}_{k_r \times k_2} & \cdots & A_r \end{bmatrix}$$

where

- A_i is a companion matrix of $p_i \in F[x]$ with $\deg p_i = k_i$ for each $i \in [r]$ and
- $p_{i+1} \mid p_i$ for each $i \in [r-1]$.

Theorem 7.2.3

Let F be a field. For any $B \in F^{n \times n}$, there uniquely exists a matrix in a rational form which is similar to B .

Proof. Let $F^n = \oplus_{i=1}^r Z(\alpha_i; B)$ be a cyclic decomposition obtained by applying Theorem 7.2.1 to $W_0 = \{0\}$. By (i) of Theorem 7.1.1, $\mathcal{B}_i = \{\alpha_1, \dots, T^{k_i-1}\alpha_i\}$ is a basis for $B_i = Z(\alpha_i; T)$ where $k_i = \dim Z(\alpha_i; B)$. Let $\mathcal{B} = (\mathcal{B}_1, \dots, \mathcal{B}_r)$ be a basis for F^n . Then,

$$[B]_{\mathcal{B}} = \begin{bmatrix} [B_1]_{\mathcal{B}_1} & 0 & \cdots & 0 \\ 0 & [B_2]_{\mathcal{B}_2} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & [B_r]_{\mathcal{B}_r} \end{bmatrix}$$

is in a rational form since $[B_i]_{\mathcal{B}_i}$ is the companion matrix of p_i , the T -annihilator of α_i .

Now, suppose that A is a $n \times n$ matrix over F which is similar to B and is in a rational form. Let A be composed of r companion matrices of p_1, \dots, p_r where $p_{i+1} \mid p_i$ for each $i \in [r-1]$. Then, we have $\beta_1, \dots, \beta_r \in F^n$ where p_i is the A -annihilator of β_i , which is the B -annihilator of β_i as well. Hence, $F^n = \oplus_{i=1}^r Z(\beta_i; B)$. By Theorem 7.2.1, r and p_1, \dots, p_r are uniquely determined. □

7.3 The Jordan Form

Example 7.3.1

Let V be an n -dimensional vector space over F and let $N \in L(V)$ be nilpotent. Applying Theorem 7.2.1 to N , we have $V = \oplus_{i=1}^r Z(\alpha_i; N)$ and $p_{i+1} \mid p_i$ for each $i \in [r-1]$ where p_i is the T -annihilator of α_i . p_1 , the minimal polynomial of N , is of the form x^k

where $1 \leq k \leq n$. Therefore, the divisibility relation simply asserts $k = k_1 \geq k_2 \geq \dots \geq k_r$ where $p_i(x) = x^{k_i}$. So the rational form of N is

$$\begin{bmatrix} A_1 & 0 & \cdots & 0 \\ 0 & A_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & A_r \end{bmatrix}$$

where A_i is the companion matrix of x^{k_i} , which is the $k_i \times k_i$ matrix

$$A_i = \begin{bmatrix} 0 & 0 & \cdots & 0 & 0 \\ 1 & 0 & \cdots & 0 & 0 \\ 0 & 1 & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & 1 & 0 \end{bmatrix}.$$

Hence, there are total $p(n)$ nilpotent $n \times n$ linear operators on V that are not similar to each other where $p(n)$ denotes the number of partitions of n .

Lemma 7.3.1

Let V be an n -dimensional vector space over F and let $N \in L(V)$ be nilpotent. Let $V = \oplus_{i=1}^r Z(\alpha_i; T)$ be the cyclic decomposition obtained by applying Theorem 7.2.1 to $W_0 = \{0\}$. Let $k_i \triangleq \deg p_i$ where p_i is the T -annihilator of α_i . Then, $\mathcal{B} = \{N^{k_1-1}\alpha_1, \dots, N^{k_r-1}\alpha_r\}$ is a basis for $\ker N$.

Proof. The fact that $\mathcal{B} \subseteq \ker N$ is evident as $p_i = x^{k_i}$. Also, \mathcal{B} is linearly independent as each vector is in independent subspaces $(Z(\alpha_i; N))$.

Take any $\alpha \in \ker N$. Then, $\alpha = \sum_{i=1}^r f_i \alpha_i$ for some $f_i \in F[x]$. WLOG, $\deg f_i < \deg p_i = k_i$. Then, $N\alpha = \sum_{i=1}^r Nf_i(N)\alpha_i = 0$, and thus $Nf_i(N)\alpha_i = 0$ for each $i \in [r]$. Therefore, $p_i \mid x f_i$. Moreover, as $p_i = x^{k_i}$, and as $\deg f_i < k_i$, we have $f_i = c_i x^{k_i-1}$ for some $c_i \in F$. Then, we have $\alpha = \sum_{i=1}^r c_i N^{k_i-1} \alpha_i$; $\ker N \subseteq \text{span } \mathcal{B}$. \square

Definition 7.3.1: Jordan Form

Let V be an n -dimensional vector space over F and let $T \in L(V)$ be triangulable. Let $f(x) = \prod_{i=1}^k (x - c_i)^{d_i}$ and $m(x) = \prod_{i=1}^k (x - c_i)^{r_i}$ be the characteristic polynomial and the minimal polynomial of T , respectively.

