LINEAR ALGEBRA II

Anita Naolekar, notes by Ramdas Singh

Second Semester

List of Symbols

Contents

Chapter 1

PERMUTATION GROUPS

January 3rd.

Let S_n denote the set of all bijections (permutations) on the set $\{1, 2, \ldots, n\}$. If $\sigma, \tau \in S_n$, let us define $\sigma\tau$ to be the bijection defined as

$$(\sigma\tau)(i) = \sigma(\tau(i)) \forall 1 \leq i \leq n. \tag{1.1}$$

This gives us a binary operation on S_n which is associative, and S_n will then contain the identity permutation 1 such that $\sigma 1 = 1\sigma = \sigma$ for all $\sigma \in S_n$. For every such σ, we can also find a $\sigma^{-1} \in S_n$ such that $\sigma\sigma^{-1} = \sigma^{-1}\sigma = 1$. The set S_n equipped with this binary operation, thus, forms a group. In this case, we call S_n as the *symmetric group* of degree n. We now define a cycle in regards to permutations.

Definition 1.1. A *cycle* is a a string of positive integers, say $(i_1, i_2, \ldots, i_k)$, which represents the permutation $\sigma \in S_n$ (with $k \leq n$) such that $\sigma(i_j) = i_{j+1}$ for all $1 \leq j \leq k-1$, and $\sigma(i_k) = i_1$, and fixes all other integers.

We also note that S_3 is the smallest Abelian group possible, upto isomorphism. S_3 is one of the only two groups of order 6, and can be written as

$$S_3 = \{1, \sigma = (1, 2, 3), \sigma^2 = (1, 3, 2), \tau = (1, 2), \sigma\tau = (1, 3), \tau\sigma = (2, 3)\}. \tag{1.2}$$

Some other observations arise. We find that $\sigma^3 = \tau^2 = 1$, and that $\tau\sigma = \sigma^2\tau$. We notice another fact via this σ;

Remark 1.2. A *k-cycle* $\sigma = (i_1, i_2, \ldots, i_k)$ is of order k, that is, $\sigma^k = 1$.

Definition 1.3. Two cycles in S_n are called disjoint if they have no intger in common.

We note that if σ and τ are two disjoint cycles in S_n then σ and τ commute, that is, $\sigma\tau = \tau\sigma$.

Proposition 1.4. *Every σ in S_n can be written uniquely as a product of disjoint cycles.*

Every cycle can be written as a product of 2-cycles. 2-cycles are called *transpositions*. This can easily be seen as

$$(a_1, a_2, \ldots, a_n) = (a_1, a_n)(a_1, a_{n-1}) \cdots (a_1, a_3)(a_1, a_2). \tag{1.3}$$

1.1 Even and Odd Permutations

Let $x_1, x_2, \ldots, x_n$ be indeterminates, and let

$$\Delta = \prod_{1 \leq i < j \leq n} (x_i - x_j). \tag{1.4}$$

Let $\sigma \in S_n$, and define

$$\sigma(\Delta) = \prod_{1 \leq i < j \leq n} (x_{\sigma(i)} - x_{\sigma(j)}). \tag{1.5}$$

We find that $\sigma(\Delta) = \pm\Delta$. Based on this, we classify permutations as odd or even.

Definition 1.5. A permutation σ is said to be an *even permutation* if $\sigma(\Delta) = \Delta$, and is said to be an *odd permutation* if $\sigma(\Delta) = -\Delta$. The sign of a permutation σ, denoted by $\epsilon(\sigma)$, is $+1$ if σ is even, and is -1 if σ is odd. So, $\sigma(\Delta) = \epsilon(\sigma)\Delta$.

Proposition 1.6. *The map $\epsilon : S_n \to \{-1, +1\}$, where $\epsilon(\sigma)$ is the sign of σ, is a homomorphism, that is, $\epsilon(\sigma\tau) = \epsilon(\sigma)\epsilon(\tau)$ for all $\sigma, \tau \in S_n$.*

Proof. Start with $\tau(\Delta)$;

$$\tau(\Delta) = \prod_{1 \le i < j \le n} (x_{\tau(i)} - x_{\tau(j)}). \tag{1.6}$$

Let there be k factors of this polynomial where $\tau(i) > \tau(j)$ with $i < j$. We find that $\tau(\Delta) = (-1)^k\Delta$, and so, $\epsilon(\tau) = (-1)^k$. Now, $\sigma\tau(\Delta)$ has exactly k factors of the form $x_{\sigma(j)} - x_{\sigma(i)}$, with $j > i$. Bringing out a factor $(-1)^k$, we find that $\sigma\tau(\Delta)$ has all factors of the form $x_{\sigma(i)} - x_{\sigma(j)}$, with $j > i$. Thus,

$$\epsilon(\sigma\tau)\Delta = \sigma\tau(\Delta) = (-1)^k \prod_{1 \le i < j \le n} (x_{\sigma(i)} - x_{\sigma(j)}) = (-1)^k\sigma(\Delta) = (-1)^k\epsilon(\sigma)\Delta = \epsilon(\tau)\epsilon(\sigma)\Delta. \tag{1.7}$$

Cancelling out the Δ, we find $\epsilon(\sigma\tau) = \epsilon(\sigma)\epsilon(\tau)$. ■

ϵ is a homomorphism to an Abelian group, so $\epsilon(\sigma\tau) = \epsilon(\sigma)\epsilon(\tau) = \epsilon(\tau)\epsilon(\sigma)$.

Proposition 1.7. *If $\lambda = (i, j)$ is a transposition, then $\epsilon(\lambda) = -1$.*

Proof. If $\lambda = (1, 2) \in S_n$, it is easy to show that

$$\lambda(\Delta) = (x_1 - x_2)\cdots(x_1 - x_n)(x_2 - x_3)\cdots(x_2 - x_n)\cdots = (-1)(\Delta). \tag{1.8}$$

Now, if $\sigma = (i, j)$, with $(i, j) \neq (1, 2)$, then $(i, j) = \lambda(1, 2)\lambda$ where λ interchanges 1 and i, and interchanges 2 and j. Using that fact that ϵ is a homomorphism, $\epsilon(\sigma) = -1$. ■

A cycle σ of length k is an even permutation if and only if k is odd. This is because it can be decomposed into $k - 1$ transpositions, and we would then have $\epsilon(\sigma) = (-1)^{k-1} = 1$ (using the fact that ϵ is a homomorphism). Some more corollaries of the previous proposition include the fact that ϵ is a surjective map, and that $\epsilon(\sigma^{-1}) = \epsilon(\sigma)$.

If, for $\sigma \in S_n$, σ can be decomposed as $\sigma_1\sigma_2\cdots\sigma_k$, where σ_i is a m_i-cycle, then $\epsilon(\sigma_i) = (-1)^{m_i-1}$, and $\epsilon(\sigma) = (-1)^{(\sum m_i)-k}$.

Proposition 1.8. *σ is an odd permutation if and only if the number of cycles of even length in its cycle decomposition is odd.*

1.2 The Determinant

Definition 1.9. If $A = (a_{ij})$ is a square matrix of order n, then the *determinant* of A is defined as

$$\det A = \sum_{\sigma \in S_n} \epsilon(\sigma) a_{1\sigma(1)} a_{2\sigma(2)} \cdots a_{n\sigma(n)}. \tag{1.9}$$

Using this definition of the determinant of a square matrix, one may derive the usual determinant properties with ease.

January 7th.

Remark 1.10. The following properties may be inferred:

- If A contains a row of zeroes, or a column of zeroes, then $\det A = 0$.
- $\det I_n = 1$.
- The determinant of a diagonal matrix is the product of the diagonal elements. This is because if $\sigma \in S_N$ is not the identity permutation, then there exists at least one element in the corresponding term where $i \neq \sigma(i)$, and $a_{i\sigma(i)}$ makes the term zero. For the identity transformation, it contains only those elements of the form a_{ii}.

Other non-trivial properties may also be shown with ease.

Corollary 1.11. *If A is an upper triangular matrix, then* $\det A$ *is the product of the diagonal entries.*

Proof. If $a_{1\sigma(1)} \cdots a_{n\sigma(n)} \neq 0$, then $a_{n\sigma(n)} \neq 0$, that is, $\sigma(n) = n$, as $a_{ni} = 0 \ \forall \ i < n$. Again, $\sigma_{(n-1)\sigma(n-1)} \neq 0$ leads us to conclude that $\sigma(n-1) = n-1$ as σ is a bijection and has to lead to a non-zero element. By similar logic, $\sigma(i) = i$ for all valid i. So, σ is the identity permutation. ■

Corollary 1.12. *If A is a lower triangular matrix, then* $\det A$ *is the product of the diagonal entries.*

Proof. The proof of this is similar to the previous proof if we consider that the determinant of the tranpose of a matrix is equal to the determinant of said matrix. ■

Theorem 1.13. *The determinant of a matrix is equal to the determinant of its transpose, that is,* $\det A = \det A^t$ *for a square matrix A.*

Proof. The proof is left as an exercise to the reader. ■

Proposition 1.14. *Let B be obtained from A by multiplying a row (or column) of A by a non-zero scalar, α. Then,* $\det B = \alpha \det A$.

