MAS242 선형대수학 Notes

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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 a get a basis of V. $S' \triangleq S_0 \cup \{ v_1, v_2, \cdots, v_r \}$ is a basis of V. $|S'| \geq |S_0| + 1$; otherwise $\operatorname{span} S_0 = V$. □

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 $\{ \alpha_1, \alpha_2, \cdots, \alpha_d \}$ as a basis for $W_1 \cap W_2$. We may extend this into bases of W_1 and W_2. Let $\{ \alpha_1, \cdots, \alpha_d, \beta_{d+1}, \beta_{d+2}, \cdots, \beta_a \}$ and $\{ \alpha_1, \cdots, \alpha_d, \gamma_{d+1}, \gamma_{d+2}, \cdots, \gamma_a \}$ be bases for W_1 and W_2 respectively.

We now claim that

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

is a basis of $W_1 + W_2$.

- Let $x \in W_1 + W_2$. Then, $x = w_1 + w_1$ where $w_i \in W_i$. Since $w_1 \in \operatorname{span}\{ \alpha_1, \cdots, \alpha_d, \beta_{d+1}, \cdots, \beta_a\}$ and $w_1 \in \operatorname{span}\{\alpha_1, \cdots, \alpha_d, \gamma_{d+1}, \cdots, \gamma_b\}$, On the other hand, $B \subseteq W_1 + W_2$. Hence, $\operatorname{span} B = W_1 + W_2$.
- 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, $\dim(W_1 + W_2) = a + b - d$. □

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 $B = \{v_1; v_2; \cdots; v_n\}$ is an ordered basis of V. Then, for each $x \in V$, there uniquely exists an expression of the form

$$x = x_1 v_2 + x_2 v_2 + \cdots + x_n v_n$$

for some $x_i \in F$.

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

(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 $B \triangleq \{\alpha_1; \cdots; \alpha_n\}$ and $B' \triangleq \{\alpha'_1; \cdots; \alpha'_n\}$ 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 $[x]_B = \begin{pmatrix} x_1 \\ \vdots \\ v_n \end{pmatrix}$ and $[x]_{B'} = \begin{bmatrix} x'_1 \\ \vdots \\ v'_n \end{bmatrix}$. Then, $x = \sum_{j=1}^n x'_j \alpha_j = \sum_{i=1}^n \left(\sum_{j=1}^n x'_j P_{ij}\right)\alpha_i$.

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

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

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. $T: V_1 \to V_2$ 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 $\{\alpha_1, \cdots, \alpha_n\}$ is a basis of V. Let $\{\beta_1, \cdots, \beta_n\}$ be any given set of vectors of W. Then, there exists a unique transformation $T: V \to W$ such that $T(\alpha_i) = \beta_i$.

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

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

This is a linear transformation indeed.

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

Definition 3.1.2: Null Space and Range Space

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

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

Note:-

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

Definition 3.1.3

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

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

Theorem 3.1.2 Rank-Nullity Theorem

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

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

Suppose $\sum_{i=k+1}^n c_i T(v_i) = 0$ for some $c_i \in F$. Then, we have $T\big(\sum_{i=k+1}^n c_i v_i\big) = 0$; hence $\sum_{i=k+1}^n c_i v_i \in \ker T$. Since $\{v_1, \cdots, v_k\}$ 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 $\{v_1, \cdots, v_n\}$ 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 $T(v) \in \operatorname{Im} T$. 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, $\operatorname{Im} T \subseteq \operatorname{span}\{T(v_{k+1}), \cdots, T(v_n)\}$

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

Theorem 3.1.3

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

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

The number of rows with leading one's in 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, $\operatorname{nullity} T = n - \operatorname{colrank} T$ $\square$

3.2 The Algebra of Linear Transformations

Definition 3.2.1

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

Theorem 3.2.1

Let $T : V \to W$ 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 $\mathcal{B} = \{\alpha_1, \cdots, \alpha_n\}$ and $\mathcal{B}' = \{\beta_1, \cdots, \beta_m\}$ be bases for V and W, respectively. For each $p \in [n]$ and $q \in [m]$, Define

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

Then,

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

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

$\square$

Lemma 3.2.1

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

Definition 3.2.2: Linear Operator (Endomorphism)

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

Exercise 3.2.1

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

Exercise 3.2.2

If $T : V \to W$ 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 $T : V \to W$ 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 $T : V \to W$ be a linear transform. TFAE

(i) T is invertible.
(ii) T is injective.
(iii) T is surjective.