Note:-

Assume T is triangulable.

Step 1 Let $f(x) = \prod_{i=1}^k (x - c_i)^{d_i}$ be the characteristic polynomial. Let $m(x) = \prod_{i=1}^k (x - c_i)^{r_i}$ be the minimal polynomial. ($1 \leq r_i \leq d_i$) Take $W_i = \ker(T - c_i I)^{r_i}$. By Theorem 6.7.1, we have $V = \oplus_{i=1}^k W_i$. Let $T_i = T|_{W_i}$. Each W_i is T -invariant and T_i 's minimal polynomial is $(x - c_i)^{r_i}$.

Step 2 For each W_i , let $N_i = T_i - c_i I \in L(W_i)$ so N_i is nilpotent. So, $T_i = N_i + c_i I$. We consider, for each W_i , the cyclic decomposition of W_i with respect to N_i .

For each W , we have $W = Z(\alpha_1; N) \oplus \dots \oplus Z(\alpha_s; N)$. Take $\mathcal{B}_j = \{\alpha_j, N\alpha_j, \dots, N^{k_j-1}\alpha_j\}$.

So $\left[N|_{Z(\alpha_j; N)}\right]_{\mathcal{B}_j}$ is $\delta_{i-1,j}$. So $\left[T|_{Z(\alpha_j; N)}\right]_{\mathcal{B}_j}$ is $\delta_{i-1,j} + c_i \delta_{ij}$. (< fix this) (This is called a *elementary Jordan block*.) $\mathcal{B}^i = \bigcup_j \mathcal{B}_j$

Chapter 8

Inner Product Spaces

8.1 Inner Products

Definition 8.1.1: Inner Product

Fix the field F to $F = \mathbb{R}$ or $F = \mathbb{C}$. An inner product $(-, -)$ on V is a function $(-, -): V \times V \rightarrow F$ satisfying

- (i) $(-, -)$ is linear over F .
- (ii) $(\beta, \alpha) = \overline{(\alpha, \beta)}$
- (iii) If $\alpha \neq 0$, $(\alpha, \alpha) > 0$.

Note:-

- If $F = \mathbb{R}$, (i) and (ii) say that $(-, -)$ is also linear over F . Thus, an inner product is symmetric and bilinear.
- If $F = \mathbb{C}$, $(\alpha, c\gamma) = \overline{c}(\alpha, \gamma)$, i.e., $(-, -)$ is sesqui-linear.
- If $F = \mathbb{C}$, $(\alpha, \alpha) = \overline{(\alpha, \alpha)}$, i.e., $(\alpha, \alpha) \in \mathbb{R}$.

Example 8.1.1

- For $[x_i], [y_i] \in \mathbb{C}^n$, the inner product defined by $([x_i], [y_i]) = \sum_{i=1}^n x_i \overline{y_i}$ is called the *standard inner product*.
- $F = \mathbb{R}$, let $A \in \mathbb{R}^{n \times n}$ such that $x^T A x > 0$ for all $x \in \mathbb{R}^n \setminus \{0\}$. We say A is positive definite. The function $(x, y) = x^T A y$ is an inner product.

Definition 8.1.2: Conjugate Transpose

For an $n \times n$ matrix A over $F = \mathbb{R}$ or $F = \mathbb{C}$, the $n \times n$ matrix A^* over F defined by

$$(A^*)_{ij} = \overline{(A)_{ji}}$$

for each $i, j \in [n]$ is called the *conjugate transpose* of A .

Definition 8.1.3: Self-adjoint Matrix

A matrix $A \in \mathbb{C}^{n \times n}$ is said to be *self-adjoint* if $A^* = A$.

Theorem 8.1.1

Let $V = \mathbb{C}^n$. Let $(-, -): V \times V \rightarrow \mathbb{C}$ be an inner product. Then, there exists a self-adjoint positive definite matrix $A \in \mathbb{C}^{n \times n}$ such that $(x, y) = x^*Ay$.

Proof. Choose a basis, e.g., the standard basis $\{e_1, \dots, e_n\}$. Let $(A)_{ij} = (e_i, e_j)$. Let $x, y \in \mathbb{C}^n$ and write $x = \sum_{i=1}^n x_i e_i$ and $y = \sum_{j=1}^n y_j e_j$. Then,

$$\begin{aligned} (x, y) &= \left(\sum_{i=1}^n x_i e_i, \sum_{j=1}^n y_j e_j \right) \\ &= \sum_{i=1}^n \sum_{j=1}^n \overline{y_j} (A)_{ij} x_i = y^*Ax. \end{aligned}$$

□

Corollary 8.1.1

Let $V = \mathbb{R}^n$. Let $(-, -): V \times V \rightarrow \mathbb{R}$ be an inner product. Then, there exists a symmetric positive definite matrix $A \in \mathbb{R}^{n \times n}$ such that $(x, y) = x^*Ay$.