Proof. The proof is left as an exercise to the reader. ■

Proposition 1.15. *If B is obtained from A by interchanging any two rows (or columns) of A, then* $\det B = -\det A$.

Proof. Let B be obtained from A by interchanging the rows k and l, with $k < l$. We then have

$$\begin{aligned}\det B &= \sum_{\sigma \in S_n} \epsilon(\sigma) b_{1\sigma(1)} b_{2\sigma(2)} \cdots b_{n\sigma(n)} \\ &= \sum_{\sigma \in S_n} \epsilon(\sigma) a_{1\sigma(1)} \cdots a_{(k-1)\sigma(k-1)} a_{l\sigma(k)} \sigma_{(k+1)\sigma(k+1)} \cdots a_{k\sigma(l)} \cdots a_{n\sigma(n)}. \qquad (1.10)\end{aligned}$$

As σ runs through all elements in S_n, $\tau = \sigma(k, l)$ also runs through all S_n. Hence, via $\epsilon(\tau) = -\epsilon(\sigma)$, the equation now looks like

$$\det B = -\sum_{\tau \in S_n} \epsilon(\tau) a_{1\tau(1)} \cdots a_{l\tau(l)} \cdots a_{k\tau(k)} \cdots a_{n\tau(n)} = -\det A. \qquad (1.11)$$

■

Proposition 1.16. *If two rows (or columns) of A are equal, then* $\det A = 0$.

Proof. Suppose that the rows k and l of A are equal. Interchanging will alter the determinant by -1, so $\det A = -\det A \implies 2\det A = 0 \implies \det A = 0$ if $2 \neq 0$ in the field F from where the elements of A arrive.

If $2 = 0$ in F, that is, F is of characteristic 2, we pair the σ term in the expression of $\det A$ with the term τ where $\tau = \sigma(k, l)$. The terms corresponding to σ and τ in the expressions are the same, differing in only the sign. Hence, $\det A = 0$. ■

Theorem 1.17. *For a fixed k, let the row k of A be the sum of the two row vectors X^t and Y^t, that is, $a_{kj} = x_j + y_j$ for all $1 \leq j \leq n$. Then* $\det A = \det B + \det C$ *where B is obtained from A by replacing the row k of A by the row vector X^t, and C is obtained from A by replacing the row k of A by the row vector Y^t.*

Proof. We utilize the fact that $a_{kj} = x_j + y_j$. We have

$$\begin{aligned}\det A &= \sum_{\sigma \in S_n} \epsilon(\sigma) a_{1\sigma(1)} \cdots a_{k\sigma(k)} \cdots a_{n\sigma(n)} \\ &= \left(\sum_{\sigma \in S_n} \epsilon(\sigma) a_{1\sigma(1)} \cdots x_{\sigma(k)} \cdots a_{n\sigma(n)} \right) + \left(\sum_{\sigma \in S_n} \epsilon(\sigma) a_{1\sigma(1)} \cdots y_{\sigma(k)} \cdots a_{n\sigma(n)} \right) \\ &= \det B + \det C.\end{aligned}$$

■

Proposition 1.18. *If a scalar multiple of a row (or column) is added to a row (or column) of a matrix, the determinant remains unchanged.*

Proof. The proof follows immediately from the previously proved properties. ∎

January 10th.

Definition 1.19. For $a_{ij} \in A$, the *cofactor* of a_{ij} is $A_{ij} = (-1)^{i+j} \det M_{ij}$, where M_{ij} is the $(n-1) \times (n-1)$ matrix obtained from A by deleting the i^{th} row and j^{th} column of A.

Lemma 1.20. *Fix k, j. If $a_{kl} = 0$ for all $l \neq j$, then $\det A = a_{kj} A_{kj}$.*

Proof. Take A to be a $n \times n$ matrix. We deal in cases.

- Case I: $k = j = n$. In the expansion of the determinant,

$$\det A = \sum_{\sigma \in S_n} \epsilon(\sigma) a_{1\sigma(1)} \cdots a_{n\sigma(n)},$$

  only those σ's survive where $\sigma(n) = n$. These σ's can be thought of as permutations of S_{n-1} instead. The sign of $\sigma \in S_n$ and $\sigma \in S_{n-1}$ is the same as n is fixed. Thus, we get

$$a_{nn} \sum_{\sigma \in S_{n-1}} \epsilon(\sigma) a_{1\sigma(1)} \cdots a_{(n-1)\sigma(n-1)} = a_{nn} \det M_{nn} = (-1)^{n+n} a_{nn} A_{nn} = a_{nn} A_{nn}. \tag{1.12}$$

- Case II: $(k, j) \neq (n, n)$. We construct a matrix B by interchanging $n-k$ rows and $n-j$ columns to bring a_{ij} to the position (n, n). Thus, we have $\det B = (-1)^{n-k+n-j} \det A = (-1)^{k+j} \det A$. But $B = a_{kj} \det M_{kj}$, so

$$\det A = (-1)^{k+j} a_{kj} \det M_{kj} = a_{kj} A_{kj}. \tag{1.13}$$

∎

Theorem 1.21. *Let A be a $n \times n$ matrix, and let $1 \leq k \leq n$. Then, $\det A = \sum\limits_{j=1}^{n} a_{kj} A_{kj}$, expansion by the k^{th} row.*

Proof. Write out the k^{th} row of A as $x_1^t + \ldots + x_n^t$, where $x_i = (0, \ldots, 0, a_{ki}, 0, \ldots, 0)^t$, and all the other rows remaining are the same. Writing the matrix A as the sum of n matrices where each matrix is the same as A but with a row that looks like x_i^t, we can easily show that $\det A = \sum_{j=1}^{n} a_{kj} A_{kj}$. ∎

Example 1.22. Let $n \geq 1$, and let $A_n = \begin{pmatrix} a_1^{n-1} & a_1^{n-2} & \ldots & a_1 & 1 \\ a_2^{n-1} & a_2^{n-2} & \ldots & a_2 & 1 \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ a_n^{n-1} & a_n^{n-2} & \ldots & a_n & 1 \end{pmatrix}$. Then, $\det A_n = \prod\limits_{1 \leq i \leq j \leq n} (a_i - a_j)$.

Proof. If $a_i = a_j$ for some $i \neq j$, then $\det A_n = 0$ as two rows are then identical. Hence, assume that the a_i's are distinct. Now construct

$$B_n = \begin{pmatrix} x_1^{n-1} & x_1^{n-2} & \ldots & x_1 & 1 \\ a_2^{n-1} & a_2^{n-2} & \ldots & a_2 & 1 \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ a_n^{n-1} & a_n^{n-2} & \ldots & a_n & 1 \end{pmatrix}. \tag{1.14}$$

Notice that $\det B_n \in F[x]$, where F is the field, and x is an indeterminate. $\det B$ is also of degree $(n-1)$; let us call this polynomial $f(x)$. Each of $a_2, \ldots, a_n$ are roots of $f(x)$, so $f(x)$ must be of the form $f(x) = C(x - a_2) \ldots (x - a_n)$. Equating coefficients of x^{n-1}, we get

$$C = \prod_{2 \leq i < j \leq n} (a_i - a_j) = \det \begin{pmatrix} a_2^{n-2} & \ldots & a_2 & 1 \\ \ldots & \ldots & \ldots & \ldots \\ a_n^{n-2} & \ldots & a_n & a_1 \end{pmatrix}. \tag{1.15}$$

Thus, we must have

$$f(x) = \left(\prod_{2 \le i < j \le n} (a_i - a_j) \right) (x - a_2) \cdots (x - a_n) \tag{1.16}$$

$$\implies \det A_n = f(1) = \prod_{1 \le i < j \le n} (a_i - a_j). \tag{1.17}$$

■

Example 1.23. Show that there exists a unique polynomial of degree n that takes arbitrary prescribed values at the $(n+1)$ points $x_0, x_1, \ldots, x_n$.

