

Linear Algebra Done Right

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1 Vector Spaces

1.1 \mathbb{R}^n and \mathbb{C}^n

Definition 1.1.1 (Complex Number). A *complex number* is an ordered pair (a, b) , where $a, b \in \mathbb{R}$, but we write it as $a + bi$.

Notation 1.1.2. $\mathbb{C} := \{a + bi \mid a, b \in \mathbb{R}\}$

Definition 1.1.3 (Addition & Multiplication).

$$(a + bi) + (c + di) = (a + c) + (b + d)i$$

$$(a + bi)(c + di) = (ac - bd) + (ad + bc)i$$

Theorem 1.1.4 Properties of Complex Arithmetic

1. commutativity: $\alpha + \beta = \beta + \alpha$; $\alpha\beta = \beta\alpha$, $\forall \alpha, \beta \in \mathbb{C}$.
2. associativity: $(\alpha + \beta) + \lambda = \alpha + (\beta + \lambda)$; $(\alpha\beta)\lambda = \alpha(\beta\lambda)$, $\forall \alpha, \beta, \lambda \in \mathbb{C}$.
3. identities: $\lambda + 0 = \lambda$; $\lambda \cdot 1 = \lambda$, $\forall \lambda \in \mathbb{C}$.
4. additive inverse: $\forall \alpha \in \mathbb{C}, \exists$ unique $\beta \in \mathbb{C}$ s.t. $\alpha + \beta = 0$.
5. multiplicative inverse: $\forall \alpha \in \mathbb{C}, \alpha \neq 0, \exists$ unique $\beta \in \mathbb{C}$ s.t. $\alpha\beta = 1$.
6. distributivity: $\lambda(\alpha + \beta) = \lambda\alpha + \lambda\beta$, $\forall \lambda, \alpha, \beta \in \mathbb{C}$.

Definition 1.1.5 (Subtraction). If $-\alpha$ is the additive inverse of α , *subtraction* on \mathbb{C} is defined by

$$\beta - \alpha = \beta + (-\alpha).$$

Definition 1.1.6 (Division). For $\alpha \neq 0$, let $\frac{1}{\alpha}$ denote the multiplicative inverse of α . Then, *division* on \mathbb{C} is defined by

$$\frac{\beta}{\alpha} = \beta \cdot \left(\frac{1}{\alpha}\right)$$

Notation 1.1.7. \mathbb{F} is either \mathbb{R} or \mathbb{C} .

Definition 1.1.8 (List/Tuple). Suppose n is a non-negative integer. A list of length n is an ordered collection of n elements separated by commas and surrounded by parentheses: $(x_1, x_2, x_3, \dots, x_n)$. Two lists are equal if and only if they have the same length and the same elements in the same order.

Remark. Lists must have a FINITE length.

Definition 1.1.9 (\mathbb{F}^n and Coordinate). \mathbb{F}^n is the set of all lists of length n of elements of \mathbb{F} :

$$\mathbb{F}^n := \{(x_1, \dots, x_n) \mid x_i \in \mathbb{F} \forall i = 1, \dots, n\},$$

where x_i is the i^{th} coordinate of (x_1, \dots, x_n) .

Example 1.1.10 $\mathbb{R}^2 = \{(x, y) \mid x, y \in \mathbb{R}\}$ and $\mathbb{R}^3 = \{(x, y, z) \mid x, y, z \in \mathbb{R}\}$.

Definition 1.1.11 (Addition on \mathbb{F}^n). Addition on \mathbb{F}^n is defined by adding corresponding coordinates:

$$(x_1, \dots, x_n) + (y_1, \dots, y_n) = (x_1 + y_1, \dots, x_n + y_n).$$

Theorem 1.1.12 Commutativity of Addition on \mathbb{F}^n

If $x, y \in \mathbb{F}^n$, then $x + y = y + x$.

Proof 1. Suppose $x = (x_1, \dots, x_n)$ and $y = (y_1, \dots, y_n)$. Then

$$\begin{aligned} x + y &= (x_1 + y_1, \dots, x_n + y_n) \\ &= (y_1 + x_1, \dots, y_n + x_n) = y + x. \end{aligned}$$

■

Definition 1.1.13 (Zero). Let 0 denote the list of length n whose coordinates are all 0: $0 := (0, \dots, 0)$.

Definition 1.1.14 (Additive Inverse on \mathbb{F}^n). For $x \in \mathbb{F}^n$, the additive inverse of x , denoted $-x$, is the vector $-x \in \mathbb{F}^n$ s.t. $x + (-x) = 0$.

Definition 1.1.15 (Scalar Multiplication in \mathbb{F}^n). The product of a number $\lambda \in \mathbb{F}$ and a vector $x \in \mathbb{F}^n$ is computed by multiplying each coordinate of the vector by λ :

$$\lambda x = \lambda(x_1, \dots, x_n) = (\lambda x_1, \dots, \lambda x_n),$$

where $x = (x_1, \dots, x_n) \in \mathbb{F}^n$.

Theorem 1.1.16 Properties of Arithmetic Operations on \mathbb{F}^n

1. $(x + y) + z = x + (y + z) \quad \forall x, y, z \in \mathbb{F}^n$
2. $(ab)x = a(bx) \quad \forall x \in \mathbb{F}^n \text{ and } \forall a, b \in \mathbb{F}.$
3. $1 \cdot x = x \quad \forall x \in \mathbb{F}^n \text{ and } 1 \in \mathbb{F}.$
4. $\lambda(x + y) = \lambda x + \lambda y \quad \forall \lambda \in \mathbb{R} \text{ and } \forall x, y \in \mathbb{F}^n.$
5. $(a + b)x = ax + bx \quad \forall a, b \in \mathbb{F} \text{ and } \forall x \in \mathbb{F}^n.$

1.2 Definition of Vector Space

Definition 1.2.1 (Addition on V). An *addition* on V is a function $(u, v) \mapsto u + v$ for all $u, v \in V$.

Definition 1.2.2 (Scalar Multiplication on V). A *scalar multiplication* on V is a function $(\lambda, v) \mapsto \lambda v$ for all $\lambda \in \mathbb{F}$ and $v \in V$.

Definition 1.2.3 (Vector Space). A *vector space* is a set V along with an addition on V and a scalar multiplication s.t. the following properties hold:

1. commutativity: $u + v = v + u \quad \forall u, v \in V$
2. associativity: $(u + v) + w = u + (v + w)$ and $(ab)v = a(bv) \quad \forall u, v, w \in V$ and $\forall a, b \in \mathbb{F}$.
3. additive identity: $\exists 0 \in V$ s.t. $v + 0 = v \quad \forall v \in V$.
4. additive inverse: $\exists w \in V$ s.t. $v + w = 0 \quad \forall v \in V$.
5. multiplicative identity: $\exists 1 \in V$ s.t. $1 \cdot v = v \quad \forall v \in V$.
6. distributive properties: $a(u + v) = au + av$ and $(a + b)v = av + bv \quad \forall u, v \in V$ and $a, b \in \mathbb{F}$.

Definition 1.2.4 (Vector). Elements of a vector space are called *vectors* or *points*.

Notation 1.2.5. V is a vector space over \mathbb{F} .

Definition 1.2.6 (Real and Complex Vector Space). A vector space over \mathbb{R} is called a *real vector space*, and a vector space over \mathbb{C} is called a *complex vector space*.

Theorem 1.2.7 Unique Additive Identity of Vector Spaces

A vector space has a unique additive identity.

Proof 1. Suppose 0 and $0'$ are both additive identities for some vector space V . So,

$$\begin{aligned} 0' &= 0' + 0 && \text{Since } 0 \text{ is an additive identity} \\ &= 0 + 0' && \text{commutativity} \\ &= 0. && \text{Since } 0' \text{ is an additive identity} \end{aligned}$$

Then, $0' = 0$. ■

Theorem 1.2.8 Unique Additive Inverse of Vector Spaces

A vector in a vector space has a unique additive inverse.

Proof 2. Let V be a vector space. Suppose w and w' are additive inverses of v for some $v \in V$. Note that

$$\begin{aligned} w &= w + 0 \\ &= w + (v + w') \\ &= (w + v) + w' \\ &= 0 + w' = w'. \end{aligned}$$
■

Notation 1.2.9. Let $v, w \in V$. Then, $-v$ denotes the additive inverse of v .

Definition 1.2.10 (Subtraction). $w - v$ is defined to be $w + (-v)$.

Theorem 1.2.11

$$0 \cdot v = 0 \quad \forall v \in V.$$

Proof3. Since $v \in V$, we know

$$\begin{aligned} 0 \cdot v &= (0 + 0)v = 0 \cdot v + 0 \cdot v \\ 0 \cdot v + (-0 \cdot v) &= 0 \cdot v + 0 \cdot v + (-0 \cdot v) \\ 0 &= 0 \cdot v \end{aligned}$$

■

Theorem 1.2.12

$$a \cdot 0 = 0 \quad \forall a \in \mathbb{F}.$$

Proof4. For $a \in \mathbb{F}$, we have

$$\begin{aligned} a \cdot 0 &= a \cdot (0 + 0) = a \cdot 0 + a \cdot 0 \\ a \cdot 0 + (-a \cdot 0) &= a \cdot 0 + a \cdot 0 + (-a \cdot 0) \\ 0 &= a \cdot 0. \end{aligned}$$

■

Theorem 1.2.13

$$(-1)v = -v \quad \forall v \in V.$$

Proof5. For $v \in V$, we have

$$v + (-1)v = 1 \cdot v + (-1) \cdot v = (1 + (-1)) \cdot v = 0 \cdot v = 0.$$

Therefore, by definition, $(-1)v = -v$.

■

Notation 1.2.14. \mathbb{F}^S

1. If S is a set, then \mathbb{F}^S denotes the set of functions from S to \mathbb{F} .
2. For $f, g \in \mathbb{F}^S$, the sum $f + g \in \mathbb{F}^S$ is the function defined by $(f + g)(x) = f(x) + g(x) \quad \forall x \in S$.
3. For $\lambda \in \mathbb{F}$ and $f \in \mathbb{F}^S$, the product $\lambda f \in \mathbb{F}^S$ is the function defined by $(\lambda f)(x) = \lambda f(x) \quad \forall x \in S$.

Theorem 1.2.15

\mathbb{F}^S is a vector space.

1.3 Subspace

Definition 1.3.1 (Subspace). A subset U of V is called a *subspace* of V if U is also a vector space using the same addition and scalar multiplication as on V .

Theorem 1.3.2 Conditions for a Subspace

A subset U of V is a subspace of V if and only if U satisfies the following conditions:

1. additive identity: $0 \in U$;
2. closed under addition: $u, w \in U \implies u + w \in U$;
3. closed under scalar multiplication: $a \in \mathbb{F}$ and $u \in U \implies au \in U$.

Proof 1.

(\Rightarrow) Suppose U is a subspace of V . By definition, U is then a vector space, and so those conditions are automatically satisfied. \square

(\Leftarrow) Suppose U satisfies the three conditions. Since U is a subset of V , U automatically has *associativity*, *commutativity*, *multiplicative identity*, and *distributivity*. So, we want to check U has additive inverse and additive identities.

For additive identity, we know $0 \in U$, by assumption.

For additive inverse, by condition #3, we know $-u = (-1)u \in U$.

Then, U is a vector space. ■

Example 1.3.3 If $b \in \mathbb{F}$, then $\{(x_1, x_2, x_3, x_4) \in \mathbb{F}^4 \mid x_3 = 5x_4 + b\}$ is a subspace of \mathbb{F}^4 if and only if $b = 0$.

Proof 2.

(\Rightarrow) Suppose $U = \{(x_1, x_2, x_3, x_4) \in \mathbb{F}^4 \mid x_3 = 5x_4 + b\}$ is a subspace of \mathbb{F}^4 . Then, $0 = (0, 0, 0, 0) \in U$. So, $0 = 5 \cdot 0 + b$, or $b = 0$. \square

(\Leftarrow) Suppose $b = 0$. Then, $x_3 = 5x_4$. So, $U = \{(x_1, x_2, 5x_4, x_4) \in \mathbb{F}^4\}$

1. $0 = (0, 0, 0, 0) \in U$

2. Note that

$$(x_1, x_2, 5x_4, x_4) + (y_1, y_2, 5y_4, y_4) = (x_1 + y_1, x_2 + y_2, 5(x_4 + y_4), x_4 + y_4) \in U$$

So, addition is closed under U .

3. $\forall a \in \mathbb{F}$, we have

$$a(x_1, x_2, 5x_4, x_4) = (ax_1, ax_2, 5(ax_4), ax_4) \in U$$

Then, U is a subspace of \mathbb{F}^4 . ■

Example 1.3.4 The set of continuous real-valued functions on interval $[0, 1]$ is a subspace of $\mathbb{R}^{[0,1]}$.

Proof 3.

1. 0 (zero mapping) $\in U$
2. Set f and $g \in \mathcal{C}[0, 1]$, the set of continuous functions on interval $[0, 1]$. Then, $f + g \in \mathcal{C}[0, 1]$.
3. From Calculus, we know that $\forall a \in \mathbb{F}, \quad af \in \mathcal{C}[0, 1]$.

■

Definition 1.3.5 (Sum of Subspaces). Suppose U_1, \dots, U_m are subspaces of V . The *sum* of U_1, \dots, U_m , denoted as $U_1 + \dots + U_m$, is the set of all possible sums of elements of U_1, \dots, U_m :

$$U_1 + \dots + U_m = \{u_1 + \dots + u_m \mid u_i \in U_i \quad \forall i = 1, \dots, m\}.$$

Example 1.3.6 Suppose $U = \{(x, 0, 0) \in \mathbb{F}^3 \mid x \in \mathbb{F}\}$ and $W = \{(0, y, 0) \in \mathbb{F}^3 \mid y \in \mathbb{F}\}$, then

$$U + W = \{(x, y, 0) \in \mathbb{F}^3 \mid x, y \in \mathbb{F}\}.$$

Theorem 1.3.7

Suppose U_1, \dots, U_m are subspaces of V . Then, $U_1 + \dots + U_m$ is the *smallest subspace* of V containing U_1, \dots, U_m .