Example 8.1.2

Let $V = \mathcal{C}([a, b], \mathbb{C})$. Define, for $f, g \in V$, $(f, g) = \int_a^b f(t) \overline{g(t)} dt$. That is an inner product on V .

8.2 Inner Product Space

Definition 8.2.1: Inner Product Space

A vector space V over $F = \mathbb{R}$ or $F = \mathbb{C}$ equipped with a specified inner product is called an *inner product space*.

Notation 8.1: Norm

We write

$$\|v\| = \sqrt{(v, v)}.$$

This is called a *norm* of v .

Theorem 8.2.1

Let V be an inner product space.

- (i) $\|c\alpha\| = |c| \cdot \|\alpha\|$ for all $c \in F$ and $\alpha \in V$.
- (ii) $\|\alpha\| > 0$ for all $\alpha \in V \setminus \{0\}$.
- (iii) $|(\alpha, \beta)| \leq \|\alpha\| \cdot \|\beta\|$ for all $\alpha, \beta \in V$. (*Cauchy-Schwarz*)
- (iv) $\|\alpha + \beta\| \leq \|\alpha\| + \|\beta\|$ for all $\alpha, \beta \in V$. (*Triangle Inequality*)

Proof.

(i) ✓

(ii) ✓

(iii) If $\alpha = 0$, we have nothing to prove, so suppose $\alpha \neq 0$. Let

$$\beta^\parallel \triangleq \frac{(\beta, \alpha)}{(\alpha, \alpha)} \alpha \quad \text{and} \quad \beta^\perp \triangleq \beta - \frac{(\beta, \alpha)}{(\alpha, \alpha)} \alpha.$$

Then, $(\beta^\perp, \alpha) = 0$ and $\beta^\parallel + \beta^\perp = \beta$. Let $c = (\beta, \alpha)/(\alpha, \alpha)$. We have

$$0 \leq \|\beta^\perp\|^2 = (\beta - c\alpha, \beta^\perp) = (\beta, \beta) - |c|^2(\alpha, \alpha) = \|\beta\|^2 - \frac{|(\alpha, \beta)|^2}{\|\alpha\|^2}.$$

Rearranging the inequality gives the result.

$$(iv) \quad \|\alpha + \beta\|^2 = (\alpha, \alpha) + (\alpha, \beta) + (\beta, \alpha) + (\beta, \beta) \leq \|\alpha\|^2 + 2\|\alpha\| \cdot \|\beta\| + \|\beta\|^2 = (\|\alpha\| + \|\beta\|)^2 \quad \square$$

Note:-

For $\alpha, \beta \in V \setminus \{0\}$, we define the *angle* between α and β be $\theta \in \mathbb{R}$ such that

$$\cos \theta = \frac{(\alpha, \beta)}{\|\alpha\| \cdot \|\beta\|}.$$

Definition 8.2.2: Orthogonality

Let V be an inner product space.

- For $\alpha, \beta \in V$, we say α and β are *orthogonal* if $(\alpha, \beta) = 0$.
- For $S \subseteq V$, we say S is *orthogonal* if $\alpha, \beta \in S$ and $\alpha \neq \beta$, then $(\alpha, \beta) = 0$.
- $\{\alpha_1, \dots, \alpha_n\} \subseteq V$ is said to be *orthonormal* if it is orthogonal and if $\|\alpha_i\| = 1$.

Theorem 8.2.2

Let V be an inner product space. Then, every orthogonal subset S of $V \setminus \{0\}$ is linearly independent.

Proof. Take any distinct $\alpha_1, \dots, \alpha_k \in S$. Suppose $\sum_{i=1}^k c_i \alpha_i = 0$ for some c_i . Then, for each $k \in [n]$,

$$0 = \left(\sum_{i=1}^k c_i \alpha_i, \alpha_k \right) = \sum_{i=1}^k c_i (\alpha_i, \alpha_k) = c_k (\alpha_k, \alpha_k).$$

Since $(\alpha_k, \alpha_k) > 0$, it must be $c_k = 0$. \square

Note:-

If $S = \{\alpha_1, \dots, \alpha_m\} \subseteq V$ is orthogonal, we may explicitly write every $\beta \in \text{span } S$ in the form of

$$\beta = c_1 \alpha_1 + c_2 \alpha_2 + \dots + c_m \alpha_m$$

by setting $c_i = \frac{(\beta, \alpha_i)}{\|\alpha_i\|^2}$.