Chapter 2

EIGENVECTORS AND EIGENVALUES

2.1 Linear Transformers and an Introduction

Let $\mathcal{B} = (v_1, \dots, v_n)$ be a basis of vector space V and $\mathcal{C} = (w_1, \dots, w_n)$ be a basis of a vector space W. As these are bases, given a $v \in V$, there exists a unique $X \in F^n$ such that $v = \mathcal{B}X$, called the *coordinate vector* of v with respect to the basis $\mathcal{B}$. We note that since the mapping from a $v \in V$ to a $X \in F^n$ is linear in nature and is bijection, the vector spaces V and F^n are isomorphic to each other. Similarly, a mapping that takes $w \in W$ to $Y \in F^m$ shows that W and F^m are isomorphic to each other.

Now suppose that there exists a linear map that takes $v \mapsto Tv$ with $v \in V$ and $Tv \in W$. This transformer T is with respect to the bases $\mathcal{B}$ and $\mathcal{C}$ of V and W, respectively. We construct the $m \times n$ matrix A so that the j^{th} column of A is the coordinate vector of Tv_j with respect to the basis $\mathcal{C}$. We will then have $T(\mathcal{B}) = \mathcal{C}A$. For any vector $v \in V$, we have

$$
\begin{aligned}
& v = \mathcal{B}X = v_1 x_1 + \dots v_n x_n \\
\implies & T(v) = T(v_1)x_1 + \dots T(v_n)x_n = (T(v_1), \dots, T(v_n)) \begin{pmatrix} x_1 \\ x_2 \\ \dots \\ x_n \end{pmatrix} = T(\mathcal{B})X = (\mathcal{C}A)X \qquad (2.1) \\
& = (w_1, \dots, w_m)AX; \qquad (2.2)
\end{aligned}
$$

the coordinate vector of Tv with respect to the basis AX. In fact, if we denote the isomorphism from V to F^n by $\phi_{\mathcal{B}}$ and the isomorphism from W to F^m by $\phi_{\mathcal{C}}$, we get $\phi_{\mathcal{C}} \circ T = (\text{mult. by } A) \circ \phi_{\mathcal{B}}$.

The next theorem will be divided into two parts.

Theorem 2.1. 1. *The vector space form. Let $T : V \to W$ be a linear mapping between finite dimensional vector spaces V and W, of dimensions n and m respectively. There are bases $\mathcal{B}$ and $\mathcal{C}$ of V and W respectively such that the matrix of T with respect to the bases $\mathcal{B}$ and $\mathcal{C}$ looks like* $\begin{pmatrix} I_r & O_{r\times(n-r)} \\ O_{(m-r)\times r} & O_{(m-r)\times(n-r)} \end{pmatrix}_{m\times n}$.

2. *The matrix form. If A is a $m \times n$ matrix, then there exists an invertible matrix $Q_{m\times m}$ and an invertible matrix $P_{n\times n}$ such that $Q^{-1}AP$ is of the form $\begin{pmatrix} I_r & 0 \\ 0 & 0 \end{pmatrix}$, where r is the rank of A.*

3. *In fact, both these forms of the theorem are equivalent.*

Proof. 1. Let $(u_1, \dots, u_{n-r})$ be a basis of $\ker T$. We can extend this to a basis $\mathcal{B}$ by appending independent vectors that do not belong to the kernel of T, that is, $(v_1, \dots, v_r, u_1, \dots, u_{n-r})$. Let $(Tv_1, \dots, Tv_r)$ be a basis of $\text{Im}T$. We can extend this to a basis of W, say $\mathcal{C} = (w_1, \dots, w_r, w_{r+1}, \dots, w_m)$, where $w_i = Tv_i$ for $1 \leq i \leq r$. These bases are the desired ones.

2. P is a sequence of column operations, multipled to form a matrix, and Q^{-1} is a sequence of row operations, multiplied to form a matrix, that get the matrix A into the desired form. These are our desired P and Q.

3. Suppose the vector space form holds. Let A be a $m \times n$ matrix over F, with $A : F^n \to F^m$ defined as $X \mapsto AX$. There then exists a basis $\mathcal{B}$ of F^n and a basis $\mathcal{C}$ of F^m such that the linear map A with respect to ther bases $\mathcal{B}$ and $\mathcal{C}$ has the desired matrix. We then have $\mathcal{B} = I_n P_{n\times n}$ and $\mathcal{C} = I_m Q_{m\times m}$, with both P and Q invertible. We claim that the matrix of the linear mapping A with respect to the bases $\mathcal{B}$ and $\mathcal{C}$ is $Q^{-1}AP$.

■

January 16th.

Proposition 2.2.
1. *Let $T : V \to W$ be a linear map, and A the matrix of T with respect to the bases $\mathcal{C}$ and $\mathcal{C}$ of V and W respectively. Let $\mathcal{B}'$ and $\mathcal{C}'$ be new bases of V and W respectively, and let the change of basis matrices be given by $\mathcal{B}' = \mathcal{B}P$ and $\mathcal{C}' = \mathcal{C}Q$. Then the matrix of T with respect to $\mathcal{B}'$ and $\mathcal{C}'$ is $Q^{-1}AP$.*

2. *If $A' = Q_1^{-1}AP_1$, where P_1 and Q_1 are $n \times n$ and $m \times m$ invertible matrices, respectively, then A' is the matrix of T with respect to the bases $\mathcal{B}P_1$ and $\mathcal{C}Q_1$.*

Proof. Let the coordinate vector of v with respect to the basis $\mathcal{B}'$ be X'. We claim that the coordinate vector of Tv with respect to the basis $\mathcal{C}'$ is Y', where $Y' = (Q^{-1}AP)X'$. We assume that $\mathcal{B}' = \mathcal{B}P_{n\times n}$, $\mathcal{C}' = \mathcal{C}Q_{m\times m}$, and $T(\mathcal{B}) = \mathcal{C}A_{m\times n}$. If $v = \mathcal{B}X$, then $T(v) = \mathcal{C}(AX)$. If we let $v = \mathcal{B}'\mathcal{X}' = v_1'x_1' + \ldots + v_n'x_n'$, then

$$T(v) = \mathcal{C}'Y' = (\mathcal{C}Q)' = \mathcal{C}(QY') = \mathcal{C}(APX') \implies QY' = APX' \implies Y' = (Q^{-1}AP)X' \tag{2.3}$$

To prove the second part, we will show that the first part implies it. Let $A_{m\times n}$ be a matrix. Let T_A be the linear map from $\mathbb{R}^n \to \mathbb{R}^m$ given by multiplication by A, that is $T_A : \mathbb{R}^n \to \mathbb{R}^m$ given by $X \mapsto AX$. By the first part, there exist bases $P_{n\times n}$ and $Q_{m\times m}$, both invertible, such that with respect P and Q, the matrix of T_A looks like $\begin{pmatrix} I & O \\ O & O \end{pmatrix}$, that is, $Q^{-1}AP = \begin{pmatrix} I & O \\ O & O \end{pmatrix}$. ■

2.1.1 Linear Operators

Let $T : V_\mathcal{B} \to V_\mathcal{B}$. Let A be the matrix of T with respect to the basis $\mathcal{B}$. The other matrices of T with respect to new bases are $P^{-1}AP$, where $P_{n\times n}$ is invertible. Also, the fact that T is bijective, one-one, or onto are all equivalent for a finite dimensional vector space V.

2.1.2 Eigenvectors and Eigenvalues

Definition 2.3. A non-zero vector $v \in V$ is said to be an *eigenvector* of T if $T(v) = \lambda v$ for some $\lambda \in \mathbb{F}$. If A is a $n \times n$ matrix, a non-zero column vector X is said to be an eigenvector of A if $AX = \lambda X$ for some $\lambda \in \mathbb{F}$. λ, in both these cases, is called the *eigenvalue* of v and X respectively.

Usually, we always disregard the zero vector being an eigenvector. If v is an eigenvector of $T : V \to V$, and $v = \mathcal{B}X$ with respect to some basis $\mathcal{B}$ of V, then X is an eigenvector of the matrix of T with respect to the basis $\mathcal{B}$. In fact,

$$\mathcal{B}(AX) = (\mathcal{B}A)X = T(\mathcal{B})X = T(\mathcal{B}X) = Tv = \lambda v = \lambda\mathcal{B}X = \mathcal{B}(\lambda X) \implies AX = \lambda X. \tag{2.4}$$

The converse is also true; if X is an eigenvector of $A_{n\times n}$, then X is also an eigenvector of $T_A : \mathbb{R}^n \to \mathbb{R}^n$.