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

Definition 3.2.4: General Linear Group

Let $\mathrm{GL}(V) \triangleq \{T \in L(V, V) \mid T$ is invertible$\}$. Then, $(\mathrm{GL}(V), \circ)$ 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 $T : V \to W$ is an *isomorphism* if T is an invertible linear transformation.
We say V and W are *isomorphic* if there exists an isomorphism $T : V \to W$, 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 $B = \{\alpha_1; \cdots; \alpha_n\}$ be a basis of V. Define $T : V \to F^n$ by $v \mapsto [v]_B$.
Suppose $T(v) = 0$. Then, $v = 0 \cdot \alpha_1 + \cdots 0 \cdot \alpha_n = 0$. Hence, T is injective. By Theorem 3.2.3, T is isomorphism. □

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 $T : V \to W$ 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. $A = \begin{bmatrix} [T(v_1)]_{B'} & [T(v_2)]_{B'} & \cdots & [T(v_n)]_{B'} \end{bmatrix}$ where v_i is the i^{th} basis vector of B. □

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, $[T]_{B_i} \triangleq [T]_{B_i,B_i}$ 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, $P[T]_{B_2} = [T]_{B_1}P$. □

Note:-

- A linear transformation $T: V \to V$ 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 $(-1)^{\deg}$(constant term) as $\det T$ and $-(n-1$ deg term) as $\operatorname{tr} T$.

3.5 Linear Functionals

Definition 3.5.1: Linear Functional

Let V be a vector space over F. A linear transformation $T: V \to F$ 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 $\{\alpha_1, \alpha_2, \cdots, \alpha_n\}$ be a basis for V. Define $f_i \in V^*$ by declaring $f_i(\alpha_j) = \delta_{ij}$. Then, $\{f_1, \cdots, f_n\}$ 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 $f_i(\alpha_j) = \delta_{ij}$, $0 = \left(\sum_{i=1}^n c_i f_i\right)(\alpha_j) = c_j f_j(\alpha_j) = c_j$. Hence, they are linearly independent. □

Definition 3.5.3: Dual Basis

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

Lemma 3.5.2

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

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

Proof.

(i) 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 $f(\alpha_j) = x_j$.
(ii) 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 $f_j(v) = y_j$.

□

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 $f : V \to F$ 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 $\varnothing \subsetneq S \subseteq V$. The *annihilator* of S, $S^\circ = \operatorname{Ann} S$ is defined to be

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

Note:-

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

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

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

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

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

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 $\mathscr{L}$ by

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

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, $\mathscr{L} : V \to V^{**}$ 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. □

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 $\alpha \in V \setminus \ker f$, $\operatorname{span}\{\ker f, \alpha\} = V$. 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, $\beta = \gamma + c\alpha \in \operatorname{span}], \{\ker f, \alpha\}$. □

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 $\operatorname{span}\{W, \alpha\} = V$. 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 $g : V \to F$ 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 $T : V \to W$ be a linear transformation. The map $T^t : W^* \to V^*$ defined by $g \mapsto g \circ T$ is called the *transpose* of T.

Lemma 3.7.1

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

Theorem 3.7.1

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

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

Theorem 3.7.2

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

(i) $\ker T^t = (\operatorname{Im} T)^\circ$.

(ii) If V and W are finite-dimensional, then $\operatorname{rank} T^t = \operatorname{rank} T$.

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

Proof.

(i) $g \in \ker T^t \iff T^t(g) = 0 \iff g \circ T = 0 \iff g \in (\operatorname{Im} T)^\circ$

(ii) Let $n \triangleq \dim V$ and $m \triangleq \dim W$. Let $r = \operatorname{rank} T$. Then, by Theorem 3.5.1, $\dim(\operatorname{Im} T)^\circ = m - r$. By (i), $(\operatorname{Im} T)^\circ = \ker T^t$; hence nullity $T^t = m - r$. By the rank-nullity theorem, $\operatorname{rank} T^t = r = \operatorname{rank} T$.