Theorem 8.2.3 Gram-Schmidt

Let V be an inner product space. Suppose $\{\beta_1, \dots, \beta_n\}$ is a linearly independent subset of V . Then, there exists an orthogonal set $\{\alpha_1, \dots, \alpha_n\}$ of vectors such that, for each $k \in [n]$, $\{\alpha_1, \dots, \alpha_k\}$ is a basis of $\text{span}\{\beta_1, \dots, \beta_k\}$.

Proof. Take $\alpha_1 = \beta_1$. Then, for each $k \in \{2, \dots, n\}$, set

$$\alpha_k \triangleq \beta_k - \sum_{i=1}^{k-1} \frac{(\beta_k, \alpha_i)}{\|\alpha_i\|^2} \alpha_i.$$

Then, $\{\alpha_1, \dots, \alpha_n\}$ satisfies the condition. \square

Corollary 8.2.1

Every finite dimensional inner product space has an orthonormal basis.

Proof. Normalize vectors from Theorem 8.2.3. □

Definition 8.2.3: Orthogonal Complement

Let V be an inner product space. Let W be a subset of V and $\beta \in V$. The subspace of V

$$W^\perp = \{ \beta \in V \mid \forall \alpha \in W, (\alpha, \beta) = 0 \}$$

is called the *orthogonal complement* of W .

Definition 8.2.4: Best Approximation

Let V be an inner product space. Let W be a subspace of V and $\beta \in V$. A *best approximation* of β to W is a vector $\alpha \in W$ such that

$$\forall \gamma \in W, \|\beta - \alpha\| \leq \|\beta - \gamma\|.$$

Theorem 8.2.4

Let V be an inner product space. Let W be a subspace of V and $\beta \in V$.

- (i) $\alpha \in W$ is a best approximation of β to W if and only if $\beta - \alpha \in W^\perp$.
- (ii) If a best approximation of β to W exists, then it is unique.
- (iii) If W is finite-dimensional and $\{\alpha_1, \dots, \alpha_n\}$ is an orthonormal basis for W , then $\alpha = \sum_{k=1}^n (\beta, \alpha_k) \alpha_k$ is the best approximation of β to W .

Proof. For any $\gamma \in V$, we have $\beta - \gamma = (\beta - \alpha) + (\alpha - \gamma)$ and thus

$$\|\beta - \gamma\|^2 = \|\beta - \alpha\|^2 + 2\Re(\beta - \alpha, \alpha - \gamma) + \|\alpha - \gamma\|^2.$$

- (i) (\Leftarrow) Suppose $\beta - \alpha \in W^\perp$. Then, for any $\gamma \in W$, as $\alpha - \gamma \in W$,

$$\|\beta - \gamma\|^2 = \|\beta - \alpha\|^2 + \|\alpha - \gamma\|^2 \geq \|\beta - \alpha\|^2.$$

(\Rightarrow) Suppose α is a best approximation of β to W . For any $\gamma \in W$, we have

$$2\Re(\beta - \alpha, \alpha - \gamma) + \|\alpha - \gamma\|^2 \geq 0$$

by the inequality above and $\|\beta - \gamma\|^2 \geq \|\beta - \alpha\|^2$. In other words, for any $\tau \in W$,

$$2\Re(\beta - \alpha, \tau) + \|\tau\|^2 \geq 0.$$

Putting

$$\tau = -\frac{(\beta - \alpha, \alpha - \gamma)}{\|\alpha - \gamma\|^2}(\alpha - \gamma),$$

we have

$$-2\frac{|(\beta - \alpha, \alpha - \gamma)|^2}{\|\alpha - \gamma\|^2} + \frac{|(\beta - \alpha, \alpha - \gamma)|^2}{\|\alpha - \gamma\|^2} \geq 0,$$

which holds if and only if $(\beta - \alpha, \alpha - \gamma) = 0$.

- (ii) Directly follows from the inequality in the proof of (i)- (\Leftarrow) .

(iii) A calculation shows that $\beta - \alpha$ is orthogonal to every vector in W . Hence, by (i), α is the best approximation of β to W . \square

Definition 8.2.5: Orthogonal Projection

Let V be an inner product space. Let W be a subspace of V .

- Let $\beta \in V$ and $\alpha \in W$. If $\beta - \alpha \in W^\perp$, then α is called the *orthogonal projection of β on W* .
- If every vector in V has an orthogonal projection on W , the mapping that assigns to each vector in V its orthogonal projection on W is called the *orthogonal projection of V on W* .

Note:-

If a subspace W of V is finite-dimensional, then there always exists the orthogonal projection of V on W .

Corollary 8.2.2

Let V be an inner product space. Let W be a finite-dimensional subspace of V . Let $E: V \rightarrow W$ be the orthogonal projection of V on W . Then, $\beta \mapsto \beta - E\beta$ is the orthogonal projection of V on W^\perp .