Proposition 2.4. *0 is an eigenvalue of $A_{n\times n}$ ($T : V \to V$) if and only if A (T) is non-invertible (not an isomorphism).*

Suppose v is an eigenvector of $T : V \to V$ with eigenvalue λ. Let W be the subspace spanned by v. Then every vector $w \in W$ is an eigenvector of T with eigenvalue λ. The proof of this is left as an exercise.

Definition 2.5. Two matrices $A'_{n\times n}$ and $A_{n\times n}$ are called *similar matrices* if there exists an invertible matrix $P_{n\times n}$ such that $P^{-1}AP = A'$.

Again let $T : V \to V$ be a linear operator, and let $\mathcal{B} = (v_1, \dots, v_n)$. Suppose, with respect to the basis $\mathcal{B}$, the matrix of T is $\begin{pmatrix} \lambda_1 & \dots & \dots & \dots \\ 0 & \dots & \dots & \dots \\ \dots & \dots & \dots & \dots \\ 0 & \dots & \dots & \dots \end{pmatrix}$. Then v_1 is an eigenvector with eigenvalue λ_1.

2.2 Finding Eigenvalues and Eigenvectors

January 21st.

Let $T : V \to V$ and let $\mathcal{B} = (v_1, \dots, v_n)$ be a basis of V. Then the matrix of T with respect to the basis $\mathcal{B}$ is a diagonal matrix if and only if each of the basis elements is an eigenvector. An equivalent statement for matrices is that an $n \times n$ matrix A is similar to a diagonal matrix if and only if $\mathbb{F}^n$ admits a basis consisting of eigenvectors of A. The proof of this is left as an exercise to the reader.

We can now discuss the computation. For a linear operator $T : V \to V$, λ is an eigenvalue of T if and only if there exists a non-zero vector v such that $Tv = \lambda v$. This can be rearranged to give

$$(\lambda I_v - T)v = 0. \tag{2.5}$$

We can now consider $\lambda I_v - T : V \to V$ to be a linear operator which maps $v \mapsto \lambda v - Tv$. If eigenvalues exist, this operator is a singular operator, that is, it contains a non-trivial kernel. The matrix of the operator $\lambda I_v - T$ comes out to be $\lambda I_n - A$, where A is the matrix of T with respect to the basis $\mathcal{B}$. This matrix is now singular, so we must have

$$\det(\lambda I_n - A) = 0. \tag{2.6}$$

The equation $\det(\lambda I_n - A)$ is called the *characteristic polynomial* of A, and also $T(?)$. The roots of this polynomial in λ which lie in $\mathbb{F}$ are the eigenvalues of A, and T as well.

We would now like to show that similar matrices have the same eigenvalues, that is,

$$\det(\lambda I_n - P^{-1}AP) = \det(\lambda I_n - A). \tag{2.7}$$

This is simple to see as $\det(\lambda I_n - P^{-1}AP) = \det(P^{-1}(\lambda I_n - A)P) = \det P^{-1} \cdot \det(\lambda I_n - A) \cdot \det P = \det(\lambda I_n - A)$. The found out eigenvalues from this equation can then be put back and solved for v to get the corresponding eigenvectors.

Proposition 2.6. *Let $\lambda_1, \dots, \lambda_r$ be distinct eigenvalues of $T : V \to V$ and let $v_1, \dots, v_r$ be the corresponding eigenvectors of T. Then $(v_1, \dots, v_r)$ is a linearly independent set in V.*

Proof. We claim that this is true for $r = 1, 2$. Using a form of induciton, we will assume the result for $r - 1$. Begin with

$$\begin{aligned} \alpha_1 v_1 + \ldots + \alpha_r v_r &= 0 \\ \implies \alpha_1 T v_1 + \ldots + \alpha_r T v_r &= 0 \\ \implies \alpha_1 \lambda_1 v_1 + \ldots + \alpha_r \lambda_r v_r &= 0. \end{aligned} \tag{2.8}$$

Multiplying the first equation by λ_1 and subtracting it from the current equation, we have

$$\begin{aligned} (\alpha_2\lambda_2 - \alpha_2\lambda_1)v_2 + (\alpha_3\lambda_3 - \alpha_3\lambda_1)v_3 + \ldots + (\alpha_r\lambda_r - \alpha_r\lambda_1)v_r &= 0 \\ \implies \alpha_2(\lambda_2 - \lambda_1) + \alpha - 3(\lambda_3 - \lambda_1)v_3 + \ldots + \alpha_r(\lambda_r - \lambda_1)v_r &= 0. \end{aligned} \tag{2.9}$$

By hypothesis, $\alpha_j(\lambda_j - \lambda_1) = 0$. As the eigenvalues are distinct, we must have $\alpha_j = 0$ for $j = 2, 3, \dots, r$. We are left with $\alpha_1 v_1 = 0$, which gives us $\alpha_1 = 0$. ■

When the n eigenvalues found of A are distinct, the corresponding eigenvectors $v_1, \dots, v_n$ are linearly independent in $\mathbb{F}^n$, and hence $\mathcal{B} = (v_1, \dots, v_n)$ is a basis of $\mathbb{F}^n$. The matrix $P^{-1}AP$ is the matrix of the linear operator $T_A : \mathbb{F}^n \to \mathbb{F}^n$ with respect to the basis $\mathcal{B}$, with the column of P being the eigenvectors $v_1, \dots, v_n$. As $\mathcal{B}$ consists of only eigenvectors, $P^{-1}AP$ is a diagonal matrix with the diagonal entries being the n eigenvalues.

We now define the determinant and trace for a linear operator. For such an operator T, $\mathrm{tr}T = \mathrm{tr}A$ where A is a matrix of T with respect to some abitrary basis. Note that since $\mathrm{tr}(P^{-1}AP) = \mathrm{tr}(APP^{-1}) = \mathrm{tr}A$, the choice of basis is not important. Similarly, we define $\det T = \det A$.

We can now have a closer look at the characteristic equation. To find the constant term of $\det(xI - A)$, we simply plug in $x = 0$ to give us $\det(-A) = (-1)^n \det A$. The coefficient of x^{n-1} in $\det(xI - A)$ is $-\mathrm{tr}A$ as the coefficients of x^{n-1} come solely from the expansion of $(x - a_{11})(x - a_{22}) \cdots (x - a_{nn})$. Clearly, we can conclude that the sum of the eigenvalues is $\mathrm{tr}A$ and the product of the eigenvalues is $\det A$.

2.2.1 Eigenspace

January 23rd.

For ease, let us denote $\chi_T(x)$ to mean $\det(xI - A)$. The *eigenspace* for a given eigenvalue λ is defined as

$$E_\lambda = \{v \in V : Tv = \lambda v\}. \tag{2.10}$$

This is a subspace of the vector space V. The *geometric multiplicity* of λ is defined as the dimension of E_λ. This geometric multiplicity of λ is always less than or equal to its algebraic multiplicity in $\chi_T(x)$. For recall, the *algebraic multiplicity* of λ is the highest power of $(x-\lambda)$ that divides $\chi_T(x)$.

Theorem 2.7. *Let λ be an eigenvalue of $T : V \to V$. Then the geometric multiplicity of λ is always less than or equal to its algebraic multiplicity.*

Proof. Let k me the geometric multiplicity of λ. Let $(v_1, \ldots, v_k)$ be an ordered basis of E_λ. Extend this to a basis $\mathcal{B} = (v_1, \ldots, v_k, u_1, \ldots, u_{n-k})$ of V. The matrix of T with respect to the basis $\mathcal{B}$ is of the form $A = \begin{pmatrix} \lambda I_k & B \\ O & D \end{pmatrix}$. Thus, the characteristic polynomial looks like

$$\chi_T(x) = \det(xI_n - A) = \det \begin{pmatrix} (x-\lambda)I_k & -B \\ O & xI_{n-k} - D \end{pmatrix} = (x-\lambda)^k \cdot \det(XI_{n-k} - D). \tag{2.11}$$

This shows that $(x-\lambda)^k$ divides $\chi_T(x)$, so we must have an algebraic multiplicity greater than or equal to this k. ■

2.3 Diagonalizability

We first define what this means for a linear mapping from V to V.

Definition 2.8. A linear operator $T : V \to V$ is said to be a *diagonizable linear operator* if there exists a basis of V consisting of eigenvectors of T. This means that the matrix of T with respect to this basis if a digaonal matrix and the matrix of T with respect to any other basis is similar to this diagonal matrix.

A similar definition works for matrices.

Definition 2.9. An $n \times n$ matrix A over $\mathbb{F}$ is said to be a *diagonizable matrix* if A is similar to a diagonal matrix. Equivalently, $\mathbb{F}^n$ then admits a basis consisting of eigenvectors of A, thinking of $T_A : \mathbb{F}^n \to \mathbb{F}^n$ as a linear operator.