Proof 4. Suppose U_1, \dots, U_m are subspaces of U . Let $U_1 + \dots + U_m = \{u_1 + \dots + u_m \mid u_j \in U_j, j = 1, \dots, m\}$. Suppose $w_j \in U_j$, then $w_1 + \dots + w_m \in U_1 + \dots + U_m$.

1. $U_1 + \dots + U_m$ is a subspace of V .

(a) Note that

$$(u_1 + \dots + u_m) + (w_1 + \dots + w_m) = (u_1 + w_1) + \dots + (u_m + w_m) \in U_1 + \dots + U_m,$$

so $U_1 + \dots + U_m$ is closed under addition.

(b) Similarly, $U_1 + \dots + U_m$ is closed under scalar multiplication.

(c) Note that U_j is a subspace, so $0 \in U_j$. Hence, $(0, \dots, 0) = 0 \in U_1 + \dots + U_m$. □

2. Now, we want to show this subspace is the smallest subspace containing U_1, \dots, U_m . That is, we want to show $\forall W \supseteq U_1 \cup \dots \cup U_m$, we have $W \supseteq U_1 + \dots + U_m$.

Note that $U_j \subseteq U_1 + \dots + U_m$, so we have $(U_1 \cup U_2 \cup \dots \cup U_m) \subseteq U_1 + \dots + U_m$. This means $U_1 + \dots + U_m$ must contain U_1, \dots, U_m . Let W be some subspace containing U_1, \dots, U_m . Then, for $j = 1, \dots, m$, we have $u_j \in U_j$, which indicates $u_j \in W$. Therefore, $u_1 + \dots + u_m \in W$ and thus $U_1 + \dots + U_m \subseteq W$.

Since W was arbitrary, we've shown $\forall W$ that contains U_1, \dots, U_m , $U_1 + \dots + U_m \subseteq W$. Therefore, $U_1 + \dots + U_m$ is the smallest.

■

Definition 1.3.8 (Direct Sum). Suppose U_1, \dots, U_m are subspaces of V . $U_1 + \dots + U_m$ is called a *direct sum* if each element of $U_1 + \dots + U_m$ can be written in only one way as a sum $u_1 + \dots + u_m$, where $u_j \in U_j$.

Notation 1.3.9. If $U_1 + \dots + U_m$ is a direct sum, then we use $U_1 \oplus \dots \oplus U_m$ to denote it.

Example 1.3.10 Let $U = \{(x, y, 0) \in \mathbb{F}^3 \mid x, y \in \mathbb{F}\}$ and $W = \{(0, 0, z) \in \mathbb{F}^3 \mid z \in \mathbb{F}\}$. Then, $\mathbb{F}^3 = U \oplus W$.

Proof 5. Note that $U + W = \{(x, y, z) \mid x, y, z \in \mathbb{F}\} = \mathbb{F}^3$. Suppose

$$(x, y, z) = (x, y, 0) + (0, 0, z), \quad (1)$$

for some $x, y, z \in \mathbb{F}$ and

$$(x, y, z) = (x', y', 0) + (0, 0, z') \quad (2)$$

for some $x', y', z' \in \mathbb{F}$. Then, (1)–(2):

$$(0, 0, 0) = (x - x', y - y', 0) + (0, 0, z - z') = (x - x', y - y', z - z').$$

Then, $x - x' = y - y' = z - z' = 0$, which indicates $x = x'$, $y = y'$, $z = z'$. So, by definition $U + W$ is a direct sum, or $\mathbb{F}^3 = U \oplus W$. ■

Example 1.3.11 Suppose U_j is the subspace of \mathbb{F}^n s.t.

$$U_1 = \{x, 0, 0, \dots, 0 \mid x \in \mathbb{F}\}$$

$$U_2 = \{0, x, 0, \dots, 0 \mid x \in \mathbb{F}\}$$

$$\vdots$$

$$U_n = \{0, 0, 0, \dots, x \mid x \in \mathbb{F}\}$$

Then, $\mathbb{F}^n = U_1 \oplus U_2 \oplus \dots \oplus U_n$.

Proof 6. Note that $\mathbb{F}^n = U_1 + U_2 + \dots + U_n$ is evident. Now, we'll prove that $U_1 + U_2 + \dots + U_n$ is a direct sum. Consider $x = (x_1, x_2, \dots, x_n) \in \mathbb{F}^n$. Assume that

$$x = (x_1, 0, \dots, 0) + \dots + (0, \dots, 0, x_n) \quad (3)$$

and

$$x = (x'_1, 0, \dots, 0) + \dots + (0, \dots, 0, x'_n) \quad (4)$$

Then, from (3)–(4), we know that

$$0 = (x_1 - x'_1, \dots, x_n - x'_n) = (0, 0, \dots, 0).$$

Then, $\forall i = 1, \dots, n$ we have $x_i - x'_i = 0$, or $x_i = x'_i$. Therefore, by definition, we know $U_1 + \dots + U_n$ is a direct sum. ■

Example 1.3.12 Let

$$U_1 = \{(x, y, 0) \mid x, y \in \mathbb{F}\}$$

$$U_2 = \{(0, 0, z) \mid z \in \mathbb{F}\}$$

$$U_3 = \{(0, y, y) \mid y \in \mathbb{F}\}$$

Show that $U_1 + U_2 + U_3$ is not a direct sum.

Proof 7. Consider $(0, 0, 0) \in \mathbb{F}^3$. Note that

$$(0, 0, 0) = (0, 0, 0) + (0, 0, 0) + (0, 0, 0)$$

and

$$(0, 0, 0) = (0, 1, 0) + (0, 0, 1) + (0, -1, -1).$$

Then, $U_1 + U_2 + U_3$ is not a direct sum by definition. ■

Theorem 1.3.13

Suppose U_1, \dots, U_m are subspaces of V . Then, $U_1 + \dots + U_m$ is a direct sum if and only if the only way to write 0 as a sum $u_1 + \dots + u_m$ is by taking each $u_j = 0$.

Proof 8.

(\Rightarrow) Since $U_1 + \dots + U_m$ is a direct sum, by definition, the only way to write $0 \in \mathbb{F}^n$ is to write it as

$$0 = 0 + \dots + 0 \quad \text{where } 0 \in U_i \forall i = 1, \dots, m. \quad \square$$

(\Leftarrow) Suppose the only way to write 0 as a sum $u_1 + \dots + u_m$ is by taking each $u_j = 0$. Assume that for some $v \in V$, we have

$$v = u_1 + \dots + u_m, \quad u_j \in U_j \tag{5}$$

and

$$v = u'_1 + \dots + u'_m, \quad u'_j \in U_j. \tag{6}$$

Then, by (5)-(6), and according to the conclusion from Example 1.3.11, we have

$$0 = (u_1 - u'_1) + \dots + (u_m - u'_m) = 0 + \dots + 0.$$

So, $\forall i \in 1, \dots, m$, we have $u_i - u'_i = 0$. that is, $u_i = u'_i$. So, $\forall v \in V$, there is only one way to write v as a sum of $u_1 + \dots + u_m$. Therefore, by definition, $U_1 + \dots + U_m$ is a direct sum. ■

Theorem 1.3.14

Suppose U and W are subspaces of V . Then, $U + W$ is a direct sum if and only if $U \cap W = \{0\}$.

Proof 9.

(\Rightarrow) Suppose $U + W$ is a direct sum. Assume $v \in U \cap W$. Then, $v \in U$ and $v \in W$. By definition of subspace, we know $-v \in W$ as well. Note that

$$0 = v + (-v) \in U \cap W.$$

Then, by Theorem 1.3.13, we know that the only representation of $0 \in U \cap W$ is $0 = 0 + 0$ since $U \cap W$

is a direct sum. Hence, it must be that $v = -v = 0$, and thus $U \cap W = \{0\}$. \square

(\Leftarrow) Suppose $U \cap W = \{0\}$. Let $u \in U$ and $w \in W$ s.t. $u + w = 0$. Then, we have $u = -w$. Since $-w \in W$, we know $u = -w \in W$. By $u \in U$ and $u \in W$, we know that $u \in U \cap W = \{0\}$. Therefore, $0 = 0 + 0$ is the only to represent $0 \in U + W$. By Theorem 1.3.13, we know $U + W$ is a direct sum. \blacksquare

Remark. When extending Theorem 1.3.14 to 3 subspaces U_1, U_2, U_3 , we cannot conclude $U_1 \oplus U_2 \oplus U_3$ if we have $U_1 \cap U_2 = U_1 \cap U_3 = U_2 \cap U_3 = \{0\}$. See Example 1.3.12 as a counterexample.

2 Finite-Dimensional Vector Spaces

2.1 Span and Linear Independence

Notation 2.1.1. We usually write list of vectors without using parentheses.

Example 2.1.2 $(4, 1, 6), (9, 5, 7)$ is a list of vectors of length 2 in \mathbb{R}^3 .

Definition 2.1.3 (Linear Combination). A *linear combination* of a list v_1, \dots, v_m of vectors in V is a vector of the form

$$a_1v_1 + \dots + a_mv_m,$$

where $a_1, \dots, a_m \in \mathbb{F}$.

Example 2.1.4 Since $(17, -4, 2) = 6(2, 1, -3) + 5(1, -2, 4)$, we say $(17, -4, 2)$ is a linear combination of $(2, 1, -3), (1, -2, 4)$.

Definition 2.1.5 (Span).

$$\text{span}(v_1, \dots, v_m) = \{a_1v_1 + \dots + a_mv_m \mid a_1 \dots a_m \in \mathbb{F}\}.$$

Example 2.1.6 Consider $\text{span}(e_1, e_2, e_3)$:

$$\begin{aligned} \text{span}(e_1, e_2, e_3) &= \{a_1e_1 + a_2e_2 + a_3e_3 \mid a_1, a_2, a_3 \in \mathbb{F}\} \\ &= \{(a_1, a_2, a_3) \mid a_1, a_2, a_3 \in \mathbb{F}\} = \mathbb{R}^3. \end{aligned}$$

Theorem 2.1.7

The span of a list of vectors in V is the smallest subspace of V containing all the vectors in the list.

Proof 1. To prove this theorem, we will prove two parts: span is a subspace and span is the smallest subspace.

1. Span is a subspace of V .

- (a) By definition of span, we know $\text{span}(v_1, \dots, v_m) = \{a_1v_1 + \dots + a_mv_m \mid a_1, \dots, a_m \in \mathbb{F}\}$. If we set $a_1, \dots, a_m = 0$, then we have $0 = 0v_1 + \dots + 0v_m$. So, $0 \in \text{span}(v_1, \dots, v_m)$.
- (b) Let $a_1v_1 + \dots + a_mv_m \in \text{span}(v_1, \dots, v_m)$ and $b_1v_1 + \dots + b_mv_m \in \text{span}(v_1, \dots, v_m)$. Then,

$$(a_1v_1 + \dots + a_mv_m) + (b_1v_1 + \dots + b_mv_m) = (a_1 + b_1)v_1 + \dots + (a_m + b_m)v_m.$$

Since $(a_1 + b_1), \dots, (a_m + b_m) \in \mathbb{F}$, we know $(a_1 + b_1)v_1 + \dots + (a_m + b_m)v_m \in \text{span}(v_1, \dots, v_m)$.

- (c) Let $\lambda \in \mathbb{F}$ and $a_1v_1 + \dots + a_mv_m \in \text{span}(v_1, \dots, v_m)$. Then,

$$\lambda(a_1v_1 + \dots + a_mv_m) = \lambda a_1v_1 + \dots + \lambda a_mv_m.$$

Since $\lambda a_1, \dots, \lambda a_m \in \mathbb{F}$, we know that $\lambda(a_1 v_1 + \dots + a_m v_m) \in \text{span}(v_1, \dots, v_m)$.

Therefore, we have proven that span is a subspace of V . \square

2. Now, we want to show that span is the smallest subspace.

Let U be a subspace of V containing v_1, \dots, v_m . If we can show that $\text{span}(v_1, \dots, v_m) \subseteq U$, we then know span is the smallest subspace containing v_1, \dots, v_m . Since U is a subspace containing v_1, \dots, v_m , it is closed under addition and scalar multiplication. So, $a_1 v_1 + \dots + a_m v_m \in \text{span}(v_1, \dots, v_m)$. Therefore, $\text{span}(v_1, \dots, v_m) \subseteq U$. \blacksquare

Definition 2.1.8 (Span as a Verb). If $\text{span}(v_1, \dots, v_m) = V$, we say v_1, \dots, v_m *spans* V .

Definition 2.1.9 (Finite-Dimensional Vector Space). A vector space V is called *finite-dimensional* if \exists a list of vectors, say v_1, \dots, v_m s.t. $\text{span}(v_1, \dots, v_m) = V$. In the following of this notes, we will use *f-d* as a shortcut for saying “finite-dimensional.”

Definition 2.1.10 (Infinte-Dimensional Vector Space). A vector space V is infinite-dimensional if it is not *f-d*. This is equivalent to say that \forall lists of vectors in V , they do not span V .

Definition 2.1.11 (Polynomial Functions). A function $p : \mathbb{F} \rightarrow \mathbb{F}$ is called a *polynomial* with coefficients in \mathbb{F} if $\exists a_0, \dots, a_m \in \mathbb{F}$ s.t. $p(z) = a_0 + a_1 z + a_2 z^2 + \dots + a_m z^m \quad \forall z \in \mathbb{F}$.

Notation 2.1.12. We use $\mathcal{P}(\mathbb{F})$ to denote the set of all polynomial with coefficients in \mathbb{F} .

Theorem 2.1.13

$\mathcal{P}(\mathbb{F})$ is a vector space over \mathbb{F} .

Proof2. Recall the definition of $\mathbb{F}^{\mathbb{F}}$. We will show $\mathcal{P}(\mathbb{F})$ is a subspace of $\mathbb{F}^{\mathbb{F}}$.

1. $0 = 0 + 0z + \dots + 0z^m \in \mathcal{P}(\mathbb{F})$.
2. Suppose $p(z) = a_m z^m + \dots + a_1 z + a_0$ and $q(z) = b_n z^n + \dots + b_1 z + b_0 \in \mathcal{P}(\mathbb{F})$. WLOG, suppose $m > n$, then we have $p(z) + q(z) = a_m z^m + \dots + (a_n + b_n) z^n + \dots + (a_0 + b_0) \in \mathcal{P}(\mathbb{F})$.
3. Suppose $\lambda \in \mathbb{F}$. Then, $\lambda p(z) = \lambda(a_m z^m + \dots + a_1 z + a_0) = \lambda a_m z^m + \dots + \lambda a_0 \in \mathcal{P}(\mathbb{F})$.