Proof. Take any $\beta \in V$. Then, $\beta - E\beta \in W^\perp$ by Theorem 8.2.4 (i). Also, for any $\gamma \in W^\perp$, $\beta - \gamma = E\beta + (\beta - E\beta - \gamma)$, and thus

$$\|\beta - \gamma\|^2 = \|E\beta\|^2 + \|\beta - E\beta - \gamma\|^2 \geq \|\beta - (\beta - E\beta)\|^2$$

as $E\beta \in W$ and $\beta - E\beta - \gamma \in W^\perp$. Hence, $\beta - E\beta$ is the best approximation of β to W^\perp . \square

Theorem 8.2.5

Let V be an inner product space. Let W be a finite-dimensional subspace of V . Let E be the orthogonal projection of V on W . Then E is an idempotent linear transformation of V to W , $\ker E = W^\perp$, and $V = W \oplus W^\perp$.

Proof. By the definition, we have

$$\forall \beta \in W, E\beta = \beta,$$

which means $E(E\beta) = E\beta$ for all $\beta \in V$. \checkmark

Take any $\alpha, \beta \in V$. Then, $(c\alpha + \beta) - (cE\alpha + E\beta) = c(\alpha - E\alpha) + (\beta - E\beta) \in W^\perp$. Also, $cE\alpha + E\beta \in W$. By (ii) of Theorem 8.2.4, $E(c\alpha + \beta) = cE\alpha + E\beta$. \checkmark

The equation $\beta = E\beta + (\beta - E\beta)$ shows that $V = W + W^\perp$. For independence, for any $\alpha \in W \cap W^\perp$, it must be $(\alpha, \alpha) = 0$; thus $\alpha = 0$. \checkmark \square

Notation 8.2: Projection

Let V be an inner product space. Let W be a finite-dimensional subspace of V . Then, as $V = W \oplus W^\perp$, we have a unique expression $v = w + w'$ where $w \in W$ and $w' \in W^\perp$. Then, we write

$$w = \text{proj}_W v \quad \text{and} \quad w' = \text{proj}_{W^\perp} v.$$

Note:-

Let $\{\alpha_1, \dots, \alpha_k\}$ and $\{\alpha_{k+1}, \dots, \alpha_n\}$ be orthogonal bases for W and W^\perp , respectively. Then,

$$\text{proj}_W \beta \triangleq \sum_{i=1}^k \frac{(\beta, \alpha_i)}{\|\alpha_i\|^2} \alpha_i \quad \text{and} \quad \text{proj}_{W^\perp} \beta \triangleq \sum_{i=k+1}^n \frac{(\beta, \alpha_i)}{\|\alpha_i\|^2} \alpha_i.$$

8.3 Linear Functionals and Adjoins

Theorem 8.3.1

Let V be an n -dimensional inner product space over $F = \mathbb{R}$ or $F = \mathbb{C}$. Then,

$$\forall f \in V^*, \exists! \beta \in V, f(-) = (-, \beta).$$

In other words, the linear transform $V \rightarrow V^*$ defined by $\beta \mapsto (-, \beta)$ is an isomorphism.

Proof. Choose an orthogonal basis $\{\alpha_1, \dots, \alpha_n\}$ of V . Let $\beta = \sum_{i=1}^n c_i \alpha_i$. Then,

$$f(\alpha_j) = (\alpha_j, \sum_{i=1}^n c_i \alpha_i) = \sum_{i=1}^n \overline{c_i} (\alpha_j, \alpha_i) = \overline{c_j} \|\alpha_j\|^2.$$

Hence, if such β exists, it must be

$$\beta = \sum_{i=1}^n \frac{\overline{f(\alpha_i)}}{\|\alpha_i\|^2} \alpha_i.$$

So, it is only left to check if this β actually works. It can be easily checked by reversing the computation above. \square

Note:-

Theorem 8.3.1 essentially says that V and V^* are naturally related if V is equipped with an inner product.

Theorem 8.3.2

Let V be an n -dimensional inner product space over $F = \mathbb{R}$ or $F = \mathbb{C}$.

$$\forall T \in L(V), \exists! T^* \in L(V), \forall \alpha, \beta \in V, (T\alpha, \beta) = (\alpha, T^*\beta).$$

Proof. Fix $\beta \in V$. For the linear functional $\alpha \mapsto (T\alpha, \beta)$, Theorem 8.3.1 guarantees the unique existence of $\beta' \in V$ such that $(T(-), \beta) = (-, \beta')$. Hence, we may define $T^* \in L(V)$ by $\beta \mapsto \beta'$ so we have $(T\alpha, \beta) = (\alpha, T^*\beta)$ for all $\alpha \in V$. (It is a linear operator.) \square

Note:-

Such T^* is called a (*Hermitian*) *transpose*.

Theorem 8.3.3

Let V be an n -dimensional inner product space over $F = \mathbb{R}$ or $F = \mathbb{C}$. Let $\mathcal{B} = \{\alpha_1, \dots, \alpha_n\}$ be an orthonormal basis for V . Let $T \in L(V)$ and $A = [T]_{\mathcal{B}}$. Then, $(A)_{ij} = (T\alpha_j, \alpha_i)$ for each $i, j \in [n]$.