Now let us suppose that T is diagonizable. Let $\lambda_1, \lambda_2, \ldots, \lambda_k$ be the distinct eigenvalues of T. There then exists an ordered basis consisting of eigenvectors of T and with respect to this basis, the matrix of T is a diagonal matrix with diagonal entries consisting solely of $\lambda_1, \lambda_2, \ldots, \lambda_k$.

If λ_i is of algebraic multiplicity d_i, then the matrix of T looks like $\begin{pmatrix} \lambda_1 I_{d_1} & & & \\ & \lambda_2 I_{d_2} & & \\ & & \cdots & \\ & & & \lambda_k I_{d_k} \end{pmatrix}$.
Thus, the characteristic polynomial then looks like $(x-\lambda_1)^{d_1}(x-\lambda_2)^{d_2} \cdots (x-\lambda_k)^{d_k}$.

The geometric multiplicity of λ_i is the dimension of E_{λ_i}, that is, the nullity of the operator $(\lambda_i I_n - A)$. But here, $\ker(\lambda_i I_n - A) = d_i$, which is just the algebraic multiplicity of λ_i. Hence, if T is diagonizable, then each eigenvalue of it has the same algebraic multiplicity and geometric multiplicity.

Proposition 2.10. *If $E_{\lambda_1}, \ldots, E_{\lambda_k}$ are the eigenspaces corresponding to the distinct eigenvalues, say, $\lambda_1, \ldots, \lambda_k$ of T, then $E = E_{\lambda_1} + \cdots + E_{\lambda_k}$ is a direct sum.*

Proof. It is enough to show that $E_{\lambda_1}, \ldots, E_{\lambda_k}$ are independent. Let $v_1 + v_2 + \ldots + v_k = 0$, where $v_i \in E_{\lambda_i}$. As $v_1, v_2, \ldots, v_k$ come from distinct eigenspaces, they are linearly independent, and our equation must imply that $v_1 = \ldots = v_k = 0$. ■

Proposition 2.11. *If T is a diagonizable operator, and if $\lambda_1, \ldots, \lambda_k$ are the distinct eigenvalues of T, then*

$$V = E_{\lambda_1} \oplus \ldots \oplus E_{\lambda_k}. \tag{2.12}$$

Proof. As T is diagonizable, the algebraic and geometric multiplicities are equal for all the eigenvalues λ_i. Denote $\dim E_{\lambda_i} = d_i$. As $\chi_T(x)$ completely factors into linear factors, due to T being diagonizable, we have $n = d_1 + \ldots + d_k$. Also, $E_{\lambda_1} + \ldots + E_{\lambda_k}$ is a direct sum, that is,

$$\dim(E_{\lambda_1} + \ldots + E_{\lambda_k}) = \dim E_{\lambda_1} + \ldots + \dim E_{\lambda_k} = n. \tag{2.13}$$

This direct sum is a subspace of V and has the dimension as V. This mut mean that the direct sum is exactly V. ■

Theorem 2.12. *Let T be a linear operator on a finite dimensional vector space V, and let $\lambda_1, \ldots, \lambda_k$ be the distinct eigenvalues of T. Also let E_{λ_i} be the eigenspace of λ_i. Then, the following are equivalent.*

- *T is diagonizable,*
- *$\chi_T(x) = (x - \lambda_1)^{d_1} \cdots (x - \lambda_k)^{d_k}$ and $\dim E_{\lambda_i} = d_i$,*
- *$V = E_{\lambda_1} \oplus \ldots \oplus E_{\lambda_k}$.*

2.4 Polynomials

January 28th.

Let $\mathbb{F}[x]$ denote the set of all polynomials with coefficients coming from the field $\mathbb{F}$. With respect to the addition, it is an Abelian group. The multiplication here is associative, commutative, and distributive; there also exists a multiplicative identity. This makes $\mathbb{F}[x]$ into a commutative ring. Note that $\mathbb{F}[x]$ is also an infinite dimensional vector space over $\mathbb{F}$, since scalar multiplication is also defined. Together, these combine to form an algebra over the field.

Definition 2.13. Let $d \in \mathbb{F}[x]$ with $d \neq 0$. For $f \in \mathbb{F}[x]$, we say that d divides f if there exists a $q \in \mathbb{F}[x]$ such that $f = dq$ in $\mathbb{F}[x]$.

Corollary 2.14. *For $f \in \mathbb{F}[x]$, $f(c) = 0$ if and only if $x - c$ divides $f(x)$.*

Corollary 2.15. *A polynomial $f \in \mathbb{F}[x]$ of degree n has at most n roots in $\mathbb{F}$.*

Proof. The proof is by induction. Note that this is true for $n = 0, 1$. If α is a root, then $f(x) = (x-\alpha)\cdot q(x)$. As $q(x)$ is of degree $n - 1$, and all roots of $q(x)$ are root of $f(x)$, this follows by hypothesis. ■

Definition 2.16. An *ideal* of $\mathbb{F}[x]$ is a subspace of $\mathbb{F}[x]$, say I, such that if $f \in I$ and $g \in \mathbb{F}[x]$, then $fg \in I$.

Example 2.17. Let $f \in \mathbb{F}[x]$. Define $I_f = \langle f \rangle = \{fg : g \in \mathbb{F}[x]\}$. Note that I_f is called a *principal ideal*, that is, it is an ideal generated by a single element.

Theorem 2.18. *$\mathbb{F}[x]$ is a principal ideal domain, that is, every ideal in $\mathbb{F}[x]$ is a principal ideal.*

Proof. Let d be a polynomial of least degree in the ideal I, where I is a non-zero ideal. Let, without loss of generatlity, d be monic (if not, simply multiply it by a sutitable scalar).

Let $f \in I$. Then there exists $q, r \in \mathbb{F}[x]$ such that $f = dq + r$ and either $r = 0$ or $\deg r < \deg d$. Note that since $f, d \in I$, $dq \in I$, so $f - dq \in I \implies r \in I$. As d was of minimal degree in I, we must have $r = 0$. Thus, $f = dq$ and, thus, $I = \langle d \rangle$. ■

If I is an ideal of $\mathbb{F}[x]$, then there exists a unique polynomial $d \in I$ such that $I = \langle d \rangle$.

2.4.1 Interaction with Linear Operators

Let $f \in \mathbb{F}[x]$, and let $T : V \to V$ be a linear mapping. If

$$f(x) = a_0 + a_1 x + \ldots + a_k x^k$$

with $a_k \neq 0$, we define

$$f(T) = a_0 I_n + a_1 T + \ldots + a_k T^k.$$

Note that $f(T)$ is also a linear mapping from V to V. Let I be the set of all $f \in \mathbb{F}[x]$ such that $f(T)$ is the zero operator. All such polynomials are called *annihilator*s. I satisfies the properties of a vector space; it is a subspace of the space of all polynomials. I is also an ideal of $\mathbb{F}[x]$.

Definition 2.19. The *minimal polynomial* of the linear operator $T : V \to V$ is the generator of the ideal of annihilators.

Denote the minimal polynomial by $m_T(x)$. So, $m_T(x)$ is

1. monic,
2. of least degree among all annihilators of T.

If A is a $n \times n$ matrix, the minimal polynomial of A is defined as the unique monic polynomial $m_A(x)$ of least degree such that $m_A(A) = O_{n\times n}$. It can be verified that if A is the matrix of a linear operator $T : V \to V$ and if $f \in \mathbb{F}[x]$, then the matrix of the operator $f(T) : V \to V$ is $f(A)$ with respect to the same basis. It follows that the minimal polynomial of T is same as the minimal polynomial of a matrix of T.

Note that T belongs to $\mathrm{Hom}_{\mathbb{F}}(V, V)$, which is of dimension n^2. Thus, $I, T, T^2, \dots, T^{n^2}$ is a linearly dependent set and there exist scalars $a_0, a_2, \dots, a_{n^2}$ such that

$$a_0 I + a_1 T + a_2 T^2 + \dots + a_{n^2} T^n = O. \tag{2.14}$$

So, an annihilator of T is

$$f(x) = a_0 + a_1 x + a_2 x^2 + \dots + a_{n^2} x^{n^2}$$

and we must have $\deg m_T(x) \le n^2$.