Hence, we've shown $\mathcal{P}(\mathbb{F})$ is a subspace over \mathbb{F} . \blacksquare

Definition 2.1.14 (Degree of a Polynomial). A polynomial $p \in \mathcal{P}(\mathbb{F})$ is said to have *degree* m if \exists scalars $a_0, \dots, a_m \in \mathbb{F}$ with $a_m \neq 0$ s.t. $p(z) = a_m z^m + \dots + a_1 z + a_0 \quad \forall z \in \mathbb{F}$. We write $\deg p = m$. Specially, $\deg 0 := -\infty$ and $\deg a_0 := 0$ when $a_0 \neq 0$.

Definition 2.1.15 ($\mathcal{P}_m(\mathbb{F})$). For $m \in \mathbb{N}^+$, $\mathcal{P}_m(\mathbb{F})$ denotes the set of all polynomial with coefficients in \mathbb{F} and degree $\leq m$. i.e.,

$$\mathcal{P}_m(\mathbb{F}) := \{p \in \mathcal{P}(\mathbb{F}) \mid \deg p \leq m\}.$$

Example 2.1.16 For each $m \in \mathbb{N}$, $\mathcal{P}_m(\mathbb{F})$ is a *f-d* vector space.

Proof3. Note that $\mathcal{P}_m(\mathbb{F})$ is a vector space because it is a subspace of $\mathcal{P}(\mathbb{F})$. Suppose $p(z) \in \mathcal{P}_m(\mathbb{F})$, then $p(z) = a_0 + a_1 z + \dots + a_m z^m \in \text{span}(1, z, \dots, z^m)$. Then, by definition, $\mathcal{P}_m(\mathbb{F})$ is *f-d*. \blacksquare

Remark. In this proof, we are abusing notation by letting z^k to denote a function.

Example 2.1.17 $\mathcal{P}(\mathbb{F})$ is infinite-dimensional.

Proof 4. For any list of vectors in $\mathcal{P}(\mathbb{F})$, by definition of list, the length of it is finite. Suppose the highest degree in this list is m . Consider a polynomial with degree of $m + 1$: z^{m+1} . Since z^{m+1} cannot be written as linear combinations of the list of polynomials, we know the list does not span $\mathcal{P}(\mathbb{F})$. So, $\mathcal{P}(\mathbb{F})$ is infinite-dimensional. ■

Definition 2.1.18 (Linear Independence). A list v_1, \dots, v_m of vectors in V is called *linearly independent* (L.I.) if the only choice of $a_1, \dots, a_m \in \mathbb{F}$ that makes $a_1v_1 + \dots + a_mv_m = 0$ is $a_1 = \dots = a_m = 0$. Specially, the empty list $()$ is declared to be L.I..

Definition 2.1.19 (Linear Dependence). v_1, \dots, v_m is called *linearly dependent* if it is not L.I.. Or, equivalently, v_1, \dots, v_m is *linearly dependent* if $\exists a_1, \dots, a_m \in \mathbb{F}$ not all 0 s.t. $\sum_{i=1}^m a_i v_i = 0$.

Example 2.1.20 Let $v_1, \dots, v_m \in V$. If v_j is a linear combination of other v 's, then v_1, \dots, v_m is linearly dependent.

Proof 5. By assumption, $v_j = a_1v_1 + \dots + a_{j-1}v_{j-1} + a_{j+1}v_{j+1} + \dots + a_mv_m$ for some a_i not all 0. So, $0 = a_1v_1 + \dots + a_{j-1}v_{j-1} + a_{j+1}v_{j+1} + \dots + a_mv_m - v_j$, a linear combination of v_1, \dots, v_m . Since $-v_j$ has a coefficient of $-1 \neq 0$, by definition, v_1, \dots, v_m is not L.I.. ■

Lemma 2.1.21 Linear Dependence Lemma Suppose v_1, \dots, v_m is a linearly dependent list in V . Then, $\exists j \in \{1, \dots, m\}$ s.t. the following hold:

1. $v_j \in \text{span}(v_1, \dots, v_{j-1})$
2. if the j^{th} term is removed from v_1, \dots, v_m , the span of the remaining list equals $\text{span}(v_1, \dots, v_m)$.

Proof 6.

1. Since v_1, \dots, v_m is linearly dependent, $a_1v_1 + \dots + a_mv_m = 0$, for some $a_i \neq 0$. Let j be the maximized index s.t. $a_j \neq 0$. Then, $a_{j+1} = \dots = a_m = 0$, by this assumption. Hence,

$$\begin{aligned} a_j v_j &= -a_1 v_1 - \dots - a_{j-1} v_{j-1} - a_{j+1} v_{j+1} - \dots - a_m v_m \\ &= -a_1 v_1 - \dots - a_{j-1} v_{j-1} \\ v_j &= -\frac{a_1}{a_j} v_1 - \dots - \frac{a_{j-1}}{a_j} v_{j-1}. \end{aligned}$$

Since $-\frac{a_1}{a_j}, \dots, -\frac{a_{j-1}}{a_j} \in \mathbb{F}$, we know $v_j \in \text{span}(v_1, \dots, v_{j-1})$. □

2. Consider

$$\begin{aligned} \text{span}(v_1, \dots, v_j, \dots, v_m) &= \text{span}\left(v_1, \dots, -\frac{a_1}{a_j} v_1 - \dots - \frac{a_{j-1}}{a_j} v_{j-1}, \dots, v_m\right) \\ &= \text{span}(v_1, \dots, v_{j-1}, v_{j+1}, \dots, v_m). \end{aligned}$$

■

Remark. By using this Lemma 2.1.21, we can do lots of proofs using the “step” strategy. Namely, we start to remove vectors from a list that are linearly dependent to obtain a L.I. list. However, this “step” strategy can only be used when dealing with FINITE-dimensional vector spaces.

Theorem 2.1.22

Let V be a f - d vector space. Let $\text{span}(w_1, \dots, w_n) = V$. Let u_1, \dots, u_m be L.I.. Then, $m \leq n$.

Proof 7.

Step 1 Note that u_1, w_1, \dots, w_n is linearly dependent because $u_1 \in V = \text{span}(w_1, \dots, w_n)$. Then, by Lemma 2.1.21, we can remove one of the w 's, say w_{j1} . Then, the list becomes

$$\{u_1, w_1, \dots, w_n\} \setminus \{w_{j1}\}.$$

Step 2 Adjoin u_2 . Apply the same reasoning, since $\text{span}(\{u_1, w_1, \dots, w_n\} \setminus \{w_{j1}\}) = V$, we know $\{u_1, u_2, w_1, \dots, w_n\} \setminus \{w_{j1}\}$ is linearly dependent. Since $u_2 \notin \text{span}(u_1)$, Lemma 2.1.21 is not applicable to u_2 . Now, we can remove another w from the list, say w_{j2} . The list becomes

$$\{u_1, u_2, w_1, \dots, w_n\} \setminus \{w_{j1}, w_{j2}\}.$$

\vdots

Step m After m steps, we list will become

$$\{u_1, \dots, u_m, w_1, \dots, w_n\} \setminus \{w_{j1}, \dots, w_{jm}\}.$$

Since $\text{span}(\{u_1, \dots, u_m, w_1, \dots, w_n\} \setminus \{w_{j1}, \dots, w_{jm}\}) = V$, this list is still linearly dependent, so by Lemma 2.1.21, we know $\exists w$ to be removed. Therefore, $n \geq m$. ■

Theorem 2.1.23

Every subspace of a f - d vector space is f - d .

Proof 8. Suppose V to be a f - d vector space and U to be a subspace of V .

Step 1 If $U = \{0\}$, then U is f - d . If $U \neq \{0\}$, then choose $v_1 \in U$ s.t. $v_1 \neq 0$.

\vdots

Step j If $U = \text{span}(v_1, \dots, v_{j-1})$, then U is f - d . If $U \neq \text{span}(v_1, \dots, v_{j-1})$, then choose $v_j \in U$ s.t. $v_j \notin \text{span}(v_1, \dots, v_{j-1})$.

By Lemma 2.1.21 and Theorem 2.1.22, we know this process will eventually terminate because the vector list that spans U cannot be longer than any spanning list of V . Therefore, U is f - d . ■

2.2 Bases

Definition 2.2.1 (Basis). A *basis* of V is a list of vectors in V that is L.I. and spans V .

Example 2.2.2

1. The standard basis of \mathbb{F}^n :

$$(1, 0, \dots, 0), (0, 1, 0, \dots, 0), \dots, (0, \dots, 0, 1).$$

2. $(1, 1, 0), (0, 0, 1)$ is a basis of V , where $V = \{(x, x, y) \in \mathbb{F}^3 \mid x, y \in \mathbb{F}\}$.

Proof 1.

- (a) Suppose $a_1(1, 1, 0) + a_2(0, 0, 1) = 0$, we have $(a_1, a_1, a_2) = 0$. So, it must be $a_1 = a_2 = 0$. Therefore, $(1, 1, 0), (0, 0, 1)$ is L.I. \square
- (b) Suppose $(x, x, y) \in V$. Note that $(x, x, y) = x(1, 1, 0) + y(0, 0, 1)$, then, $V = \text{span}((1, 1, 0), (0, 0, 1))$.

Therefore, we've proven $(1, 1, 0), (0, 0, 1)$ is a basis of V according to the definition of basis. \blacksquare

Theorem 2.2.3 Criterion for Basis

A list $v_1, \dots, v_n \in V$ is a basis list of V if and only if every $v \in V$ can be written uniquely in the form $v = a_1v_1 + \dots + a_nv_n$, where $a_i \in \mathbb{F}$.

Proof 2.

(\Rightarrow) Let v_1, \dots, v_n be a basis of V . Let $v \in V$. By definition of basis, $V = \text{span}(v_1, \dots, v_n)$. So, $v \in \text{span}(v_1, \dots, v_n)$, and thus $v = a_1v_1 + \dots + a_nv_n$ for some $a_i \in \mathbb{F}$. Assume for the sake of contradiction that $v = b_1v_1 + \dots + b_nv_n$ for some $b_i \neq a_i \in \mathbb{F}$. Then,

$$\begin{aligned} v - v &= (a_1 - b_1)v_1 + \dots + (a_n - b_n)v_n \\ 0 &= (a_1 - b_1)v_1 + \dots + (a_n - b_n)v_n. \end{aligned}$$

Since v_1, \dots, v_n is a basis, it is L.I.. So, $0 = 0v_1 + \dots + 0v_n$. Therefore, we know $a_1 - b_1 = \dots = a_n - b_n = 0$. That is, $a_1 = b_1, \dots, a_n = b_n$. * This is a contradiction with the assumption that $\exists a_i \neq b_i$. Hence, it must be that $v = a_1v_1 + \dots + a_nv_n$ is unique. \square

(\Leftarrow) Suppose $v = a_1v_1 + \dots + a_nv_n$ is the unique representation $\forall v \in V$. Then, $v \in \text{span}(v_1, \dots, v_n)$. Since $v \in V$, then $V \subseteq \text{span}(v_1, \dots, v_n)$. However, $v_1, \dots, v_n \in V$, so $\text{span}(v_1, \dots, v_n) \subseteq V$. Therefore, $\text{span}(v_1, \dots, v_n) = V$. To show v_1, \dots, v_n is L.I., further consider $0 = a_1v_1 + \dots + a_nv_n$. Since $0 \in V$, by assumption, \exists a unique way to write 0 as $a_1v_1 + \dots + a_nv_n$, and that unique way is to take every $a_i = 0$. Hence, by definition, we know v_1, \dots, v_n is L.I.. Since v_1, \dots, v_n is L.I. and $\text{span}(v_1, \dots, v_n) = V$, we know v_1, \dots, v_n is a basis list of V . \blacksquare

Theorem 2.2.4

Every spanning list can be reduced to a basis of the vector space.

Proof 3. Suppose $V = \text{span}(v_1, \dots, v_n)$. If $v_i = 0$, we just remove v_i . So, let's suppose $v_i \neq 0$.

Step 1 If $v_2 \in \text{span}(v_1)$, delete it. If $v_2 \notin \text{span}(v_1)$, keep it.

\vdots

Step j If $v_j \in \text{span}(v_1, \dots, v_{j-1})$, delete it. If $v_j \notin \text{span}(v_1, \dots, v_{j-1})$, keep it.

\vdots

Step n After n steps, we will have a “sub-list” from the original list *s.t.* it spans V and is L.I.. Therefore, the basis list is contained in the spanning list. ■

Corollary 2.2.5 Every f - d vector space has a basis.

Proof 4. By definition, f - d vector space always has a spanning list. By Theorem 2.2.4, a spanning list contain a basis. ■

Theorem 2.2.6

Every linearly independent list of vectors in a f - d vector space can be extended to a basis of the vector space.

Proof 5. Suppose u_1, \dots, u_m is L.I. in a f - d vector space of V . Let w_1, \dots, w_n be a basis of V . Then, $u_1, \dots, u_m, w_1, \dots, w_n$ spans V . According to Lemma 2.1.21 and Theorem 2.1.22, we can reduce $u_1, \dots, u_m, w_1, \dots, w_n$ to some list of u_1, \dots, u_m and some w 's. ■

Theorem 2.2.7

Suppose V is f - d and U is a subspace of V . Then, there is a subspace W of V *s.t.* $V = U \oplus W$.

Proof 6. Since V is f - d , U , as V 's subspace, is also f - d . So, \exists a basis of U , say u_1, \dots, u_m . Then, u_1, \dots, u_m is L.I. and $\in V$. By Theorem 2.2.6, this list can be extended to a basis

$$u_1, \dots, u_m, w_1, \dots, w_n \text{ of } V.$$

Let $W = \text{span}(w_1, \dots, w_n)$. We'll show $V = U \oplus W$.