Proof. Take any $\alpha \in V$ and write $\alpha = \sum_{i=1}^n (\alpha, \alpha_i) \alpha_i$. Hence,

$$T(\alpha_j) = \sum_{i=1}^n (T\alpha_j, \alpha_i) \alpha_i.$$

By definition, we have $T(\alpha_j) = \sum_{i=1}^n A_{ij} \alpha_i$. Therefore, $A_{ij} = (T\alpha_j, \alpha_i)$. □

Corollary 8.3.1

Let V be an n -dimensional inner product space over $F = \mathbb{R}$ or $F = \mathbb{C}$. Let $T \in L(V)$. Let \mathcal{B} be an orthonormal basis for V . Then, $[T^*]_{\mathcal{B}} = ([T]_{\mathcal{B}})^*$, i.e., the matrix representation of T^* equals the Hermitian transpose of the matrix representation of T .

Proof. Let $A = [T]_{\mathcal{B}}$ and $B = [T^*]_{\mathcal{B}}$. By the Theorem 8.3.3, we have

$$(A)_{ij} = (T\alpha_j, \alpha_i) \quad \text{and} \quad (B)_{ij} = (T^*\alpha_j, \alpha_i).$$

Then, $\overline{(B)_{ij}} = (\alpha_i, T^*\alpha_j)$, and thus $\overline{(B)_{ji}} = (\alpha_j, T^*\alpha_i)$. However, we have $(T\alpha_j, \alpha_i) = (\alpha_j, T^*\alpha_i)$ by the definition of T^* , and thus $(A)_{ij} = \overline{(B)_{ji}}$. □

Note:-

Corollary 8.3.1 essentially says that all transposes we discussed represents the same object when orthonormal basis is given.

Definition 8.3.1: Hermitian Operator

Let V be an n -dimensional inner product space over $F = \mathbb{R}$ or $F = \mathbb{C}$. Let $T \in L(V)$. We say T is *Hermitian* (or, *self-adjoint*) if $T = T^*$. If $F = \mathbb{R}$, we sometimes call it *symmetric*.

Definition 8.3.2: Isometry

Let V and W be inner product spaces over $F = \mathbb{R}$ or $F = \mathbb{C}$. $T \in L(V, W)$ is said to *preserve the inner products*, or is called an *isometry*, if

$$\forall \alpha, \beta \in V, (\alpha, \beta) = (T\alpha, T\beta).$$

Definition 8.3.3: Isomorphism of Inner Product Spaces

Let V and W be inner product spaces over $F = \mathbb{R}$ or $F = \mathbb{C}$. $T \in L(V, W)$ is called an *isomorphism of inner product spaces* if it is an isomorphism of vector spaces and it preserves the inner products.

Theorem 8.3.4

Let V and W be finite-dimensional inner product spaces over $F = \mathbb{R}$ or $F = \mathbb{C}$. Let $T \in L(V, W)$. TFAE.

- (i) T preserves the inner products.
- (ii) T is an isomorphism of inner product spaces.
- (iii) For any arbitrary orthonormal basis \mathcal{B} of V , $T(\mathcal{B})$ is an orthonormal basis for W .
- (iv) For some orthonormal basis \mathcal{B} for V , $T(\mathcal{B})$ is an orthonormal basis for W .

Proof. ((i) \Rightarrow (ii)) We need to show that T is an isomorphism of vector spaces. Take any $\alpha \in \ker T$. Then, $0 = (T\alpha, T\alpha) = (\alpha, \alpha) = \|\alpha\|^2$; hence $\alpha = 0$. Therefore, T is injective, and thus is an isomorphism.

((ii) \Rightarrow (iii)) Let $\mathcal{B} = \{\alpha_1, \dots, \alpha_n\}$ be an orthonormal basis for V . Hence, $(T\alpha_i, T\alpha_j) = (\alpha_i, \alpha_j) = \delta_{ij}$; and thus $T(\mathcal{B}) = \{T\alpha_1, \dots, T\alpha_n\}$ is an orthonormal basis for W .
(ii) \Rightarrow (i) and (iii) \Rightarrow (iv) are obvious.
(iv) \Rightarrow (i)) Let $\mathcal{B} = \{\alpha_1, \dots, \alpha_n\}$ be an orthonormal basis for V such that $T(\mathcal{B})$ is also an orthonormal basis for W . Then, $(T\alpha_i, T\alpha_j) = \delta_{ij} = (\alpha_i, \alpha_j)$. \square

Theorem 8.3.5

Let V and W be inner product spaces over $F = \mathbb{R}$ or $F = \mathbb{C}$. For $T \in L(V, W)$,

$$T \text{ preserves the inner products} \iff \forall \alpha \in V, \|T\alpha\| = \|\alpha\|.$$

Proof. (\Rightarrow) $\|T\alpha\|^2 = (T\alpha, T\alpha) = (\alpha, \alpha) = \|\alpha\|^2$.