Theorem 2.20. *Let $T : V \to V$ with n the dimension of the space V. The characteristic polynomial of T and the minimal polynomial of T have the same roots, except (possibly) for the multiplicities.*

Proof. We claim that $m_T(c) = 0$ if and only if c is an eigenvalue. Let $m_T(c) = 0$. Thus, $m_T(c) = (x - c) \cdot q(x)$, with $q \in \mathbb{F}[x]$ and $\deg q < \deg m$. Also, $q(T)$ is *not* the zero operator. So, there exists a $u \in V$ (non-zero vector) such that $q(T)(u) = v \neq 0$. Then,

$$0 = m(T)(u) = (T - cI) \cdot q(T)(u) = (T - cI)v \tag{2.15}$$

which shows that v is an eigenvector of T with eigenvalue c. So all roots of $m_T(x)$ are roots of the characteristic polynomial.

Conversely, let c be an eigenvalue of T. Say, $Tv = cv$ for some $v \neq 0$. Thus, $m_T(T)(v) = m(c)(v)$. But $m_T(T) = 0$ must mean that $0 = m(c)(v)$, and $m(c) = 0$. So every root of the characteristic polynomial is a root of the minimal polynomial. ■

January 30th.

Proposition 2.21. *If λ is an eigenvalue of T, then $f(\lambda)$ is an eigenvalue of $f(T)$ for $f \in \mathbb{F}[x]$.*

Proof. The proof is left as an exercise to the reader. ■

Proposition 2.22. *Let $T : V \to V$ be a diagonizable operator. The minimal polynomial is the product of distinct linear factors, that is, if*

$$\chi_T(x) = \prod_{i=1}^{k} (x - \lambda_i)^{d_i}$$

where the λ_i's are the distinct eigenvalues, then

$$m_T(x) = \prod_{i=1}^{k} (x - \lambda_i).$$

Proof. As T is a diagonalizable operator, there exists a basis of V consisting of eigenvectors of T, say $\mathcal{B} = (v_1, v_2, \dots, v_n)$. Note that $m_T(T)v_i = 0$ for all valid i. For each $v_i \in \mathcal{B}$, there exists a λ_i such that $(T - \lambda_i I)v_i = 0$, which tells us

$$m_T(T) = (T - \lambda_1 I)(T - \lambda_2 I) \cdots (T - \lambda_k I)v_i = 0. \tag{2.16}$$

Hence, $m_T(x)$ is an annihilator for T, and it is of minimal degree by the above theorem. ■

Theorem 2.23 (*Cayley-Hamilton theorem*)**.** *Let $T : V \to V$ be a linear operator on a finite dimensional vector space V. If $\chi_T(x)$ is the characteristic polynomial of T, then $\chi_T(T) = 0$, that is, the characteristic polynomial annihilates T. Hence, the minimal polynomial of T divides the characteristic polynomial.*

Proof. Let $\mathcal{B} = (v_1, v_2, \ldots, v_n)$ be a basis of V, and let $A = (a_{ij})$ be the matrix of T with respect to the basis $\mathcal{B}$. We have

$$\begin{aligned} a_{1j}v_1 + a_{2j}v_2 + \ldots + a_{nj}v_{nj} &= Tv_j \\ \implies -a_{1j}v_1 - a_{2j}v_2 - \ldots + (T - a_{jj})v_j - a_{(j+1)(j)}v_{j+1} - \ldots - a_{nj}v_n &= 0. \end{aligned} \tag{2.17}$$

This sysmte of equations can be written as

$$B_{n\times n}\begin{pmatrix} v_1 \\ \vdots \\ v_n \end{pmatrix} = \begin{pmatrix} 0 \\ \vdots \\ 0 \end{pmatrix} \tag{2.18}$$

where

$$B = \begin{pmatrix} T - a_{11}I & -a_{21} & \cdots & -a_{n1} \\ -a_{12} & T - a_{22}I & \cdots & -a_{n2} \\ \vdots & \vdots & \ddots & \vdots \\ -a_{1n} & -a_{2n} & \cdots & T - a_{nn}I \end{pmatrix}. \tag{2.19}$$

Therefore $\det B = \chi_T(T)$. It is enough to show that $\det B = 0$ as an operator, that is, to show $\det B(b_i) = 0$ for all $v_i \in \mathcal{B}$. Let $(\text{adj}B)_{ij} = c_{ij}$, and $(B)_{ij} = b_{ij}$. Note that

$$\sum_{k=1}^{n} c_{ik}b_{kj} = \begin{cases} \det B & \text{if } i = j, \\ 0 & \text{if otherwise.} \end{cases}$$

Now,

$$\begin{aligned} &\sum_{j=1}^{n} b_{kj}v_j = 0 \text{ for all } 1 \le k \le n \\ \implies &\sum_{j=1}^{n} b_{kj}v_j = 0. \end{aligned}$$

Summing over all rows,

$$\begin{aligned} &\sum_{k=1}^{n}\left(\sum_{j=1}^{n} c_{ik}b_{kj}v_j\right) = 0 \\ \implies &\sum_{j=1}^{n}\left(\sum_{k=1}^{n} c_{ik}b_{kj}\right)v_j = 0. \end{aligned} \tag{2.20}$$

The left hand side is zero except for when $i = j$, in which case it is $\det B$—

$$0 = \sum_{j=1}^{n}\left(\sum_{k=1}^{n} c_{ik}b_{kj}\right)v_j = (\det B)v_i \tag{2.21}$$

which implies that the operator $\det B$ is zero on all the basis vectors, and hence it is the zero vecotr. Thus, since $\chi_T(T) = \det B$, $\chi_T(T)$ is also the zero operator. ∎

February 4th.

Proposition 2.24. *If the minimal polynomial $m_T(x) \in \mathbb{F}[x]$ of a linear operator $T : V \to V$ splits into distinct linear factors, then T is diagonalizable.*

Proof. Let $m_T(x) = (x - \lambda_1)(x - \lambda_2)\cdots(x - \lambda_k)$ where the λ_i's are distinct. We are to show that $V = E_{\lambda_1} \oplus \ldots \oplus E_{\lambda_k}$. We wish to find polynomials $h_1(x), \ldots, h_k(x)$ such that

1. $h_1(x) + \ldots + h_k(x) = 1$,
2. $(x - \lambda_i) \cdot h_i(x)$ is divisible by $m_T(x)$ for all $1 \le i \le k$.

The second condition implies that $(T - \lambda_i I) \cdot h_i(T)$ is the zero operator. The first condition implies that $\sum_{i=1}^{k} h_i(T)(v) = v$. But the second condition again implies that $h_i(T)(v)$ is an eigenvector corresponding to λ_i, that is, $h_i(T)(v) \in E_{\lambda_i}$. If we can find these h_i's satisfying the two conditions then we can say that V is the direct sum of the eigenspaces.

For $1 \le i \le k$, let $f_i(x) = \frac{m_T(x)}{(x-\lambda_i)} = \prod_{j \ne i}(x - \lambda_j)$. As the λ_i's are distinct, the f_i's are relatively prime, so there exist $g_1, \ldots, g_k$ such that

$$f_1(x)g_1(x) + \ldots + f_k(x)g_k(x) = 1. \tag{2.22}$$

Let $h_i(x) = f_i(x)g_i(x)$ for all $1 \le i \le k$. Both the conditions hold, and the result follows. ■

Corollary 2.25. *Let $T : V \to V$ be a linear operator on a finite dimensional complex vector space such that $T^m = I$ for some positive integral m. Then T is diagonalizable.*

Proposition 2.26. *Let $T : V \to V$ be linear operator, and let U be an invariant subspace of T, that is, $T(U) \subseteq U$ (or equivalently, $T(u) \in U$ for all $u \in U$). The minimal polynomial $m_{T|_U}(x)$ of the operator $T|_U : U \to U$ divides the minimal polynomial $m_T(x)$ of the operator $T : V \to V$ in $\mathbb{F}[x]$.*

Proof. Note that $m_T(T)(u) = 0$ for all $u \in U$ as $U \subseteq V$. Thus, $m_T(T) = 0$ on the subspace U. So $m_T(x)$ annihilates $T|_U$. So, as $m_{T|_U}(x)$ is the minimal polynomial of $T|_U$, it should divide all annihilators of $T|_U$ and thus divides $m_T(x)$ in $\mathbb{F}[x]$. ■

2.5 Triangularizability

A similar definition works as in the case of diagonalizability.

Definition 2.27. A linear operator $T : V \to V$ is said to be a *triangularizable linear operator* if there exists a basis of V with respect to which the matrix of T is a triangular matrix, be it upper or lower.

If our basis is $\mathcal{B} = (v_1, v_2, \ldots, v_n)$, then we can show that $Tv_k \in \operatorname{span}(v_1, \ldots, v_k)$.