1. WTS: $V = U + W$. Suppose $v \in V$. Then,

$$v = \underbrace{a_1 u_1 + \dots + a_m u_m}_{\in U} + \underbrace{b_1 w_1 + \dots + b_n w_n}_{\in W}.$$

So, $v \in U + W$, or $V = U + W$. □

2. WTS: $U \cap W = \{0\}$. Suppose $v \in U \cap W$. Then, $v \in U$ and $v \in W$. So,

$$v = a_1 u_1 + \dots + a_m u_m = b_1 w_1 + \dots + b_n w_n.$$

Hence,

$$a_1 u_1 + \dots + a_m u_m - b_1 w_1 - \dots - b_n w_n = 0. \quad (7)$$

Since by assumption, $u_1, \dots, u_m, w_1, \dots, w_n$ is a basis of V , so $u_1, \dots, u_m, w_1, \dots, w_n$ is L.I.. Therefore, the only way for Equation (7) to hold is when $a_1 = \dots = a_m = b_1 = \dots = b_n = 0$. Hence, $v = 0u_1 + \dots + 0u_m = 0$. That is, $U \cap W = \{0\}$.

Therefore, we've shown that $V = U \oplus W$. ■

2.3 Dimension

Theorem 2.3.1

Let B_1 and B_2 be two bases of V , then B_1 and B_2 have the same length.

Proof 1. Since B_1 is L.I. in V and B_2 spans V , by Theorem 2.1.22, we know $\text{len}(B_1) \leq \text{len}(B_2)$. Interchanging the roles of B_1 and B_2 , we have $\text{len}(B_2) \leq \text{len}(B_1)$. So, we have $\text{len}(B_1) = \text{len}(B_2)$. ■

Definition 2.3.2 (Dimension). The *dimension* of a f -d vector space V is the length of any basis of V .

Notation 2.3.3. We use $\dim V$ to denote the dimension of a f -d vector space V .

Example 2.3.4 $\dim \mathbb{F}^n = n$ and $\dim \mathcal{P}_m(\mathbb{F}) = m + 1$ ($1, z, z^2, \dots, z^m$).

Theorem 2.3.5

If V is f -d and U is a subspace of V , then $\dim U \leq \dim V$.

Proof 2. Let B_1 be a basis of U and B_2 be a basis of V . Then, B_1 is a L.I. list of V and B_2 spans V . Then, By Theorem 2.1.22, we know that $\text{len}(B_1) \leq \text{len}(B_2)$. So, by definition of dimension, we know $\dim U \leq \dim V$. ■

Extension. If V is f -d and U is a subspace of V , given $U \subsetneq V$, then $\dim U < \dim V$.

Proof 3. Let u_1, \dots, u_m be a basis of U . Since $U \subsetneq V$, we know $V - U \neq \emptyset$. So, choose $v \in V - U$. Then, $v \notin \text{span}(u_1, \dots, u_m)$. Therefore, u_1, \dots, u_m, v is L.I. in V . That is

$$\begin{aligned} \dim V &\geq \dim(\text{span}(u_1, \dots, u_m, v)) \\ &> \dim(\text{span}(u_1, \dots, u_m)) \\ &= \dim U. \end{aligned}$$

■

Theorem 2.3.6

Let V be f -d, then every L.I. list of vectors in V with length $\dim V$ is a basis of V .

Proof 4. Let $v_1, \dots, v_n \in V$ be L.I.. Let $n = \dim V$. When extending the list to basis, we get

$$\{v_1, \dots, v_n\} \cup \emptyset$$

as a basis of V . That is, v_1, \dots, v_n has already been a basis of V . ■

Remark. The proof given above is not that straight-forward, so we are giving an easier-understanding proof as follows.

Proof 5. Suppose for the sake of contradiction that $\exists v_1, \dots, v_n \in V$ not a basis of V for $n = \dim V$. Then, $\text{span}(v_1, \dots, v_n) \neq V$. That is, $\exists v_{n+1}$ s.t. $v_{n+1} \notin \text{span}(v_1, \dots, v_n)$. Adding v_{n+1} to the vector list, we have v_1, \dots, v_n, v_{n+1} is L.I.. By Theorem 2.3.5, we know $\text{len}(v_1, \dots, v_{n+1}) = n + 1 \leq \dim V$. * This contradicts with the fact that $\dim V = n < n + 1$. So, our assumption is incorrect, and it must be that v_1, \dots, v_n is a basis of V . ■

Theorem 2.3.7

Suppose V is f - d . Then, every spanning list of vectors in V with length $\dim V$ is a basis of V .

Example 2.3.8 Show that $1, (x-5)^2, (x-5)^3$ is a basis of the subspace U of $\mathcal{P}_3(\mathbb{R})$ defined by

$$U = \{p \in \mathcal{P}_3(\mathbb{R}) \mid p'(5) = 0\}.$$

Proof 6. Consider $a_1 + a_2(x-5)^2 + a_3(x-5)^3 = 0$, we will get $a_1 = a_2 = a_3 = 0$ easily from the equation. Then, $1, (x-5)^2, (x-5)^3$ is L.I.. So, by Theorem 2.3.5, we know $\dim U \geq 3$. Since $U \subsetneq \mathcal{P}_3(\mathbb{R})$, we have $\dim U < \dim \mathcal{P}_3(\mathbb{R}) = 4$. Therefore, $\dim U = 3 = \text{len}(1, (x-5)^2, (x-5)^3)$. By Theorem 2.3.6, we know $1, (x-5)^2, (x-5)^3$ is a basis of U . ■

Theorem 2.3.9

If U_1 and U_2 are subspaces of a f - d vector space, then

$$\dim(U_1 + U_2) = \dim(U_1) + \dim(U_2) - \dim(U_1 \cap U_2).$$

Proof 7. Let u_1, \dots, u_m be a basis of $U_1 \cap U_2$, then $\dim(U_1 \cap U_2) = m$. Also, u_1, \dots, u_m is L.I. in U_1 , so we can extend it to a basis of U_1 as $u_1, \dots, u_m, v_1, \dots, v_j$. Then, $\dim(U_1) = m + j$. Similarly, extending u_1, \dots, u_m to a basis of U_2 , we will get $u_1, \dots, u_m, w_1, \dots, w_k$. So, $\dim(U_2) = m + k$. Now, we want to show $u_1, \dots, u_m, v_1, \dots, v_j, w_1, \dots, w_k$ is a basis of $U_1 + U_2$.

1. Since $U_1, U_2 \subseteq \text{span}(u_1, \dots, u_m, v_1, \dots, v_j, w_1, \dots, w_k)$, we know that

$$\text{span}(u_1, \dots, u_m, v_1, \dots, v_j, w_1, \dots, w_k) = U_1 + U_2. \quad \square$$

2. Suppose $a_1u_1 + \dots + a_mu_m + b_1v_1 + \dots + b_jv_j + c_1w_1 + \dots + c_kw_k = 0$. Then we know that

$$c_1w_1 + \dots + c_kw_k = -a_1u_1 - \dots - a_mu_m - b_1v_1 - \dots - b_jv_j.$$

Since $c_1w_1 + \dots + c_kw_k \in U_2$, and $-a_1u_1 - \dots - a_mu_m - b_1v_1 - \dots - b_jv_j \in U_1$, we know that $c_1w_1 + \dots + c_kw_k \in U_1 \cap U_2$. Therefore, $c_1w_1 + \dots + c_kw_k = d_1u_1 + \dots + d_mu_m$. Since $u_1, \dots, u_m, w_1, \dots, w_k$ is L.I., we know $c_1 = \dots = c_k = 0$. So, $-a_1u_1 - \dots - a_mu_m - b_1v_1 - \dots - b_jv_j = 0$. Since $u_1, \dots, u_m, v_1, \dots, v_j$ is L.I., we have $a_1 = \dots = a_m = b_1 = \dots = b_j = 0$. Therefore, we've proven $u_1, \dots, u_m, v_1, \dots, v_j, w_1, \dots, w_k$ is L.I. and thus is a basis of $U_1 + U_2$. ■

Since $u_1, \dots, u_m, v_1, \dots, v_j, w_1, \dots, w_k$ is a basis of $U_1 + U_2$, we know $\dim(U_1 + U_2) = m + j + k$. Further note that

$$\begin{aligned} \dim(U_1) + \dim(U_2) - \dim(U_1 \cap U_2) &= (m + j) + (m + k) - m \\ &= m + j + k \\ &= \dim(U_1 + U_2). \end{aligned}$$

■

3 Linear Maps

Notation 3.0.1. In this section, we use V and W to denote vector spaces over \mathbb{F} .

3.1 The Vector Space of Linear Maps

Definition 3.1.1 (Linear Map). A *linear map* from V to W is a function $T : V \rightarrow W$ with the following properties:

- additivity: $T(u + v) = Tu + Tv \quad \forall u, v \in V$.
- homogeneity: $T(\lambda v) = \lambda(Tv) \quad \forall \lambda \in \mathbb{F} \text{ and } \forall v \in V$.

Notation 3.1.2. The set of all linear maps from V to W is denoted by $\mathcal{L}(V, W)$.

Example 3.1.3

1. Zero-mapping: $0 \in \mathcal{L}(V, W)$ is defined by $0v = 0$.
2. Identity-mapping: $I \in \mathcal{L}(V, V)$ is defined by $Iv = v$.
3. Differentiation: $D \in \mathcal{L}(\mathcal{P}(\mathbb{R}), \mathcal{P}(\mathbb{R}))$ is defined by $Dp = p'$.

Proof 1. Note that $(f + g)' = f' + g'$ and $(\lambda f)' = \lambda f'$. ■

4. Integration: $T \in \mathcal{L}(\mathcal{P}(\mathbb{R}), \mathbb{R})$ is defined by $Tp = \int_0^1 p(x) dx$

Proof 2. Note that $\int_0^1 (f + g) = \int_0^1 f + \int_0^1 g$ and $\int_0^1 \lambda f = \lambda \int_0^1 f$. ■

5. Backward shift: $T \in \mathcal{L}(\mathbb{F}^\infty, \mathbb{F}^\infty)$ as $T(x_1, x_2, x_3, \dots) = (x_2, x_3, \dots)$.

Proof 3. Note that

$$\begin{aligned} T(x_1, x_2, x_3, \dots) + T(y_1, y_2, y_3, \dots) &= (x_2, x_3, \dots) + (y_2, y_3, \dots) \\ &= (x_2 + y_2, x_3 + y_3, \dots) \\ &= T(x_1 + y_1, x_2 + y_2, x_3 + y_3, \dots). \end{aligned}$$

Therefore, T is additive. Homogeneity of T is trivial and thus omitted here. ■

6. From \mathbb{F}^n to \mathbb{F}^m , we define $T \in \mathcal{L}(\mathbb{F}^n, \mathbb{F}^m)$ as

$$T(x_1, \dots, x_n) = (A_{1,1}x_1 + \dots + A_{1,n}x_n, \dots, A_{m,1}x_1 + \dots + A_{m,n}x_n),$$

where $A_{j,k} \in \mathbb{F} \quad \forall j = 1, \dots, m \text{ and } k = 1, \dots, n$.

Theorem 3.1.4

Suppose v_1, \dots, v_n is a basis of V and $w_1, \dots, w_n \in W$. Then, \exists a unique linear map $T : V \rightarrow W$ s.t. $Tv_j = w_j \quad \forall j = 1, \dots, n$.

Remark. If T in Theorem 3.1.1 is a linear mapping, we should have

1. $T(v_1 + \cdots + v_n) = Tv_1 + \cdots + Tv_n = w_1 + \cdots + w_n$, by additivity of T , and
2. $T(\lambda_j v_j) = \lambda_j Tv_j$, by homogeneity of T .

Combine the two properties, we should have

$$T(\lambda_1 v_1 + \cdots + \lambda_n v_n) = \lambda_1 Tv_1 + \cdots = \lambda_n Tv_n = \lambda_1 w_1 + \cdots + \lambda_n w_n.$$

This remark will be very helpful in our following proof of the theorem.

Proof 4. Let's define $T : V \rightarrow W$ by $T(c_1 v_1 + \cdots + c_n v_n) = c_1 w_1 + \cdots + c_n w_n$, where c_1, \dots, c_n are arbitrary elements of \mathbb{F} . Now, we want to show that T is a linear mapping.

Suppose $u, v \in V$, $u = a_1 v_1 + \cdots + a_n v_n$, and $v = c_1 v_1 + \cdots + c_n v_n$. Then, we have

$$\begin{aligned} T(u + v) &= T((a_1 + c_1)v_1 + \cdots + (a_n + c_n)v_n) \\ &= (a_1 + c_1)w_1 + \cdots + (a_n + c_n)w_n \\ &= (a_1 w_1 + \cdots + a_n w_n) + (c_1 w_1 + \cdots + c_n w_n) \\ &= Tu + Tv. \quad \square \end{aligned}$$

Now, we want to show T has homogeneity. Suppose $\lambda \in \mathbb{F}$. Then, we know

$$\begin{aligned} T(\lambda v) &= T(\lambda c_1 v_1 + \cdots + \lambda c_n v_n) \\ &= \lambda c_1 w_1 + \cdots + \lambda c_n w_n \\ &= \lambda(c_1 w_1 + \cdots + c_n w_n) \\ &= \lambda Tv. \quad \square \end{aligned}$$

Also, we want to show that this T satisfy the condition the theorem is asking (i.e., $Tv_j = w_j$). Note that when $c_j = 0$ and other c 's equal 0, we will get $Tv_j = w_j$. \square

Finally, we will prove the uniqueness of this T . Suppose that $T' \in \mathcal{L}(V, W)$ and $T'v_j = w_j$. Let $c_1, \dots, c_n \in \mathbb{F}$. Then, $T'(c_j v_j) = c_j w_j$. So, we know that $T'(c_1 v_1 + \cdots + c_n v_n) = c_1 w_1 + \cdots + c_n w_n$. However, by definition, we know $c_1 w_1 + \cdots + c_n w_n = T(c_1 v_1 + \cdots + c_n v_n)$. So, we can conclude that $T'(c_1 v_1 + \cdots + c_n v_n) = T(c_1 v_1 + \cdots + c_n v_n)$. Thus, $T' = T$, and thus the T we defined above is unique in $\mathcal{L}(V, W)$. \blacksquare

Definition 3.1.5 (Addition and Scalar Multiplication on $\mathcal{L}(V, W)$). Suppose $S, T \in \mathcal{L}(V, W)$ and $\lambda \in \mathbb{F}$. Then, the *addition* is defined as $(S + T)(v) := Sv + Tv$, and the *scalar multiplication* is defined as $(\lambda T)(v) := \lambda(Tv) \quad \forall v \in V$.