(\Leftarrow) (Polarization identity) (α, β) can be expressed in terms of $\|\alpha \pm \beta\|$ and $\|\alpha \pm i\beta\|$. (Exercise) \square

Definition 8.3.4: Unitary Operator

Let V be an inner product space over $F = \mathbb{R}$ or $F = \mathbb{C}$. $T \in L(V)$ is called a *unitary operator* if it is an isomorphism of inner product spaces.

Theorem 8.3.6

Let V be an inner product space over $F = \mathbb{R}$ or $F = \mathbb{C}$. For $U \in L(V)$,

$$U \text{ is unitary} \iff U^* \text{ exists and } UU^* = U^*U = \text{Id}.$$

Proof. (\Rightarrow) For U being an isomorphism, there exists the inverse $U^{-1} \in L(V)$ of U . Then, for all $\alpha, \beta \in V$, $(U\alpha, \beta) = (U\alpha, UU^{-1}\beta) = (\alpha, U^{-1}\beta)$. Hence, $U^{-1} = U^*$.

(\Leftarrow) U is invertible and $U^{-1} = U^*$. Then, for all $\alpha, \beta \in V$, $(U\alpha, U\beta) = (\alpha, U^*U\beta) = (\alpha, \beta)$. Hence, U preserves the inner product. Moreover, U is an isomorphism of vector spaces as well. Hence, U is unitary. \square

Note:-

For finite-dimensional inner product spaces, for any $T: V \rightarrow V$, we have T^* . If the dimension is infinite, the existence of T^* is not immediate.

Definition 8.3.5: Unitary Matrix

Let A be an $n \times n$ matrix over $F = \mathbb{R}$ or $F = \mathbb{C}$. We say A is a *unitary matrix* if

$$AA^* = A^*A = I_n.$$

Theorem 8.3.7

Let V be a finite-dimensional inner product space over $F = \mathbb{R}$ or $F = \mathbb{C}$. For $U \in L(V)$,

$$U \text{ is unitary} \iff \exists \text{ orthonormal basis } \mathcal{B} \text{ for } V, [U]_{\mathcal{B}} \text{ is a unitary matrix.}$$

Theorem 8.3.8

Let V be a finite-dimensional inner product space over $F = \mathbb{R}$ or $F = \mathbb{C}$. Let $U_1, U_2 \in L(V)$ be unitary operators. Then, $U_1 \circ U_2$ is also unitary.

Proof. For all $\alpha, \beta \in V$, $(U_1 U_2 \alpha, U_1 U_2 \beta) = (U_2 \alpha, U_2 \beta) = (\alpha, \beta)$. □

Theorem 8.3.9

Let V be a finite-dimensional inner product space over $F = \mathbb{R}$ or $F = \mathbb{C}$. If $U \in L(V)$ is unitary, then U^{-1} is unitary as well.

Proof. $U^{-1} = U^*$, and $UU^* = U^*U = \text{Id}$. □

Definition 8.3.6

Let V be an n -dimensional inner product space over $F = \mathbb{R}$ or $F = \mathbb{C}$. Let

$$U(V) \triangleq \{ T \in L(V) \mid T \text{ is unitary} \}.$$

$$O(n) \triangleq \{ A \in F^{n \times n} \mid AA^t = A^t A = I \}.$$

- When $F = \mathbb{C}$, the group $(U(V), \circ) \simeq (U(\mathbb{C}^n), \circ)$ is called the n -th unitary group.
- When $F = \mathbb{R}$, the group $(O(n), \cdot)$ is called the real orthogonal group.
- When $F = \mathbb{C}$, the group $(O(n, \mathbb{C}), \cdot)$ is called the complex orthogonal group.
- $SU(n) = \{ A \in U(n) \mid \det A = 1 \}$ is called the special unitary group.
- $SO(n) = \{ A \in O(n) \mid \det A = 1 \}$ is called the special orthogonal group.

8.4 Normal Operators

Definition 8.4.1: Normal Operator

Let V be a finite-dimensional inner product space over $F = \mathbb{R}$ or $F = \mathbb{C}$. $T \in L(V)$ is normal if $TT^* = T^*T$.

Note:-

If we can find an orthonormal basis \mathcal{B} for V such that the vectors in \mathcal{B} are also characteristic vectors of T , then $[T]_{\mathcal{B}}$ is diagonal, and thus $TT^* = T^*T$. In other words, T having an orthonormal basis consisting of characteristic vectors implies T is normal. In this section, we prove the converse.

Theorem 8.4.1

Let V be an n -dimensional inner product space over $F = \mathbb{R}$ or $F = \mathbb{C}$. Let $T \in L(V)$ be normal. Then, for a characteristic vector $\alpha \in V$, $c \in F$ is a eigenvalue of T associated to α if and only if \bar{c} is an eigenvalue of T^* associated to α .