(iii) Take any $f \in \operatorname{Im} T^t$. 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, $f \in (\ker T)^\circ$; $\operatorname{Im} T^t \subseteq (\ker T)^\circ$. 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 $\mathcal{A} \times \mathcal{A} \to \mathcal{A}$ 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 $1, x, x^2, \cdots$. 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 $\mathrm{ev}_\alpha : F[x] \to F$ 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 $g_0 \in \operatorname{argmin}_{g \in M \setminus \{0\}} \deg g$ 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 $p_1, \cdots, p_n \in F[x]$ 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) $p_1 F[x] + p_2 F[x] + \cdots + p_n F[x] = (g_0)$

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

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

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

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). $g_0=\sum_{j=1}^n p_jg_j=f\sum_{j=1}^n h_jg_j$. □

Definition 4.1.8: Relatively Prime

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

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 irreduciple 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.

($\Rightarrow$) 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, $p\mid h$.

($\Leftarrow$) 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. □

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 $f=p_1p_2\cdots p_r$. 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 $f=g_1g_2$. Then, $\deg g_1$ and $\deg g_2$ are less than f. Hence, $g_1=p_1p_2\cdots p_r$ and $g_2=q_1q_2\cdots q_s$ where p_j and q_j are irreducible, yielding $f=p_1\cdots p_rq_1\cdots q_s$.

(*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. □

Definition 4.1.11: (Formal) Derivative

For $f(x) = a_0 + a_1 x + \cdots + a_n x^n \in F[x]$, we define

$$f'(x) \triangleq a_1 + 2a_2 x + \cdots + n a_n x^{n-1}.$$

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 $f = p^2 h$ for some irreducible polynomial p for the sake of contradiction. Then, $f' = p(2p'h + ph')$, which contradicts $(f, f') = (1)$.

($\Rightarrow$) □

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 $\deg g \geq 1$ 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 $\mathcal{D} \to K^{n\times n} \to K$ 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 $\mathcal{D}\colon K^{n\times n} \to K$ 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 $A(i \mid j)$ be the $(n-1)\times(n-1)$ matrix with the i^{th} row and the j^{th} column are removed. $A(i \mid j)$ is called (i, j)*-minor* of A.

Theorem 5.1.1

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

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

Suppose we have found a function $\mathcal{D}\colon K^{(n-1)\times(n-1)}$ which is $(n-1)$-linear and alternating. We shall denote $\mathcal{D}(A(i \mid j)) = D_{ij}(A)$. Define $E_i(A) \triangleq \sum_{i=1}^{n}(-1)^{i+j}A_{ij}D_{ij}(A)$ 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 $i \neq k+1$, $A(i \mid j)$ has two identical rows; thus $D_{ij}(A) = D(A(i \mid j)) = 0$. Thus, $E_j(A) = (-1)^{k+j}A_{kj}D_{kj}(A) + (-1)^{k+j+1}A_{(k+1),j}D_{(k+1),j}(A)$.

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

Claim. $E_j(I_n) = 1$.

$I_n(i \mid j) = I_{n-1}$. □

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 $\sigma : S \to S$.
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 $(i_1, i_2, \cdots, i_n)$.

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

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

Corollary 5.1.2

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

Theorem 5.1.3

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

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

Proof. Let $e_1, \cdots, e_n$ 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 $\mathcal{D}(e_{j_1}, \cdots, e_{j_n}) = 0$. Also, if $\sigma \in S_n$, $\mathcal{D}(e_{\sigma(1)}, \cdots, e_{\sigma(n)}) = \mathrm{sign}(\sigma)\mathcal{D}(I_n) = \mathrm{sign}(\sigma)$.

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

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, $\operatorname{adj} A \triangleq C^t$ where $(C)_{ij} = C_{ij}$ is called the *adjoint* of A.

Corollary 5.1.6

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

Chapter 6

Elementary Canonical Forms

6.1 Eigenvalues

Definition 6.1.1: Eigenvalue

Let V be a vector space over F. Let $T : V \to V$ 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 $T : V \to V$ 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. □

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. □

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 $\mathcal{B} = \{v_1, \cdots, v_n\}$ and $Tv_i = c_i v_i$ for each $i \in [n]$, then $[T]_{\mathcal{B}} = \operatorname{diag}(c_1, c_2, \cdots, c_n)$.
- 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 $c_1, \cdots, c_k \in F$ 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 $T, T^2, \cdots, T^{k-1}$, we get

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

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

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

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

Note:-

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

Theorem 6.1.2

Let V be a n-dimensional vector space over F. Let $T \in L(V)$. Suppose $c_1, \cdots, c_k \in F$ 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.