Theorem 3.1.6

$\mathcal{L}(V, W)$ is a vector space.

Proof 5.

1. additive identity: Note that the zero-mapping $0 \in \mathcal{L}(V, W)$ satisfies the following equation:

$$(0 + T)(v) = 0v + Tv = 0 + Tv = Tv. \quad \square$$

2. commutativity: Note that

$$(S + T)(v) = Sv + Tv = Tv + Sv = (T + S)(v). \quad \square$$

3. associativity: Let $S, T, R \in \mathcal{L}(V, W)$. Then,

$$\begin{aligned} ((S + T) + R)(v) &= (S + T)(v) + Rv = Sv + Tv + Rv \\ &= Sv + (Tv + Rv) \\ &= Sv + (T + R)(v) \\ &= (S + (T + R))(v). \end{aligned}$$

Let $a, b \in \mathbb{F}$. Then,

$$((ab)T)(v) = T(abv) = T(a(bv)) = aT(bv) = (a(bT))(v). \quad \square$$

4. multiplicative identity: Note we have $1 \in \mathbb{F}$ s.t.

$$(1 \cdot T)(v) = T(1 \cdot v) = Tv. \quad \square$$

5. additive inverse: Note that

$$(T + (-T))(v) = Tv + (-T)(v) = Tv + T(-v) = T(v - v) = T0 = 0. \quad \square$$

6. distributivity: Note that

$$a(T + S)(v) = a(Tv + Sv) = aTv + aSv,$$

and

$$(a + b)Tv = T((a + b)v) = T(av + bv) = T(av) + T(bv) = aTv + bTv.$$

■

Definition 3.1.7 (Product of Linear Maps). If $T \in \mathcal{L}(U, V)$ and $S \in \mathcal{L}(V, W)$, then the *product* $ST \in \mathcal{L}(U, W)$ is defined by $(ST)(u) = S(Tu) \quad \forall u \in U$.

Remark. Compare this definition with composite functions. ST is only defined when T maps into the domain of S .

Theorem 3.1.8 Algebraic Properties of Products of Linear Maps

1. associativity: $(T_1 T_2) T_3 = T_1 (T_2 T_3)$.
2. identity: $TI = IT = T$, where I is the identity mapping
3. distributive properties: $(S_1 + S_2)T = S_1 T + S_2 T$ and $S(T_1 + T_2) = ST_1 + ST_2$.

Proof 6. First, we want to show the associativity. Note that

$$[(T_1 T_2) T_3](v) = (T_1 T_2)(T_3 v) = (T_1)(T_2(T_3 v)) = (T_1)[(T_2 T_3)(v)]. \quad \square$$

Then, we want to show the identity. This proof can be done using the following diagram:

$$\begin{array}{ccc}
 V & \xrightarrow{T} & W \\
 I_V \uparrow & & \downarrow I_W \\
 V & & W
 \end{array}
 \quad \square$$

Finally, we will show the distributive properties. Note that

$$\begin{aligned}
 [(S_1 + S_2)T](v) &= (S_1 + S_2)(Tv) = S_1(Tv) + S_2(Tv) \\
 &= (S_1T)(v) + (S_2T)(v) \\
 &= (S_1T + S_2T)(v).
 \end{aligned}$$

Similarly, we can show

$$\begin{aligned}
 [S(T_1 + T_2)](v) &= S[(T_1 + T_2)(v)] = S(T_1v + T_2v) \\
 &= S(T_1v) + S(T_2v) \\
 &= (ST_1)(v) + (ST_2)(v) \\
 &= (ST_1 + ST_2)(v).
 \end{aligned}$$

■

Example 3.1.9 Suppose $D \in \mathcal{L}(\mathcal{P}(\mathbb{R}), \mathcal{P}(\mathbb{R}))$ is the differentiation map, and $T \in \mathcal{L}(\mathcal{P}(\mathbb{R}), \mathcal{P}(\mathbb{R}))$ be defined by $(Tp)(x) = x^2p(x)$. Show that $DT \neq TD$.

Proof 7. Note that $(DT)p = D(Tp) = D(x^2p(x)) = 2xp(x) + x^2p'(x)$. Similarly, we can compute a general formula for TD : $(TD)p = T(Dp) = T(p') = x^2p'(x)$. Since $2xp(x) + x^2p'(x) \neq x^2p'(x)$, we know $DT \neq TD$. ■

Theorem 3.1.10

Let $T \in \mathcal{L}(V, W)$, then $T(0) = 0$.

Proof 8. Since $T(0) = T(0 + 0) = T(0) + T(0)$, we know $0 = T(0)$, or $T(0) = 0$. ■

Corollary 3.1.11 If $T(0) \neq 0$, then $T \notin \mathcal{L}(V, W)$.

3.2 Null Spaces and Ranges

Definition 3.2.1 (Null Space/Kernel). For $T \in \mathcal{L}(V, W)$, the *null space* of T , denoted $\text{null } T$, is the subset of V consisting of those vectors that T maps to 0: $\text{null } T = \{v \in V \mid Tv = 0\}$.

Remark. Sometimes, null space of T is also called the kernal of T , denoted as $\ker T$.

Example 3.2.2

1. Null space of zero-mapping: Let T be the zero mapping from V to W . Since $Tv = 0 \quad \forall v \in V$, we know $\text{null } T = V$.
2. $D \in \mathcal{L}(\mathcal{P}(\mathbb{R}), \mathcal{P}(\mathbb{R}))$ as $Dp = p'$: $\text{null } D = \{a \mid a \in \mathbb{R}\}$.
3. $T \in \mathcal{L}(\mathbb{F}^\infty, \mathbb{F}^\infty)$ as $T(x_1, x_2, x_3, \dots) = (x_2, x_3, \dots)$: $\text{null } T = \{(a, 0, 0, \dots) \mid a \in \mathbb{F}\}$.

Theorem 3.2.3

Suppose $T \in \mathcal{L}(V, W)$. Then, $\text{null } T$ is a subspace of V .

Proof 1.

1. Note that $T(0) = 0$, so $0 \in \text{null } T$. \square
2. Suppose $u, v \in \text{null } T$. Then, $Tu = Tv = 0$. So, $T(u + v) = Tu + Tv = 0 + 0 = 0$. Hence, $u + v \in \text{null } T$. \square
3. Suppose $u \in \text{null } T$ and $\lambda \in \mathbb{F}$. Then, $Tu = 0$. So, $T(\lambda u) = \lambda Tu = \lambda \cdot 0 = 0$. Therefore, $\lambda u \in \text{null } T$. \blacksquare

Definition 3.2.4 (Injective/Injection). A function $T : V \rightarrow W$ is called *injective* if $Tu = Tv$ implies $u = v$.

Remark. Sometimes, the contrapositive will be much more helpful: T is injective if $u \neq v$, then $Tu \neq Tv$.

Theorem 3.2.5

Let $T \in \mathcal{L}(V, W)$. Then, T is injective if and only if $\text{null } T = \{0\}$.

Proof 2.

(\Rightarrow) Suppose T is an injective. We've already known that $\{0\} \subseteq \text{null } T$. Then, we need to show $\text{null } T \subseteq \{0\}$. Suppose $v \in \text{null } T$, then $Tv = 0$. However, since T is an injection, and $Tv = T0 = 0$, then we have $v = 0$. So, $\text{null } T \subseteq \{0\}$. Therefore, it's sufficient to say $\text{null } T = \{0\}$. \square

(\Leftarrow) Suppose $\text{null } T = \{0\}$. Suppose $u, v \in V$ and $Tu = Tv$. Then, $Tu - Tv = T(u - v) = 0$. Hence, $u - v \in \text{null } T$. By $\text{null } T = \{0\}$, we know $u - v = 0$, so $u = v$. Then, T is an injection. \blacksquare

Definition 3.2.6 (Range/Image). For $T \in \mathcal{L}(V, W)$, the range of T is the subset of W consisting of those vectors that are of the form Tv for some $v \in V$: $\text{range } T = \{Tv \mid v \in V\}$.

Theorem 3.2.7

If $T \in \mathcal{L}(V, W)$, then $\text{range } T$ is a subspace of W .

Proof 3.

1. Since $T(0) = 0$, we know $0 \in \text{range } T$. \square
2. Suppose $w_1, w_2 \in \text{range } T$. Then, $\exists v_1, v_2 \in V$ s.t. $Tv_1 = w_1$ and $Tv_2 = w_2$. Then, $w_1 + w_2 = Tv_1 + Tv_2 = T(v_1 + v_2)$. Since $v_1 + v_2 \in V$, we have $w_1 + w_2 = T(v_1 + v_2) \in \text{range } T$. \square
3. Suppose $w \in \text{range } T$ and $\lambda \in \mathbb{F}$. Then, $\exists v \in V$ s.t. $w = Tv$. So, $\lambda w = \lambda(Tv) = T(\lambda v)$. Since $\lambda v \in V$, $\lambda w = T(\lambda v) \in \text{range } T$. \blacksquare

Definition 3.2.8 (Surjective/Surjection). A function $T : V \rightarrow W$ is called *surjective* if $\text{range } T = W$.

Remark. A function $T : V \rightarrow W$ is called a *bijection*, or is *bijjective*, if it is both injective and surjective.

Theorem 3.2.9 Fundamental Theorem of Linear Maps

Suppose V is f - d and $T \in \mathcal{L}(V, W)$. Then, $\text{range } T$ is f - d and

$$\dim V = \dim \text{null } T + \dim \text{range } T.$$

Proof 4. Let u_1, \dots, u_m be a basis of $\text{null } T$. Then, $\dim \text{null } T = m$. By Theorem 3.2.3, we know $\text{null } T$ is a basis of V , so we can extend the basis to a basis of V : $u_1, \dots, u_m, v_1, \dots, v_n$. Thus, $\dim V = m + n$. WTS: $\dim \text{range } T = n$. Further WTS: Tv_1, \dots, Tv_n is a basis of $\text{range } T$.

Suppose $v \in V$. Then

$$v = a_1u_1 + \dots + a_mu_m + b_1v_1 + \dots + b_nv_n.$$

Since $u_1, \dots, u_m \in \text{null } T$, we know $Tu_1, \dots, Tu_m = 0$. Therefore,

$$Tv = a_1Tu_1 + \dots + a_mTu_m + b_1Tv_1 + \dots + b_nTv_n = b_1Tv_1 + \dots + b_nTv_n.$$

Hence, $\text{span}(Tv_1, \dots, Tv_n) = \text{range } T$, and thus $\text{range } T$ is f - d . Now, WTS: Tv_1, \dots, Tv_n is L.I..

Consider $c_1Tv_1 + \dots + c_nTv_n = 0$. Then, $T(c_1v_1 + \dots + c_nv_n) = 0$. Hence, $c_1v_1 + \dots + c_nv_n \in \text{null } T$. Since u_1, \dots, u_m is a basis of $\text{null } T$, we know

$$c_1v_1 + \dots + c_nv_n = d_1u_1 + \dots + d_mu_m \quad f.s. d_i \in \mathbb{F}.$$

So,

$$c_1v_1 + \dots + c_nv_n - d_1u_1 - \dots - d_mu_m = 0. \quad (8)$$

However, by assumption, we know $v_1, \dots, v_n, u_1, \dots, u_m$ is a basis of V , and thus it is L.I.. So, the only way to make Equation (8) hold is by taking $c_1 = \dots = c_n = -d_1 = \dots = -d_m = 0$. Therefore, we've shown Tv_1, \dots, Tv_n is L.I., and thus is a basis of $\text{range } T$. Then, $\dim \text{range } T = n$.

So, we've shown that $\dim \text{null } T + \dim \text{range } T = m + n = \dim V$. \blacksquare

Theorem 3.2.10

Suppose V and W are f - d vector spaces s.t. $\dim V > \dim W$. Then, no linear map from V to W is injective.

Proof 5. Let $T \in \mathcal{L}(V, W)$. By the Fundamental Theorem of Linear Maps, we have $\dim V = \dim \text{null } T + \dim \text{range } T$. Then, we know

$$\begin{aligned} \dim \text{null } T &= \dim V - \dim \text{range } T \\ &\geq \dim V - \dim W > 0 \quad [\dim \text{range } T \leq \dim W] \end{aligned}$$

This implies that $\text{null } T \neq \{0\}$. So, T is not injective by Theorem 3.2.5. ■

Theorem 3.2.11

Suppose V and W are f - d vector space s.t. $\dim V < \dim W$. Then, no linear map from V to W is surjective.

Proof 6. We know

$$\begin{aligned} \dim \text{range } T &= \dim V - \dim \text{null } T \\ &\leq \dim V < \dim W \end{aligned}$$

Then, T cannot be surjective by definition. ■

Example 3.2.12 Solving Linear Systems Using Linear Maps I

For a homogenous system of linear equations,

$$\begin{cases} A_{1,1}x_1 + \cdots + A_{1,n}x_n = 0 \\ \vdots \\ A_{m,1}x_1 + \cdots + A_{m,n}x_n = 0 \end{cases},$$

where $A_{j,k} \in \mathbb{F}$ and $(x_1, \dots, x_n) \in \mathbb{F}^n$, we can defined a linear map $T : \mathbb{F}^n \rightarrow \mathbb{F}^m$ as

$$T(x_1, \dots, x_n) = \left(\sum_{k=1}^n A_{1,k}x_k, \dots, \sum_{k=1}^n A_{m,k}x_k \right).$$

Apparently, $(x_1, \dots, x_n) = 0$ is a solution to the system, but the question is “If there are any non-zero solutions for this linear system?”

Theorem 3.2.13

A homogeneous system of linear equations with more variables than equations has non-zero solutions.