Theorem 2.28. *A linear operator $T : V \to V$ is triangularizable if and only if the minimal polynomial splits into linear factors.*

Proof. Let $T : V \to V$ be triangularizable, that is, there exists a basis with respect to which the matrix of T is a triangular matrix, with diagonal entries $\lambda_1, \ldots, \lambda_n$, say. Then the characteristic polynomial of T is $(x - \lambda_1)(x - \lambda_2) \cdots (x - \lambda_n)$ where the λ_i's are not necessarily distinct. But $m_T(x)$ divides $\chi_T(x)$, hence is again a product of linear factors.

Conversely, let $m_T(x) = (x - \lambda_1)(x - \lambda_2) \cdots (x - \lambda_k)$ where the λ_i's are not necessarily distinct. We prove by induction on the number of factors of $m_T(x)$. If $k = 1$, then $m_T(x) = x - \lambda_1$; as $m_T(T) = 0$, $T = \lambda_1 I$, matrix of T is the scalar matrix. Now let $k > 1$, and let the result hold for smaller positive integers. Let $U = \operatorname{Im}(T - \lambda_k I)$. We find that U is a proper subspace of V. Note that U is an invariant subspace of T; if we let $u = (T - \lambda_k I)(v)$ for some $v \in V$, then

$$T(u) = T(T - \lambda_k I)(v) = (T - \lambda_k I)T(v) \in U. \tag{2.23}$$

The minimal polynomial $m_{T|_U}(x)$ of $T|_U$ divides $m_T(x)$, and hence $m_{T|_U}(x) = (x - \alpha_1) \cdots (x - \alpha_l)$, where $l \le k$, and $\alpha_1, \ldots, \alpha_l \in \{\lambda_1, \ldots, \lambda_k\}$. By hypothesis, $T|_U$ is triangularizable. So there exists a basis of U, say $(u_1, \ldots, u_m)$ with respect to which the matrix of $T|_U$ is a triangular matrix. So $T|_U(u_k) \in \operatorname{span}(u_1, \ldots, u_k)$. Extend this to a basis $\mathcal{B} = (u_1, \ldots, u_m, v_{m+1}, \ldots, v_n)$. If we rewrite $Tv_j = (T - \lambda_k I)v_j + \lambda_k I v_j$, we see that $(T - \lambda_k I)v_j \in U = \operatorname{span}(u_1, \ldots, u_m)$, and $Tv_j \in \operatorname{span}(u_1, \ldots, u_m, v_j)$; the matrix of T with respect to $\mathcal{B}$ is a triangular matrix. ■

Corollary 2.29. *Every operator $T : V \to V$, where V is a complex finite dimensional vector space, is triangularizable.*

2.5.1 Determinant of Partitioned Matrices

Proposition 2.30. *Let* $\Gamma = \begin{pmatrix} A & O \\ O & I \end{pmatrix}$ *or* $\Gamma = \begin{pmatrix} I & O \\ O & A \end{pmatrix}$*, where A is a square matrix. Then we necessarily have* $\det \Gamma = \det A$.

Proof. Let Γ be of order $(n+1) \times (n+1)$ and A be of order $n \times n$. By definition,

$$\det \Gamma = \sum_{\sigma \in S_{n+1}} \epsilon(\sigma) g_{1\sigma(1)} \cdots g_{(n+1)\sigma(n+1)}. \tag{2.24}$$

Note that $g_{(n+1)\sigma(n+1)}$ is 1 if $\sigma(n+1) = n+1$, and 0 otherwise. Also, $\epsilon(\sigma)$ remains the same when σ is considered to be an element of S_n. Thus,

$$\det \Gamma = \sum_{\sigma \in S_n} \epsilon(\sigma) g_{1\sigma(1)} \cdots g_{n\sigma(n)} = \det A. \tag{2.25}$$

Iterating this, we get the desired result. A similar proof works for the other type of matrix stated. ■

Proposition 2.31. *Let* $\Gamma = \begin{pmatrix} A & B \\ O & D \end{pmatrix}$ *where A and D are square matrices. Then we necessarily have* $\det \Gamma = \det A \cdot \det D$.

Proof. Let the orders be $A_{k\times k}$, $D_{l\times l}$, $B_{k\times l}$ and $O_{l\times k}$. Note that Γ can be broken up as

$$\Gamma = \begin{pmatrix} I_k & O_{k\times l} \\ O_{l\times k} & D_{l\times l} \end{pmatrix} \begin{pmatrix} I_k & B_{k\times l} \\ O_{l\times k} & I_l \end{pmatrix} \begin{pmatrix} A_{k\times k} & O_{k\times l} \\ O_{l\times k} & I_l \end{pmatrix}. \tag{2.26}$$

The determinant is multiplicative, so $\det \Gamma = \det D \cdot \det A$ as the determinant of the middle matrix can be shown to be 1. ■

Proposition 2.32. *Let* $\Gamma = \begin{pmatrix} A & B \\ C & D \end{pmatrix}$ *where A and D are square matrices. If A is invertible, then we necessarily have* $\det \Gamma = \det A \cdot \det(D - CA^{-1}B)$.

Proof. Again, we break down Γ.

$$\Gamma = \begin{pmatrix} I & O \\ CA^{-1} & I \end{pmatrix} \begin{pmatrix} A & O \\ O & D - CA^{-1}B \end{pmatrix} \begin{pmatrix} I & A^{-1}B \\ O & I \end{pmatrix}. \tag{2.27}$$

From here, it is clear that $\det \Gamma = \det A \cdot \det(D - CA^{-1}B)$. ■

Proposition 2.33. *Let* $\Gamma = \begin{pmatrix} A & B \\ C & D \end{pmatrix}$ *where A and D are square matrices. If D is invertible, then we necessarily have* $\det \Gamma = \det D \cdot \det(A - BD^{-1}C)$.

Proof. Yet again, we break down Γ.

$$\Gamma = \begin{pmatrix} I & BD^{-1} \\ O & I \end{pmatrix} \begin{pmatrix} A - BD^{-1}C & O \\ O & D \end{pmatrix} \begin{pmatrix} I & O \\ D^{-1}C & I \end{pmatrix}. \tag{2.28}$$

From here, it is clear that $\det \Gamma = \det D \cdot \det(A - BD^{-1}C)$. ■

2.6 On the Characteristic and Minimal Polynomials

February 6th.

Theorem 2.34. *Let A be a $m \times n$ matrix and B be a $n \times m$ matrix with $m \leq n$. Then,*

$$\chi_{BA}(x) = x^{n-m} \chi_{AB}(x). \tag{2.29}$$

Proof. Note that there exist non-singular matrices P and Q such that $PAQ = \begin{pmatrix} I_r & O \\ O & O \end{pmatrix}$, where r is the rank of A. Partition $Q^{-1}BP^{-1}$ as $\begin{pmatrix} C & D \\ E & G \end{pmatrix}$ where C is of order $r \times r$, with the other submatrices being of appropriate order. Then,

$$PABP^{-1} = PAQQ^{-1}BP^{-1} = \begin{pmatrix} I_r & O \\ O & O \end{pmatrix} \begin{pmatrix} C_{r\times r} & D \\ E & G \end{pmatrix} = \begin{pmatrix} C & D \\ O & O \end{pmatrix}. \tag{2.30}$$

Similarly,

$$Q^{-1}BAQ = Q^{-1}BP^{-1}PAQ = \begin{pmatrix} C_{r\times r} & D \\ E & G \end{pmatrix} \begin{pmatrix} I_r & O \\ O & O \end{pmatrix} = \begin{pmatrix} C & O \\ E & O \end{pmatrix}. \tag{2.31}$$

Thus,

$$\chi_{AB}(x) = \chi_{PABP^{-1}}(x) = \det \begin{pmatrix} xI_r - C & -D \\ O & xI \end{pmatrix} = x^{m-r}\det(xI - C) \tag{2.32}$$

and

$$\chi_{BA}(x) = \chi_{Q^{-1}BAQ}(x) = \det \begin{pmatrix} xI - C & O \\ -E & xI \end{pmatrix} = x^{n-r}\det(xI - C) \tag{2.33}$$

which tells us that $\chi_{BA}(x) = x^{n-m}\chi_{AB}(x)$. ■

1. Suppose $T : V \to V$ and $U \subseteq V$.
   (a) If $U \subseteq \ker T$, then U is T-invariant.
   (b) If $T(V) \subseteq U$, then U is T-invariant.
2. If $V_1, \ldots, V_m$ are T-invariant subspaces, then $V_1 + \ldots + V_m$ is T-invariant.
3. Let $P : V \to V$ be a linear operator such that $P^2 = P$; then the eigenvalues of P are 0 or 1.
4. Let $T : V \to V$ be an invertible operator. Then λ is an eigenvalue of T if and only if $\frac{1}{\lambda}$ is an eigenvalue of T^{-1}.
5. Let $T : V \to V$, with $0 \neq v \in V$. Then $W = \text{span}(v, Tv, T^2v, \ldots)$ is T-invariant, and is the smallest T-invariant subspace of V containing v.
6. Let $T : V \to V$ and rank$T = k \leq n$, where n is the dimension of V. Then T has at most $k + 1$ distinct eigenvalues.
7.