Proof. For any $\beta \in V$ and any normal $U \in L(V)$, we have

$$\|U\beta\|^2 = (U\beta, U\beta) = (\beta, U^*U\beta) = (\beta, UU^*\beta) = (U^*\beta, U^*\beta) = \|U^*\beta\|^2.$$

Also, for any $c \in F$, $T - cI$ is normal. Hence, if $c \in F$ is an eigenvalue and $\alpha \in V$ is an eigenvector associated to c , we have $\|(T^* - \bar{c}I)\alpha\| = \|(T - cI)\alpha\| = 0$, and thus \bar{c} is an eigenvalue and α is an eigenvector associated to \bar{c} . □

Theorem 8.4.2

Let V be an n -dimensional inner product space over $F = \mathbb{R}$ or $F = \mathbb{C}$. Let $T \in L(V)$.

Suppose \mathcal{B} is an orthonormal basis for V such that $[T]_{\mathcal{B}}$ is upper triangular. Then,

$$T \text{ is normal} \iff [T]_{\mathcal{B}} \text{ is diagonal.}$$

Proof. Let $A \triangleq [T]_{\mathcal{B}}$. Then $A^* = [T^*]_{\mathcal{B}}$ by Corollary 8.3.1.

(\Leftarrow) We apparently have $AA^* = A^*A$, i.e., $TT^* = T^*T$. T is normal.

(\Rightarrow) A is upper triangular. Let $a_{ij} = (A)_{ij}$ so $a_{ij} = 0$ if $i > j$. Let $\mathcal{B} = \{\alpha_1, \dots, \alpha_n\}$. We immediately have that $T\alpha_1 = a_{11}\alpha_1$, and thus $T^*\alpha_1 = \overline{a_{11}}\alpha_1$ by Theorem 8.4.1. On the other hand, we have $T^*\alpha_1 = \sum_{j=1}^n \overline{a_{1j}}\alpha_j$. Hence, $a_{1j} = 0$ for $1 < j \leq n$.

Repeating the argument above, we get $a_{ij} = 0$ if $i < j$. Hence, A is diagonal. \square

Lemma 8.4.1

Let V be an n -dimensional inner product space over $F = \mathbb{R}$ or $F = \mathbb{C}$. Let $T \in L(V)$. Let W be a T -invariant subspace of V . Then, W^\perp is T^* -invariant.

Proof. Take any $\beta \in W^\perp$. For all $\alpha \in W$, we have $(\alpha, T^*\beta) = (T\alpha, \beta) = 0$ as W is T -invariant. Hence, $T^*\beta \in W^\perp$. \square

Theorem 8.4.3

Let V be an n -dimensional inner product space over \mathbb{C} . Let $T \in L(V)$. Then, there exists an orthonormal basis \mathcal{B} for V such that $[T]_{\mathcal{B}}$ is upper triangular.

Proof. We prove by induction on $\dim V$. Suppose that $n = \dim V > 1$ and that the theorem holds for any inner product space with dimension less than n .

Since \mathbb{C} is algebraically closed, there exists an eigenvalue $c \in \mathbb{C}$ and an eigenvector $\alpha \in V$ such that $T^*\alpha = c\alpha$. WLOG, $\|\alpha\| = 1$. Then, as $\text{span}\{\alpha\}$ is T^* -invariant, we have $W \triangleq (\text{span}\{\alpha\})^\perp$ is T -invariant by Lemma 8.4.1. By the induction hypothesis on W and $T|_W$, there exists an orthonormal basis $\mathcal{B}' = \{\alpha_1, \dots, \alpha_{n-1}\}$ for W such that $[T|_W]_{\mathcal{B}'}$ is upper triangular. Then, $\mathcal{B} = \mathcal{B}' \cup \{\alpha\}$ is a basis for V and

$$[T]_{\mathcal{B}} = \begin{bmatrix} [T|_W]_{\mathcal{B}'} & * \\ 0 & * \end{bmatrix}$$

is upper triangular. \square

Corollary 8.4.1

Let V be an n -dimensional inner product space over \mathbb{C} . Let $T \in L(V)$ be normal. Then, there exists an orthonormal basis for V consisting of eigenvectors of T .

Corollary 8.4.2

Let $A \in \mathbb{C}^{n \times n}$.

- (i) There exists a unitary matrix $P \in U(n)$ such that $P^{-1}AP$ is upper triangular.
- (ii) If A is normal, then $P^{-1}AP$ is diagonal. In other words, A is *unitarily diagonalizable*.

Example 8.4.1

Let V be an n -dimensional inner product space over \mathbb{C} . Let $T \in L(V)$.

- (i) If T is Hermitian, then T is normal.

(ii) If T is unitary, then T is normal.

End.