Proof 7. Suppose $T \in \mathcal{L}(V, W)$. Then, $\dim V = n$ and $\dim W = m$. Suppose $n > m$. So, $\dim V > \dim W$. By the Theorem 3.2.5, we know T is not injective. ■

Example 3.2.14 Solving Linear Systems Using Linear Maps II

For an inhomogeneous system of linear equations

$$\begin{cases} \sum_{k=1}^n A_{1,k}x_k = c_1 \\ \vdots \\ \sum_{k=1}^n A_{m,k}x_k = c_m \end{cases},$$

where $A_{j,k} \in \mathbb{F}$ and $(c_1, \dots, c_m) \in \mathbb{F}^m$ and $(x_1, \dots, x_n) \in \mathbb{F}^n$, we can define $T : \mathbb{F}^n \rightarrow \mathbb{F}^m$ by

$$T(x_1, \dots, x_n) = \left(\sum_{k=1}^n A_{1,k}x_k, \dots, \sum_{k=1}^n A_{m,k}x_k = c_1 \right).$$

However, in this case, $(x_1, \dots, x_n) = 0$ may not be a solution to the system.

Theorem 3.2.15

An inhomogeneous system of linear equations with more equations than variables has no solution for some choice of the constant terms.

Proof 8. Suppose $T \in \mathcal{L}(V, W)$. So, $\dim V = n$ and $\dim W = m$. Suppose $n < m$. Then, $\dim V < \dim W$. By Theorem 3.2.11, we know T is not surjective. ■

3.3 Matrices

Definition 3.3.1 (Matrix). Let $m, n \in \mathbb{Z}^+$. An m -by- n *matrix* A is a rectangular array of elements of \mathbb{F} with m rows and n columns:

$$A = \begin{pmatrix} A_{1,1} & \cdots & A_{1,n} \\ \vdots & & \vdots \\ A_{m,1} & \cdots & A_{m,n} \end{pmatrix}.$$

The notation $A_{j,k}$ denotes the entry in row j , column k of A .

Definition 3.3.2 (Matrix of a Linear Map). Suppose $T \in \mathcal{L}(V, W)$ and v_1, \dots, v_n is a basis of V and w_1, \dots, w_m is a basis of W . The *matrix of T* with respect to these bases is the $m \times n$ matrix $\mathcal{M}(T)$ whose $A_{j,k}$ are defined by

$$Tv_k = A_{1,k}w_1 + \cdots + A_{m,k}w_m.$$

If the bases are not clear from the context, then the notation $\mathcal{M}(T, (v_1, \dots, v_n), (w_1, \dots, w_m))$ is used.

Example 3.3.3 Suppose $T \in \mathcal{L}(\mathbb{F}^2, \mathbb{F}^3)$ is defined by $T(x, y) = (x + 3y, 2x + 5y, 7x + 9y)$. Find the matrix of T with respect to the standard bases of \mathbb{F}^2 and \mathbb{F}^3 .

Solution 1.

Note that $T(1, 0) = (1, 2, 7)$ and $T(0, 1) = (3, 5, 9)$. Then,

$$\mathcal{M}(T) = \begin{pmatrix} 1 & 3 \\ 2 & 5 \\ 7 & 9 \end{pmatrix}.$$

□

Example 3.3.4 Suppose $D \in \mathcal{L}(\mathcal{P}_3(\mathbb{R}), \mathcal{P}_2(\mathbb{R}))$ is the differentiation map defined by $Dp = p'$. Find the matrix of D with respect to the standard bases of $\mathcal{P}_3(\mathbb{R})$ and $\mathcal{P}_2(\mathbb{R})$.

Solution 2.

Standard bases of $\mathcal{P}_3(\mathbb{R})$: $1, x, x^2, x^3$. Standard bases of $\mathcal{P}_2(\mathbb{R})$: $1, x, x^2$. Since $(x^n)' = nx^{n-1}$, so we have

$$D(1) = 0 = 0 \cdot 1 + 0 \cdot x + 0 \cdot x^2$$

$$D(x) = 1 = 1 \cdot 1 + 0 \cdot x + 0 \cdot x^2$$

$$D(x^2) = 2x = 0 \cdot 1 + 2 \cdot x + 0 \cdot x^2$$

$$D(x^3) = 3x^2 = 0 \cdot 1 + 0 \cdot x + 3 \cdot x^2$$

So, we have

$$\mathcal{M}(D) = \begin{pmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 2 & 0 \\ 0 & 0 & 0 & 3 \end{pmatrix}.$$

□

Definition 3.3.5 (Matrix Addition). The *sum of two matrices of the same size* is the matrix obtained by

adding corresponding entries in the matrices:

$$\begin{pmatrix} A_{1,1} & \cdots & A_{1,n} \\ \vdots & & \vdots \\ A_{m,1} & \cdots & A_{m,n} \end{pmatrix} + \begin{pmatrix} C_{1,1} & \cdots & C_{1,n} \\ \vdots & & \vdots \\ C_{m,1} & \cdots & C_{m,n} \end{pmatrix} = \begin{pmatrix} A_{1,1} + C_{1,1} & \cdots & A_{1,n} + C_{1,n} \\ \vdots & & \vdots \\ A_{m,1} + C_{m,1} & \cdots & A_{m,n} + C_{m,n} \end{pmatrix}.$$

Theorem 3.3.6

Suppose $S, T \in \mathcal{L}(V, W)$. Then, $\mathcal{M}(S + T) = \mathcal{M}(S) + \mathcal{M}(T)$.

Proof 3. Let v_1, \dots, v_n be a basis of V and w_1, \dots, w_m be a basis of W . Suppose $\mathcal{M}(S) = A$ and $\mathcal{M}(T) = C$. Then, if $1 \leq k \leq n$, we have

$$\begin{aligned} (S + T)v_k &= Sv_k + Tv_k \\ &= (A_{1,k}w_1 + \cdots + A_{m,k}w_m) + (C_{1,k}w_1 + \cdots + C_{m,k}w_m) \\ &= (A_{1,k} + C_{1,k})w_1 + \cdots + (A_{m,k} + C_{m,k})w_m. \end{aligned}$$

Hence, we have $\mathcal{M}(S + T) = \mathcal{M}(S) + \mathcal{M}(T)$. ■

Definition 3.3.7 (Scalar Multiplication of a Matrix). The *product of a scalar and a matrix* is the matrix obtained by multiplying each entry in the matrix by the scalar:

$$\lambda \begin{pmatrix} A_{1,1} & \cdots & A_{1,n} \\ \vdots & & \vdots \\ A_{m,1} & \cdots & A_{m,n} \end{pmatrix} = \begin{pmatrix} \lambda A_{1,1} & \cdots & \lambda A_{1,n} \\ \vdots & & \vdots \\ \lambda A_{m,1} & \cdots & \lambda A_{m,n} \end{pmatrix}.$$

In other words, $(\lambda A)_{j,k} = \lambda A_{j,k}$.

Theorem 3.3.8

Suppose $\lambda \in \mathbb{F}$ and $T \in \mathcal{L}(V, W)$. Then, $\mathcal{M}(\lambda T) = \lambda \mathcal{M}(T)$.

Proof 4. Let v_1, \dots, v_n be a basis of V and $\mathcal{M}(T) = A$. When $1 \leq k \leq n$, note that

$$\begin{aligned} (\lambda T)v_k &= \lambda(Tv_k) \\ &= \lambda(A_{1,k}w_1 + \cdots + A_{m,k}w_m) \\ &= (\lambda A_{1,k})w_1 + \cdots + (\lambda A_{m,k})w_m. \end{aligned}$$

So, $\mathcal{M}(\lambda T) = \lambda \mathcal{M}(T)$. ■

Notation 3.3.9. $\mathbb{F}^{m,n} :=$ the set of all $m \times n$ matrices with entries in \mathbb{F} .

Theorem 3.3.10

Suppose $m, n \in \mathbb{Z}^+$. With addition and scalar multiplication defined above, $\mathbb{F}^{m,n}$ is a vector space and $\dim \mathbb{F}^{m,n} = mn$.

Proof 5. It is trivial to prove $\mathbb{F}^{m,n}$ is a vector space. □

Define $A_{j,k}$ as the matrix with 1 on its j^{th} row, k^{th} column and 0 elsewhere. Then, we can see that $A_{j,k}$ for $j = 1, \dots, m$ and $k = 1, \dots, n$ is a basis for $\mathbb{F}^{m,n}$. So, $\dim \mathbb{F}^{m,n} = m \cdot n$. ■

Definition 3.3.11 (Matrix Multiplication). Suppose A is an $m \times n$ matrix and C is an $n \times p$ matrix. Then,

AC is defined to be the $m \times p$ matrix whose entry in row j . column k is given by

$$(AC)_{j,k} = \sum_{r=1}^n A_{j,r} C_{r,k}.$$

Remark. *Matrix multiplication is not commutative. i.e., $AC \neq CA$. However, it is distributive and associative.*

Theorem 3.3.12

If $T \in \mathcal{L}(U, V)$ and $S \in \mathcal{L}(V, W)$, then $\mathcal{M}(ST) = \mathcal{M}(S)\mathcal{M}(T)$.

Notation 3.3.13. Suppose A is an $m \times n$ matrix.

1. If $1 \leq j \leq m$, then $A_{j,\cdot}$ denotes the $1 \times n$ matrix consisting of row j of A .
2. If $1 \leq k \leq n$, then $A_{\cdot,k}$ denotes the $m \times 1$ matrix consisting of column k of A .

In other words,

$$A = \begin{pmatrix} A_{1,1} & \cdots & A_{1,n} \\ \vdots & & \vdots \\ A_{m,1} & \cdots & A_{m,n} \end{pmatrix}; \quad A_{j,\cdot} = (A_{j,1} \quad \cdots \quad A_{j,n}) \in \mathbb{F}^{1,n}; \quad A_{\cdot,k} = \begin{pmatrix} A_{1,k} \\ \vdots \\ A_{m,k} \end{pmatrix} \in \mathbb{F}^{m,1}.$$

Theorem 3.3.14 Practical Interpretations of Matrix Multiplication

1. Suppose A is an $m \times n$ matrix and C is an $n \times p$ matrix. Then, $(AC)_{j,k} = A_{j,\cdot} C_{\cdot,k}$ for $1 \leq j \leq m$ and $1 \leq k \leq p$.
2. Suppose A is an $m \times n$ matrix and C is an $n \times p$ matrix. Then, $(AC)_{\cdot,k} = AC_{\cdot,k}$ for $1 \leq k \leq p$.

3. Suppose A is an $m \times n$ matrix and $C = \begin{pmatrix} c_1 \\ \vdots \\ c_n \end{pmatrix}$ is an $n \times 1$ matrix. Then,

$$AC = c_1 A_{\cdot,1} + \cdots + c_n A_{\cdot,n}.$$

In other words, AC is a linear combination of the columns of A , with the scalars that multiply the columns coming from C .

Example 3.3.15

$$\begin{pmatrix} 1 & 2 \\ 3 & 4 \\ 5 & 6 \end{pmatrix} \begin{pmatrix} 5 \\ 1 \end{pmatrix} = 5 \begin{pmatrix} 1 \\ 3 \\ 5 \end{pmatrix} + 1 \begin{pmatrix} 2 \\ 4 \\ 6 \end{pmatrix} = \begin{pmatrix} 7 \\ 19 \\ 31 \end{pmatrix}.$$

3.4 Invertibility and Isomorphic Vector Spaces

Definition 3.4.1 (Invertible). A linear map $T \in \mathcal{L}(V, W)$ is called *invertible* if \exists a linear map $S \in \mathcal{L}(W, V)$ s.t. ST equals the identity map on V and TS equals the identity map on W .

Definition 3.4.2 (Inverse). A linear map $S \in \mathcal{L}(W, V)$ satisfying $ST = I$ and $TS = I$ is called an *inverse* of T .

Theorem 3.4.3

An invertible linear map has a unique inverse.

Proof 1. Suppose $T \in \mathcal{L}(V, W)$ is invertible. Let S_1 and S_2 be inverses of T . Then,

$$S_1 = S_1 I = S_1 (TS_2) = (S_1 T) S_2 = I S_2 = S_2.$$

Thus, $S_1 = S_2$, and so inverse is unique. ■

Notation 3.4.4. If T is invertible, then its inverse is denoted by T^{-1} .

Theorem 3.4.5

A linear map is invertible if and only if it is injective and surjective.

Proof 2.

(\Rightarrow) Let $T \in \mathcal{L}(V, W)$ be invertible. Then, $TT^{-1} = I_W$ and $T^{-1}T = I_V$. Let $Tv = 0$. Note that $(T^{-1}T)v = 0$, so $Iv = 0$ and thus $v = 0$. Therefore, $\text{null } T = \{0\}$, and so T is an injection.

To show T is surjective, suppose $w \in W$. Note that since $T^{-1} \in \mathcal{L}(W, V)$, $T^{-1}w \in V$. So,

$$T(T^{-1}w) = (TT^{-1})w = I_W w = w \in W.$$

Therefore, $T^{-1}w$ is the $v \in V$ we intend to find. Hence, T is also a surjection. □

(\Leftarrow) Let T be surjective and injective. For $w \in W$, define $Sw \in V$ s.t. $T(Sw) = w$. So, we know Sw is unique. Since $(T \circ S)w = w$, we know $(T \circ S) = I_W$. Consider $(S \circ T)v = S(Tv)$, we have $T(S(Tv)) = Tv$, by definition of S . Since T is injective, we know $S(Tv) = v$. So, $(S \circ T)v = v$, and thus $ST = I_V$. Therefore T is invertible.

Now, we want to show S is a linear map. Let $w_1, w_2 \in W$, then

$$T(S(w_1 + w_2)) = (TS)(w_1 + w_2) = I_W(w_1 + w_2) = w_1 + w_2.$$

By definition, $w_1 + w_2 = T(Sw_1) + T(Sw_2) = T(Sw_1 + Sw_2)$. So, $T(S(w_1 + w_2)) = T(Sw_1 + Sw_2)$. By T is an injection, we have $S(w_1 + w_2) = Sw_1 + Sw_2$. So, S is additive. Further consider

$$T(S(\lambda w)) = \lambda w = \lambda(T(Sw)) = T(\lambda Sw)$$

for some $w \in W$. Again, since T is injective, $S(\lambda w) = \lambda Sw$. So, S has homogeneity. Then, S is a linear map. ■

Definition 3.4.6 (Isomorphism). An *isomorphism* is an invertible linear map.