(i) T is diagonalizable.

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

(iii) $\sum_{i=1}^k d_i = n$.

Proof. ((i) ⇒ (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 $\operatorname{span} B_i = W_i$. Hence, on rearranging, $[T]_{\mathcal{B}} = \operatorname{diag}(\overbrace{c_1, \cdots, c_1}^{d_1}, \overbrace{c_2, \cdots, c_2}^{d_2}, \cdots, \overbrace{c_k, \cdots, c_k}^{d_k})$.

((ii) ⇒ (iii)) A direct consequence of Lemma 6.1.1.

((iii) ⇒ (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. □

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 $\{I, T, T^2, \cdots, T^{n^2}\}$ 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., $m(c) = 0$. $\square$

Corollary 6.2.1

Let V be a n-dimensional vector space over F. Let $T \in L(V)$. Suppose $c_1, \cdots, c_k \in F$ are all the possible distinct characteristic values of T. If $p(x)$ is the characteristic polynomial of T and $m(x)$ is the minimal polynomial of T, then, $p(x) = \prod_{i=1}^{k}(x-c_i)^{d_i}$ and $p(x) = \prod_{i=1}^{k}(x-c_i)^{r_i}$ where $d_i \geq r_i$ for each $i \in [k]$.

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 $\mathcal{B} = \{\alpha_1, \cdots, \alpha_n\}$ 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, $(\operatorname{adj} B)B = B(\operatorname{adj} B) = (\det B)I$. By construction, $\sum_{j=1}^{n}(\operatorname{adj} B)_{ki}B_{ij}\alpha_j = 0$ for all $k, i \in [n]$.

Taking sum over i, we have

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

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

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 $T\big|_W$ 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 $T\big|_W$ and T, and f_W and f are characteristic polynomials of $T\big|_W$ and T.

Proof. Let $\mathcal{B}' = \{\alpha_1, \cdots, \alpha_k\}$ be a basis for W, and extend it to $\mathcal{B} = \{\alpha_1, \cdots, \alpha_n\}$ 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 $A = \left[T\big|_W\right]_{\mathcal{B}'}$. Hence, $f(x) = \det(xI - M) = \det(xI - A)\det(xI - C) = f_W(x)\det(xI - C)$.

Now, noting that $M^r = \left[\begin{smallmatrix} A^r & * \\ 0 & C^r \end{smallmatrix}\right]$, 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 $m_W \mid m$. □

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 $g(T)\alpha \in W$. □

Definition 6.3.3: T-conductor

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 $T : V \to V$ 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 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 $(T - c_jI)\alpha = (T - c_jI)h(T)\beta = g(T)\beta \in W$. □

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) $T\alpha \in \operatorname{span}\{W, \alpha\}$.

Theorem 6.3.1

Let V be a finite-dimensional vector space over F. Let $T : V \to V$ 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 $\det(xI - A) = \prod_{i=1}^{n} \left(x - (A)_{ii}\right)$. 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:

- $W_i = \operatorname{span}\{\alpha_1, \cdots, \alpha_i\}$.
- 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, $\mathcal{B} = \{\alpha_1, \cdots, \alpha_n\}$ is a basis for V and $[T]_{\mathcal{B}}$ is an upper triangular matrix since $T\alpha_{i+1} \in \operatorname{span}\{\alpha_1, \cdots, \alpha_i\} + d_{i+1}\alpha_{i+1}$. □

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 $c_1, \cdots, c_k$ 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 $\{\alpha_1, \cdots, \alpha_n\}$ 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 $\beta \triangleq (T - c_j)\alpha \in W$.

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. □

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 $\forall T \in \mathcal{F}$, $T\alpha \in \operatorname{span}\{W, \alpha\}$.