Chapter 3

INNER PRODUCT SPACES

February 13th.

3.1 An Introduction

The function $\langle , \rangle : \mathbb{R}^n \times \mathbb{R}^n \to \mathbb{R}$ defined as

$$\langle X, Y \rangle = x_1 y_1 + x_2 y_2 + \ldots + x_n y_n \tag{3.1}$$

is called an inner product. Specifically, this is the dot product on the vector space over the reals. It satisfies the following properties;

1. $\langle X, X \rangle \geq 0$ for all $X \in \mathbb{R}^n$.
2. $\langle X, X \rangle = 0$ if and only if $X = 0$.
3. $\langle X, Y \rangle = \langle Y, X \rangle$.
4. $\langle X_1 + X_2, Y \rangle = \langle X_1, Y \rangle + \langle X_2, Y \rangle$.
5. $\langle \alpha X, Y \rangle = \alpha \langle X, Y \rangle$.

In $\mathbb{C}^n$, we have the product

$$\langle Z, W \rangle = z_1 \overline{w_1} + z_2 \overline{w_2} + \ldots + z_n \overline{w_n}. \tag{3.2}$$

This satisfies the properties—

1. $\langle Z, Z \rangle \geq 0$.
2. $\langle Z, Z \rangle = 0$ if and only if $Z = 0$.
3. $\langle Z, W \rangle = \overline{\langle W, Z \rangle}$.
4. $\langle Z_1 + Z_2, W \rangle = \langle Z_1, W \rangle + \langle Z_2, W \rangle$.
5. $\langle \alpha Z, W \rangle = \alpha \langle Z, W \rangle$.

These properties are, respectively, called the positivity, the definiteness, the conjugate symmetry, the additivity, and the homogeneity of the inner product over the complex vector space. We now define a general inner product.

Let the underlying field be either $\mathbb{R}$ or $\mathbb{C}$, and let V be a vector space over this field. An *inner product* on V is simply a function $\langle , \rangle : V \times V \to \mathbb{F}$ such that it satisfies the following properties for all $v, u, v_1, v_2 \in V$ and $\alpha \in \mathbb{F}$—

1. $\langle v, v \rangle \geq 0$,
2. $\langle v, v \rangle = 0$ if and only if $v = 0$,

3. $\langle v_1 + v_2, u \rangle = \langle v_1, u \rangle + \langle v_2, u \rangle$,
4. $\langle \alpha v, u \rangle = \alpha \langle v, u \rangle$, and
5. $\langle v, u \rangle = \overline{\langle u, v \rangle}$.

A vector space over $\mathbb{F}$, $\mathbb{F}$ being either $\mathbb{R}$ or $\mathbb{C}$, is called an *inner product space* if V is equipped with a valid inner product. As seen earlier, on $\mathbb{R}^n$, the usual dot product makes $\mathbb{R}^n$ an inner product space. As another example, if V is the space of all real valued continuous function $f : (-1, 1) \to \mathbb{R}$, then the inner product on here can be defined as

$$\langle f, g \rangle = \int_{-1}^{1} f(x)g(x)dx. \tag{3.3}$$

On $\mathbb{C}^{m\times n}$, we can define the inner product as

$$\langle A, B \rangle = \mathrm{tr}(B^* A). \tag{3.4}$$

Every inner product $\langle u, v \rangle$ for any vector space V will look like

$$\langle u, v \rangle = Y^* A X, \tag{3.5}$$

where Y and X are the coordinate vectors of v and u with respect to some basis $\mathcal{B}$. This will be proved later.

For an inner product space V, the following properties may be derived from the basic properties;

1. $\langle 0, v \rangle = 0$ for all $v \in V$.
2. Fix $v \in V$. Define $f_v : V \to \mathbb{F}$ as $u \mapsto \langle u, v \rangle$. Then f_v is a linear mapping from the space V to the space $\mathbb{F}$ for any $v \in V$.
3. Let $v = \alpha_1 v_2 + \alpha_2 v_2 + \ldots + \alpha_k v_k$ and $u = \beta_1 u_1 + \beta_2 u_2 + \ldots + \beta_l u_l$ where $u, v, u_j, v_i \in V$ and $\alpha_i, \beta_j \in \mathbb{F}$. Then,

$$\langle v, u \rangle = \sum_{i=1}^{k} \sum_{j=1}^{l} \alpha_i \overline{\beta_j} \langle v_i, u_j \rangle. \tag{3.6}$$

3.2 The Notion of Length and Orthogonality

Let $(V, \langle , \rangle)$ be an inner product space. We define the *norm* of a vector $v \in V$, denoted by $\|v\|$, as

$$\|v\| = \sqrt{\langle v, v \rangle}. \tag{3.7}$$

For V being either $\mathbb{R}^n$ or $\mathbb{C}^n$, we can easily verify that the norm becomes the usual Euclidean length of a vector. Note that $\|v\| = 0$ if and only if v is the zero vector in V. It can also be shown that $\|\lambda v\| = |\lambda| \|v\|$ for some $\lambda \in \mathbb{F}$.

Definition 3.1. We say that two vectors $v, w \in V$ are *orthogonal vectors* if $\langle v, w \rangle = 0$.

Note that the zero vector is orthogonal to every vector in the vector space, even itself; in fact, it is the only vector othogonal to itself. We can also make sense of a Pythogrean theorem here. If $u, v \in V$ are orthogonal, then we can show that

$$\|u + v\|^2 = \|u\|^2 + \|v\|^2. \tag{3.8}$$

Given two vectos $u, v \in V$, we can write u as the sum of a scalar multiple of v, say cv, and a vector w such that $\langle w, v \rangle = 0$. If we rewrite u as $u = cv + (u - cv)$, and impose that $\langle u - cv, v \rangle = 0$, then we get $c = \dfrac{\langle u, v \rangle}{\|v\|^2}$ fulfulling our conditions.

We also have a *Cauchy-Schwarz* inequality. It says that for any $u, v \in V$, then

$$|\langle u, v \rangle| \leq \|u\| \|v\| \tag{3.9}$$

and equality holds if and only if one of the vectors is a scalar multile of the other.

Proof. If either one of the vectors is the zero vector, both sides are just zero. Hence, assume that neither vector is zero, and note that we can write

$$u = \frac{\langle u, v\rangle}{\|v\|^2} v + w \tag{3.10}$$

where $\langle w, v\rangle = 0$. Thus,

$$\|u\|^2 = \langle \frac{\langle u, v\rangle}{\|v\|^2} v + w, \frac{\langle u, v\rangle}{\|v\|^2} v + w\rangle = \frac{\langle u, v\rangle\overline{\langle u, v\rangle}}{\|v\|^4}\langle v, v\rangle + \langle w, w\rangle = \frac{|\langle u, v\rangle|^2}{\|v\|^2} + \langle w, w\rangle \geq \frac{|\langle u, v\rangle|^2}{\|v\|^2}. \tag{3.11}$$

The inequality follows. The equality is left as an exercise to the reader. ■

Let V be an inner product space, and let $\mathcal{B} = (v_1, \ldots, v_n)$ be a basis of V. Let $X = (x_1, \ldots, x_n)^t$ and $Y = (y_1, \ldots, y_n)^t$ be the coordinate vectors of $v, w \in V$, respectively, with respect to the basis $\mathcal{B}$ Then,

$$\langle v, w\rangle = Y^*AX \text{ where } A = (a_{ij}) \text{ and } a_{ij} = \langle v_j, v_i\rangle. \tag{3.12}$$

This can be seen since

$$\langle v, w\rangle = \langle \sum_{i=1}^{n} x_i v_i, \sum_{j=1}^{n} y_j v_j\rangle = \sum_{i=1}^{n}\sum_{j=1}^{n} x_i \overline{v_j}\langle v_i, v_j\rangle. \tag{3.13}$$

Conversely, let V be a vector space of dimension n and $\mathcal{B}$ be a basis of V. Then defining $\langle v, w\rangle = Y^tAX$, where A is of order $n \times n$ satisfying $A^* = A$, gives an inner product

Appendices

Chapter A

Appendix

Extra content goes here.

Appendix

Index