Definition 3.4.7 (Isomorphic). Two vector spaces are called *isomorphic* if there is an isomorphism from one vector space onto the other one.

Notation 3.4.8. If two vector spaces V and W are isomorphic, we denote them as $V \cong W$.

Theorem 3.4.9

Suppose V and W are f -d vector spaces, then $V \cong W$ if and only if $\dim V = \dim W$.

Proof 3.

(\Rightarrow) Suppose $V \cong W$. By Fundamental Theorem of Linear Maps, we know

$$\dim V = \dim \text{null } T + \dim \text{range } T.$$

Since $V \cong W$, T is invertible and thus is injective and surjective. So, $\dim \text{null } T = 0$ and $\dim \text{range } T = \dim W$. Therefore, $\dim V = 0 + \dim W = \dim W$. \square

(\Leftarrow) Suppose $\dim V = \dim W$. Suppose v_1, \dots, v_n and w_1, \dots, w_n are bases of V and W , respectively. Then, $\dim V = \dim W = n$. Here, we want to define a bijection between V and W . Let T be defined as $Tv_i = wi$ ($i = 1, \dots, n$).

Let $Tv = 0$. Then, $T(a_1v_1 + \dots + a_nv_n) = 0$. So, by definition, $a_1w_1 + \dots + a_nw_n = 0$. Since w_1, \dots, w_n is a basis, we have $a_1 = \dots = a_n = 0$. So, $\text{null } T = \{0\}$, and thus T is an injection.

Let $w \in W$ be any vector. Then, we know $w = c_1w_1 + \dots + c_nw_n$. Note that, by definition of T , we have $T(c_1v_1 + \dots + c_nv_n) = c_1w_1 + \dots + c_nw_n$. Hence, $\forall w \in W, \exists v = c_1v_1 + \dots + c_nv_n \in V$ s.t. $Tv = w$. Therefore, T is a surjection.

Finally, it is trivial to show that T is indeed a linear map, and so the proof is complete. \blacksquare

Theorem 3.4.10

Suppose v_1, \dots, v_n is a basis of V and w_1, \dots, w_m is a basis of W . then, \mathcal{M} is an isomorphism between $\mathcal{L}(V, W)$ and $\mathbb{F}^{m,n}$.

Proof 4. We already know \mathcal{M} is linear, so we just need to show \mathcal{M} is a bijection.

To prove \mathcal{M} is injective, consider $\mathcal{M}(T) = 0$ for some $T \in \mathcal{L}(V, W)$. So, we get $Tv_k = 0$. Since v_1, \dots, v_n is a basis of V , we know $Tv = 0 \quad \forall v \in V$. Then, T is the zero-mapping, or $T = 0$. Therefore, $\text{null } \mathcal{M} = \{0\}$.

To show \mathcal{M} is surjective, suppose $A \in \mathbb{F}^{m,n}$. Let T be a linear map from V to W s.t.

$$Tv_k = \sum_{j=1}^m A_{j,k} w_j, \quad k = 1, \dots, n.$$

Obviously, $\mathcal{M}(T) = A$, and thus $\text{range } \mathcal{M} = \mathbb{F}^{m,n}$. So, \mathcal{M} is also a surjection. \blacksquare

Theorem 3.4.11

Suppose V and W are f -d. Then, $\mathcal{L}(V, W)$ is f -d and $\dim \mathcal{L}(V, W) = (\dim V)(\dim W)$.

Proof 5. By Theorem 3.4.10 and Theorem 3.4.9, we know $\dim \mathcal{L}(V, W) = \dim \mathbb{F}^{m,n}$. Further by Theorem 3.3.10, we know $\dim \mathbb{F}^{m,n} = (m)(n)$. As $\dim V = n$ and $\dim W = m$, so we have

$$\dim \mathcal{L}(V, W) = (\dim V)(\dim W).$$

Definition 3.4.12 (Matrix of a Vector, $\mathcal{M}(v)$). Suppose $v \in V$ and v_1, \dots, v_n is a basis of V . The *matrix*

of v with respect to this basis is the $n \times 1$ matrix

$$\mathcal{M}(v) = \begin{pmatrix} c_1 \\ \vdots \\ c_n \end{pmatrix},$$

where c_1, \dots, c_n are scalars s.t. $v = c_1 v_1 + \dots + c_n v_n$.

Theorem 3.4.13 $\mathcal{M}(T)_{\cdot, k} = \mathcal{M}(v_k)$

Suppose $T \in \mathcal{L}(V, W)$ and v_1, \dots, v_n is a basis of V and w_1, \dots, w_m is a basis of W . Let $1 \leq k \leq n$. Then, the k^{th} column of $\mathcal{M}(T)$, which is denoted by $\mathcal{M}(T)_{\cdot, k}$, equals $\mathcal{M}(v_k)$.

Proof 6. This theorem is an immediate result by definitions of matrix of a linear mapping and a vector. ■

Theorem 3.4.14

Suppose $T \in \mathcal{L}(V, W)$ and $v \in V$. Suppose v_1, \dots, v_n is a basis of V and w_1, \dots, w_m is a basis of W . Then, $\mathcal{M}(Tv) = \mathcal{M}(T)\mathcal{M}(v)$.

Proof 7. Note that $v = c_1 v_1 + \dots + c_n v_n$, so we have $Tv = c_1 T v_1 + \dots + c_n T v_n$. So, by Theorem 3.4.13, we know

$$\begin{aligned} \mathcal{M}(Tv) &= c_1 \mathcal{M}(T v_1) + \dots + c_n \mathcal{M}(T v_n) \\ &= c_1 \mathcal{M}(T)_{\cdot, 1} + \dots + c_n \mathcal{M}(T)_{\cdot, n} \\ &= \mathcal{M}(T) \mathcal{M}(v). \end{aligned}$$

The final equality holds due to our interpretation of matrix multiplication as column linear combinations (Theorem 3.3.14(3)) ■

Remark. $\mathcal{M} : \mathbb{F}^n \rightarrow \mathbb{F}^{n,1}$ is an isomorphism:

$$v = c_1 v_1 + \dots + c_n v_n \mapsto \begin{pmatrix} c_1 \\ \vdots \\ c_n \end{pmatrix}.$$

Proof 8. Suppose $\mathcal{M}(v) = 0$: $\mathcal{M}(c_1 v_1 + \dots + c_n v_n) = 0$. So, we have $c_1 w_1 + \dots + c_n w_n = 0$. Since w_1, \dots, w_n is a basis, $c_1 = \dots = c_n = 0$. So, $v = 0$. Therefore, $\text{null } \mathcal{M} = \{0\}$, and so \mathcal{M} is injective. □

Now, prove \mathcal{M} is surjective. Note that $\forall \begin{pmatrix} c_1 \\ \vdots \\ c_n \end{pmatrix}$, we have $\mathcal{M}(c_1 v_1 + \dots + c_n v_n) = \begin{pmatrix} c_1 \\ \vdots \\ c_n \end{pmatrix}$. So, \mathcal{M} is a surjection. □

Finally, it's trivial to prove \mathcal{M} is a linear map. □

Since \mathcal{M} is both surjective and injective, \mathcal{M} is an isomorphism. ■

Definition 3.4.15 (Operator). A linear map from a vector space to itself is called an *operator*.

Notation 3.4.16. The notation $\mathcal{L}(V)$ denotes the set of all operators on V . So, $\mathcal{L}(v) = \mathcal{L}(V, V)$.

Theorem 3.4.17

Suppose V is f - d and $T \in \mathcal{L}(V)$. Then, the following are equivalent: (a) T is invertible; (b) T is injective; and (c) T is surjective.

Proof 9.

1. Clearly (a) implies (b). \square

2. Suppose (b): T is injective. So, $\text{null } T = \{0\}$. Then, by Fundamental Theorem of Linear Maps, we know

$$\dim V = \dim \text{null } T + \dim \text{range } T = 0 + \dim \text{range } T.$$

Since $\dim \text{range } T = \dim V$, we know T is surjective. \square

3. Suppose (c): T is surjective. So, $\text{range } T = V$. Then, by Fundamental Theorem of Linear maps, we have

$$\dim \text{null } T = \dim V - \dim \text{range } T = 0.$$

So, $\text{null } T = \{0\}$, and thus T is injective. Since T is surjective and injective, T is invertible. ■

Example 3.4.18 Show that for each polynomial $q \in \mathcal{P}(\mathbb{R})$, there exists a polynomial $p \in \mathcal{P}(\mathbb{F})$ such that $((x^2 + 5x + 7)p)'' = q$.

Proof 10. We know that every non-zero polynomial must have a degree of m . So, we can think of this problem under $\mathcal{P}_m(\mathbb{R})$. Note that

$$((x^2 + 5x + 7)p)'' = 2p + (4x + 10)p' + (x^2 + 5x + 7)p'' = q.$$

Therefore, the degree of p and q should be the same. Define $T : \mathcal{P}_m(\mathbb{R}) \rightarrow \mathcal{P}_m(\mathbb{R})$ as

$$Tp = ((x^2 + 5x + 7)p)'.$$

Then, T is an operator on $\mathcal{P}_m(\mathbb{R})$. Consider $Tp = 0$. We have $ax + b = (x^2 + 5x + 7)p$. Note that only when $p = 0$, the equation above holds. So, it must be that $p = 0$ when $Tp = 0$. That is, $\text{null } T = \{0\}$, and so T is injective. By Theorem 3.4.18, we know T is also surjective, and so our proof is complete. ■

3.5 Duality

Definition 3.5.1 (Linear Functional). A *linear functional* on V is a linear map from V to \mathbb{F} . That is, a linear functional is an element of $\mathcal{L}(V, \mathbb{F})$.

Example 3.5.2

1. Fix $(c_1, \dots, c_n) \in \mathbb{F}^n$. Define $\varphi : \mathbb{F}^n \rightarrow \mathbb{F}$ by $\varphi(x_1, \dots, x_n) = c_1x_1 + \dots + c_nx_n$. Then, φ is a linear functional on \mathbb{F}^n .
2. Define $\varphi : \mathcal{P}(\mathbb{R}) \rightarrow \mathbb{R}$ as $\varphi(p) = 3p''(5) + 7p(4)$.
3. Define $\varphi : \mathcal{P}(\mathbb{R}) \rightarrow \mathbb{R}$ as $\varphi(p) = \int_0^1 p(x)dx$.

Definition 3.5.3 (Dual Space/ V'/V^*). The *dual space* of V , denoted as V' , is the vector space of all linear functionals on V . In other words, $V' = \mathcal{L}(V, \mathbb{F})$.

Theorem 3.5.4

Suppose V is f - d . Then, V' is also f - d and $\dim V' = \dim V$.

Proof 1. Note that for a general linear map, $\mathcal{L}(V, W) \cong \mathbb{F}^{m,n}$. So, $\mathcal{L}(V, \mathbb{F}) = V' \cong \mathbb{F}^{1,n}$. Hence,

$$\dim V' = \dim \mathbb{F}^{1,n} = 1 \cdot n = n = \dim V.$$

■

Definition 3.5.5 (Dual Basis). If v_1, \dots, v_n is a basis of V , then the *dual basis* of v_1, \dots, v_n is the list $\varphi_1, \dots, \varphi_n$ of elements of V' , where each φ_j is the linear functional on V s.t.

$$\varphi_j(v_k) = \begin{cases} 1 & \text{if } k = j \\ 0 & \text{if } k \neq j \end{cases}.$$

Example 3.5.6 Find the dual basis of $e_1, \dots, e_n \in \mathbb{F}^n$

Solution 2.

$$\begin{array}{cccc} \varphi_1(e_1) = 1 & \varphi_2(e_1) = 0 & \cdots & \varphi_n(e_1) = 0 \\ \varphi_1(e_2) = 0 & \varphi_2(e_2) = 1 & \cdots & \varphi_n(e_2) = 0 \\ \vdots & \vdots & \ddots & \vdots \\ \varphi_1(e_n) = 0 & \varphi_2(e_n) = 0 & \cdots & \varphi_n(e_n) = 1 \end{array}$$

Define φ_j as

$$\varphi_j(x) = \varphi_j(x_1, \dots, x_n) = x_1\varphi_j(e_1) + \dots + x_j\varphi_j(e_j) + \dots + x_n\varphi_j(e_n) = x_j.$$

□

Theorem 3.5.7

Suppose V is f -d. Then, the dual basis of a basis of V is a basis of V' .

Proof3. Suppose v_1, \dots, v_n is a basis of V and $\varphi_1, \dots, \varphi_n$ denotes the dual basis. Since we've shown $\dim V = \dim V'$ in Theorem 3.5.4, we only need to show $\varphi_1, \dots, \varphi_n$ is L.I.. Select $c_1\varphi_1 + \dots + c_n\varphi_n = 0$. Then,

$$(c_1\varphi_1 + \dots + c_n\varphi_n)(v) = 0 \quad \forall v \in V.$$

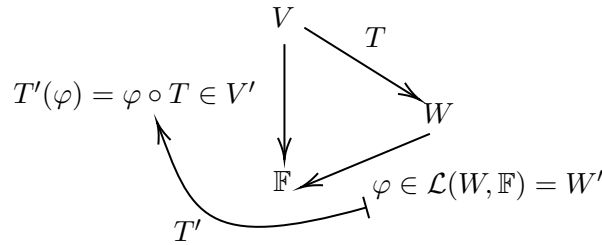
Suppose $v = v_1 + \dots + v_n$, then

$$(c_1\varphi_1 + \dots + c_n\varphi_n)(v_j) = c_j \quad \text{for } j = 1, \dots, n.$$

So, $(c_1\varphi_1 + \dots + c_n\varphi_n)(v) = c_1 + \dots + c_n = 0$. So, it must be that $c_1 = \dots = c_n = 0$. Therefore, $\varphi_1, \dots, \varphi_n$ is L.I. and our proof is complete. ■

Definition 3.5.8 (Dual Map). If $T \in \mathcal{L}(V, W)$, then the *dual map* of T is the linear map $T' \in \mathcal{L}(W', V')$ defined by $T'(\varphi) = \varphi \circ T$ for $\varphi \in W'$.

Remark. The following diagram represents dual map (but not an exact representation).



Also, dual map is a linear map, so it is additive and homogeneous.