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

Let $V_0 = V$. Construct $V_1, \cdots, V_r$ and $\beta_1, \cdots, \beta_r$ as follows. For each $i \in [r]$,

(i) Let $U_i = T_i\big|_{V_{i-1}}$. 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 $T_i\beta_r \in \operatorname{span}\{W, \beta_r\}$ 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 $\alpha_2, \cdots, \alpha_n$ as following. For each $i \in [n-1]$,

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

Then, $\mathcal{B} = \{\alpha_1; \cdots; \alpha_n\}$ 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 $c_1, \cdots, c_k$ be its distinct characteristic values. For each $i \in [k]$, let $\mathcal{F}_i \triangleq \left\{ T\big|_{W_i} \in L(W_i, V) : T \in \mathcal{F} \right\}$ 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 $T'\big|_{W_i}$ 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, $\mathcal{B} = (\mathcal{B}_1, \cdots, \mathcal{B}_k)$ is an ordered basis for V due to Lemma 6.1.1, and $\mathcal{B}$ is the basis we are looking for. □

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 $W_1, \cdots, W_k$ of V are *independent* if, whenever $a_1 + \cdots + a_k = 0$ 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 $W_1, \cdots, W_k$ be the finite number of subspaces of V. Then, we say that the sum $W = \sum_{i=1}^{k} W_i$ is *direct* if $W_1, \cdots, W_k$ are independent. We write $W = W_1 \oplus \cdots \oplus W_k = \oplus_{i=1}^{k} W_i$ 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 $V_1 = \operatorname{Im} E$ 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 $v_1 \in \operatorname{Im} E$ 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 $E(v_1 + v_2) = E(v_1) = v_1$. □

Theorem 6.5.1

Let V be a n-dimensional vector space over F. Suppose $V = \oplus_{i=1}^{k} W_i$ 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) $\operatorname{Im} E_i = W_i$ 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 $E_i : V \to V$ by $v \mapsto v_i$. Then, E_i's satisfy the four constraints. □

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 $V = \oplus_{i=1}^{k} W_i$ for some subspaces W_i of V. Let $E_1, \cdots, E_k$ 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, $E_i T\alpha = \sum_{j=1}^{k} E_i T\alpha_j = T\alpha_i = TE_i\alpha$.

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

Theorem 6.6.2

Let V be a n-dimensional vector space over F. Let $T \in L(V)$. If T is diagonalizable and $c_1, \cdots, c_k$ 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 $V = \oplus_{i=1}^{k} W_i$ 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 $W_i \triangleq \ker\left(p_i(T)^{r_i}\right)$. Then, the following hold.
(i) $V = \oplus_{i=1}^{k} W_i$.
(ii) Each W_i is T-invariant.
(iii) The minimal polynomial of $T_i = T\big|_{W_i}$ 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 $f_1, \cdots, f_k$ are also relatively prime, there exists $g_1, \cdots, g_k \in F[x]$ such that $f_1 g_1 + \cdots + f_k g_k = 1$. 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, $V = \oplus_{i=1}^{k} \operatorname{Im} E_i$ and each $\operatorname{Im} E_i$ is T-invariant.

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

- Take any $\alpha \in \operatorname{Im} E_i$. 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, $\operatorname{Im} E_i \subseteq W_i$.
- Take any $\alpha \in \ker\big(p_i(T)^{r_i}\big)$. 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: $\alpha \in \operatorname{Im} E_i$. Hence, $W_i \subseteq \operatorname{Im} E_i$.

It remains to show that $T_i = T\big|_{W_i}$ 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 $p_i(T)^{r_i}\big|_{W_i} = 0$. Hence, $m_i \mid p_i^{r_i}$; we now know $m_i = p_i^{s_i}$ for some $1 \le s_i \le r_i$. Let g be any polynomial in $F[x]$ such that $g(T_i) = 0$. We now claim that $p_i^{r_i} \mid g$. Since $g(T_i) = 0$, we have $g(T) f_i(T) = 0$ as well. $m \mid g f_i$. 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 $p_i^{r_i} \mid g$. □

Corollary 6.7.1

If $E_1, \cdots, E_k$ 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

(i) $T = D + N$ and
(ii) $DN = ND$.

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 $W_i \triangleq \ker(T - c_i I)^{r_i} = \operatorname{Im} E_i$ 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 $N = N'$. □

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 $Z(\alpha; T) = \operatorname{span}\{\alpha\}$.
- If $\dim Z(\alpha; T) = 1$, then $\alpha \neq 0$ and $Z(\alpha; T) = \operatorname{span}\{\alpha\}$; 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 $k = \deg p_\alpha$, $\{\alpha, T\alpha, \cdots, T^{k-1}\alpha\}$ is a basis for $Z(\alpha; T)$, hence $\deg p_\alpha = \dim Z(\alpha; T)$.

(ii) Let $U \triangleq T\big|_{Z(\alpha;T)} \in L(Z(\alpha;T))$. 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, $Z(\alpha;T) = \operatorname{span}\{\alpha, T\alpha, \cdots, T^{k-1}\alpha\}$. We are left with proving that they are linearly independent.

Suppose they are not linearly independent for the sake of contradiction. Then there exist $c_0, \cdots, c_{k-1} \in F$ not all zero such that $\left(\sum_{i=0}^{k-1} c_i T^i\right)\alpha = 0$, 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) 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, $p_\alpha(U) = 0$.

Moreover, there does not exist $q \in F[x]$ with $q(U) = 0$ by the definition of p_α. Hence, the result follows.

$\square$

Note:-

With respect to the ordered basis $\mathcal{B} = \{\alpha; T\alpha; \cdots; T^{k-1}\alpha\}$ 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.

Definition 7.1.4: 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 7.1.5: 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) $\forall f \in F[x], \forall \beta \in V, \big(f(T)\beta \in W \implies \exists \gamma \in W, f(T)\beta = f(T)\gamma\big)$.

Lemma 7.1.1

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, $f(T)\beta = f(T)\gamma$. $\square$

Theorem 7.1.2 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 $\alpha_1, \cdots, \alpha_r \in V \setminus \{0\}$ such that

(i) $V = W_0 \oplus \left(\oplus_{i=1}^{r} Z(\alpha_i; T) \right)$ and

(ii) $p_{i+1} \mid p_i$ for each $i \in [r-1]$

where p_i is the T-annihilator of α_i. Furthermore, r and $p_1, \cdots, p_r$ are uniquely decided.

Proof. In this proof we denote the monic generator of $S_T(\alpha; W)$ by $\underline{s_T(\alpha; W)}$ and $f(T)\beta$ by $\underline{f\beta}$ for conciseness.

Claim 0. For $\alpha, \beta \in V$ and a 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 $Z(\alpha; T) + W \subseteq Z(\beta; T) + W$. ✓

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 $S_T(\alpha; W) = M(\alpha; T)$ and $W \cap Z(\alpha; T) = \{0\}$.

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

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, $W \cap \operatorname{argmax}_{\alpha \in V} \deg s_T(\alpha; W) = \varnothing$. 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, $A = \operatorname{argmax}_{\alpha \in V} \deg s_T(\alpha; W) \neq \varnothing$, 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 $\alpha = s_T(\beta; W)\alpha \in W$, contradicting $W \subsetneq V$. ✓

Algorithm: Construct $\beta_1, \cdots, \beta_r$ and $W_1, \cdots, W_r$

$i \leftarrow 0$;

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

  Take any $\beta_{i+1} \in \operatorname{argmax}_{\alpha \in V} \deg s_T(\alpha; W_i)$; ▷ 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 $f = s_T(\beta; W_{k-1})$, $g_i \in F[x]$, 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 $\gamma \triangleq \beta - \sum_{i=1}^{k-1} h_i \beta_i$. Then, we have:

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

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 $g\big(\beta_0 + \sum_{i=1}^{j-1} r_i \beta_i\big) \in W_{j-1}$ 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:

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

As k is arbitrary, we have

$$W_k = W_0 \oplus \big(\oplus_{i=1}^{k} Z(\alpha_k; T)\big).$$

Moreover, note that $\alpha_1, \cdots, \alpha_r$ retains the defining property of $\beta_1, \cdots, \beta_r$, i.e., $\alpha_k \in \operatorname{argmax}_{\alpha \in V} \deg s_T(\alpha; W_{k-1})$. ***Claim 4*** holds when $\beta_1, \cdots, \beta_r$ are replaced with $\alpha_1, \cdots, \alpha_r$. Hence, applying the alternative version of ***Claim 4*** to the trivial equation

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

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

Now, we shall show the uniqueness of such decomposition. □

Corollary 7.1.1

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. (⇒) Theorem 7.1.2 (⇐) Lemma 7.1.1 □

End.