1. $T'(\varphi + \psi) = (\varphi + \psi) \circ T = \varphi \circ T + \psi \circ T = T'(\varphi) + T'(\psi)$.
2. $T'(\lambda\varphi) = (\lambda\varphi) \circ T = \lambda(\varphi \circ T) = \lambda T'(\varphi)$.

Example 3.5.9 Suppose $D : \mathcal{P}(\mathbb{R}) \rightarrow \mathcal{P}(\mathbb{R})$ as $Dp = p'$.

1. Define a linear functional $\varphi : \mathcal{P}(\mathbb{R}) \rightarrow \mathbb{R}$ as $\varphi(p) = p(3)$. Find $D'(\varphi)$.

Solution 4.

$$(D'(\varphi))(p) = (\varphi \circ D)(p) = \varphi(Dp) = \varphi(p') = p'(3).$$

□

2. Define $\varphi : \mathcal{P}(\mathbb{R}) \rightarrow \mathbb{R}$, a linear functional, as $\varphi(p) = \int_0^1 p(x) dx$. Find $D'(\varphi)$.

Solution 5.

$$(D'(\varphi))(p) = (\varphi \circ D)(p) = \varphi(Dp) = \varphi(p') = \int_0^1 p'(x) dx = p(1) - p(0).$$

□

Theorem 3.5.10 Algebraic Properties of Dual Maps

1. $(S + T)' = S' + T' \quad \forall S, T \in \mathcal{L}(V, W)$
2. $(\lambda T)' = \lambda T' \quad \forall T \in \mathcal{L}(V, W)$
3. $(ST)' = T'S' \quad \forall T \in \mathcal{L}(U, V) \text{ and } S \in \mathcal{L}(V, W)$

Proof 6.

1. $(S + T)' \in \mathcal{L}(W', V')$. Let $\varphi \in W'$. Then,

$$(S + T)'(\varphi) = \varphi \circ (S + T) = \varphi \circ S + \varphi \circ T = S'(\varphi) + T'(\varphi) = (S' + T')(\varphi). \quad \square$$

2. $(\lambda T)' \in \mathcal{L}(W', V')$. Let $\varphi \in W'$. Then,

$$(\lambda T)'(\varphi) = \varphi \circ (\lambda T) = \lambda(\varphi \circ T) = \lambda T'(\varphi) = (\lambda T')(\varphi). \quad \square$$

3. $(ST)' \in \mathcal{L}(W', U')$. Let $\varphi \in W'$. Then,

$$(ST)'(\varphi) = \varphi \circ (ST) = \varphi \circ (S \circ T) = (\varphi \circ S) \circ T = (S'(\varphi)) \circ T = T'(S'(\varphi)) = (T'S')(\varphi).$$

Definition 3.5.11 (Transpose/ A^t). The transpose of a matrix A , denoted A^t , is the matrix obtained from A by interchanging the rows and columns. i.e., $(A^t)_{k,j} = A_{j,k}$. ■

Remark. Transpose is additive and homogeneous. That is, $(A + C)^t = A^t + C^t$ and $(\lambda A)^t = \lambda A^t$.

Theorem 3.5.12

If A is an $m \times n$ matrix and C is an $n \times p$ matrix, then $(AC)^t = C^t A^t$.

Proof 7. Note that

$$(AC)^t_{k,j} = (AC)_{j,k} = \sum_{r=1}^n A_{j,r} C_{r,k} = \sum_{r=1}^n (C^t)_{k,r} (A^t)_{r,j} = (C^t A^t)_{k,j}$$

Theorem 3.5.13

Suppose $T \in \mathcal{L}(V, W)$. Then, $\mathcal{M}(T') = (\mathcal{M}(T))^t$. ■

Proof 8. Suppose v_1, \dots, v_n is a basis of V , w_1, \dots, w_m is a basis of W , $\varphi_1, \dots, \varphi_n$ is a basis of V' , and ψ_1, \dots, ψ_m is a basis of W' . Let $A = \mathcal{M}(T)$ and $C = \mathcal{M}(T')$. Since $T'(\psi_j) = C_{1,j}\varphi_1 + \dots + C_{n,j}\varphi_n$ and $T'(\psi_j) = \psi_j \circ T$, we have $\psi_j \circ T = C_{1,j}\varphi_1 + \dots + C_{n,j}\varphi_n$. Consider

$$(\psi_j \circ T)(v_k) = (C_{1,j}\varphi_1 + \dots + C_{n,j}\varphi_n)(v_k) = C_{k,j}\varphi_k(v_k) = C_{k,j}.$$

Also, we have

$$(\psi_j \circ T)(v_k) = \psi_j(Tv_k) = \psi_j(A_{1,k}w_1 + \cdots + A_{m,k}w_m) = \psi_j(A_{j,k}w_j) = A_{j,k}(\varphi_j(w_j)) = A_{j,k}.$$

Therefore, we have $A_{j,k} = C_{k,j}$, and thus $A = C^t$. So, $\mathcal{M}(T) = (\mathcal{M}(T'))^t$. ■

Definition 3.5.14 (Annihilator/ U^0). For $U \subseteq V$, the *annihilator* of U , denoted as U^0 , is defined by

$$U^0 = \{\varphi \in V' \mid \varphi(u) = 0 \quad \forall u \in U\}.$$

Theorem 3.5.15

Suppose $U \subseteq V$. Then U^0 is a subspace of V' .

Proof 9.

1. $0 \in U^0$: Since $0(u) = 0 \quad \forall u \in U$, then $0 \in U^0$. □

2. Let $\varphi, \psi \in U^0$. Then,

$$(\varphi + \psi)(u) = \varphi(u) + \psi(u) = 0.$$

So, $\varphi + \psi \in U^0$. □

3. Let $\lambda \in \mathbb{F}$ and $\varphi \in U^0$. Then

$$(\lambda\varphi)(u) = \lambda\varphi(u) = \lambda \cdot 0 = 0.$$

So, $\lambda\varphi \in U^0$. ■

Lemma 3.5.16 Suppose V is f - d vector space. If U is a subspace of V and $S \in \mathcal{L}(U, W)$, then there exists $T \in \mathcal{L}(V, W)$ s.t. $Tu = Su \quad \forall u \in U$.

Proof 10. Suppose u_1, \dots, u_m is a basis of U . Then, we can extend it to a basis of V as $u_1, \dots, u_m, v_{m+1}, \dots, v_n$. Define $T \in \mathcal{L}(V, W)$ as $Tu_i = Su_i, Tv_j = 0$, where $i = 1, \dots, m$ and $j = m+1, \dots, n$. Note that

$$\begin{aligned} Tu &= T(a_1u_1 + \cdots + a_mu_m) \\ &= a_1Tu_1 + \cdots + a_mTu_m \\ &= a_1Su_1 + \cdots + a_mSu_m \\ &= S(a_1u_1 + \cdots + a_mu_m) = Su. \end{aligned}$$

Therefore, we've found such a T . ■

Theorem 3.5.17

Let V be f - d and U be a subspace of V , then $\dim U + \dim U^0 = \dim V$.

Proof 11. Let $i \in \mathcal{L}(U, V)$ as $i(u) = u \quad \forall u \in U$. Then, $i' \in \mathcal{L}(V', U')$. So, by Fundamental Theorem of Linear Map, we know

$$\dim V' = \dim \text{null } i' + \dim \text{range } i'. \quad (9)$$

By Theorem 3.5.4, we know $\dim V = \dim V'$. Note that $U^0 = \{\varphi \in V' \mid \varphi(u) = 0 \quad \forall u \in U\}$ and

$$\begin{aligned} \text{null } i' &= \{\varphi \in V' \mid i'(\varphi) = 0\} \\ &= \{\varphi \in V' \mid \varphi \circ i = 0\} \\ &= \{\varphi \in V' \mid (\varphi \circ i)(u) = 0 \quad \forall u \in U\} \\ &= \{\varphi \in V' \mid \varphi(u) = 0 \quad \forall u \in U\} \end{aligned}$$

So, $U^0 = \text{null } i'$, and thus $\dim \text{null } i' = \dim U^0$.

Further, if $\varphi \in U'$, then $\varphi : U \rightarrow \mathbb{F}$. By Lemma 3.5.16, φ can be extended to $\psi \in V'$ with $\psi(u) = \varphi(u) \quad \forall u \in U$. Note that $i'(\psi) = \psi \circ i$, so $(\psi \circ i)(u) = \psi(u) = \varphi(u) \quad \forall u \in U$. Then, $\exists \psi \in V'$ s.t. $i'(\psi) = \varphi$. So, $\varphi \in \text{range } i'$. So, $\dim \text{range } i' = \dim U' = \dim U$.

Substitute $\dim V' = \dim V$, $\dim \text{null } i' = \dim U^0$, and $\dim \text{range } i' = \dim U$ to Equation (9), we get

$$\dim V = \dim U^0 + \dim U.$$

Theorem 3.5.18 The Null Space of T'

Suppose V and W are f -d and $T \in \mathcal{L}(V, W)$. Then,

1. $\text{null } T' = (\text{range } T)^0$
2. $\dim \text{null } T' = \dim \text{null } T + \dim W - \dim V$

Proof 12.

1. (\subseteq) Suppose $\varphi \in \text{null } T' \subseteq W'$. Then, $T'(\varphi) = \varphi \circ T = 0 \in V'$. So, we know

$$(\varphi \circ T)(v) = 0 \quad \forall v \in V. \quad \text{i.e., } \varphi(Tv) = 0.$$

Note that $Tv \in \text{range } T$. By definition, we have $\varphi \in (\text{range } T)^0$ \square

(\supseteq) Suppose $\varphi \in (\text{range } T)^0$. Then, $\varphi(w) = 0 \quad \forall w \in \text{range } T$. That is, $\varphi(Tv) = 0 \quad \forall v \in V$. So, $(\varphi \circ T)(v) = 0 \quad \forall v \in V$. Hence, we know $\varphi \circ T = T'(\varphi) = 0 \in V'$. Thus, $\varphi \in \text{null } T'$ \blacksquare

- 2.

$$\begin{aligned} \dim \text{null } T' &= \dim(\text{range } T)^0 \\ &= \dim W - \dim \text{range } T \\ &= \dim W - (\dim V - \dim \text{null } T) \\ &= \dim W - \dim V + \dim \text{null } T. \end{aligned}$$

Theorem 3.5.19

Suppose V and W are f -d and $T \in \mathcal{L}(V, W)$. Then, T is surjective if and only if T' is injective.

Proof 13.

(\Rightarrow) Suppose T is surjective. Then, $\dim \text{range } T = W$. So, $(\text{range } T)^0 = \{0\}$. Hence,

$$\dim \text{null } T' = \dim(\text{range } T)^0 = 0.$$

Thus, T' is injective. \square

(\Leftarrow) Suppose T' is injective. Then,

$$\dim \text{null } T' = 0.$$

So, $\dim(\text{range } T)^0 = \dim \text{null } T' = 0$. Then, $(\text{range } T)^0 = \{0\}$. So, $\dim \text{range } T = W$, and thus T is surjective. \blacksquare

Theorem 3.5.20 The Range of T'

Suppose V and W are f -d and $T \in \mathcal{L}(V, W)$. Then,

1. $\dim \text{range } T' = \dim \text{range } T$
2. $\text{range } T' = (\text{null } T)^0$

Proof 14.

1. By Fundamental Theorem of Linear Map, we have

$$\begin{aligned} \dim \text{range } T' &= \dim W' - \dim \text{null } T' \\ &= \dim W' - \dim(\text{range } T)^0 \\ &= \dim W' - \dim W' + \dim \text{range } T \\ &= \dim \text{range } T. \end{aligned}$$

2. Suppose $\varphi \in \text{range } T' \subseteq V'$. Then, $\exists \psi \in W'$ s.t. $T'(\psi) = \psi \circ T = \varphi$. Let $v \in \text{null } T$. Then,

$$\varphi(v) = (\psi \circ T)(v) = \psi(Tv) = \psi(0) = 0.$$

Then, $\varphi \in (\text{null } T)^0$. So, $\text{range } T' \subseteq (\text{null } T)^0$. \square

Note that

$$\dim \text{range } T' = \dim \text{range } T = \dim V - \dim \text{null } T = \dim(\text{null } T)^0.$$

Then, $\text{range } T' \subseteq (\text{null } T)^0$ and $\dim \text{range } T' = \dim(\text{null } T)^0$, so it must be that $\text{range } T' = (\text{null } T)^0$. \blacksquare

Theorem 3.5.21

Suppose V and W are f -d and $T \in \mathcal{L}(V, W)$. Then, T is injective if and only if T' is surjective.

Proof 15.

(\Rightarrow) If T is injective, $\text{null } T = \{0\}$. So,

$$\dim \text{null } T = \dim V - \dim(\text{null } T)^0 = \dim V - \dim \text{range } T' = 0.$$

So, $\dim \text{range } T' = \dim V = \dim V'$. Then, T' is surjective. \square

(\Leftarrow) If T' is surjective, $\dim \text{range } T' = \dim V' = \dim V$. So,

$$\dim \text{null } T = \dim V - \dim(\text{null } T)^0 = \dim V - \dim \text{range } T' = 0.$$

Then, $\text{null } T = \{0\}$, and so T is injective. \blacksquare

Definition 3.5.22 (Row Rank & Column Rank). Suppose A is an $m \times n$ matrix with entries in \mathbb{F} .

1. The *row rank* of A is the dimension of the span of the rows of A in $\mathbb{F}^{1,n}$.
2. The *column rank* of A is the dimension of the span of the columns of A in $\mathbb{F}^{m,1}$.

Theorem 3.5.23

Suppose V and W are f -d and $T \in \mathcal{L}(V, W)$. Then, $\dim \text{range } T$ equals the column rank of $\mathcal{M}(T)$.

Proof 16. Suppose v_1, \dots, v_n is a basis of V and w_1, \dots, w_m is a basis of W . Then,

$$Tv_k = A_{1,k}w_1 + \dots + A_{m,k}w_m$$

and thus

$$\mathcal{M}(Tv_k) = \begin{pmatrix} A_{1,k} \\ \vdots \\ A_{m,k} \end{pmatrix} \in \mathbb{F}^{m,1}$$

Therefore, $\mathcal{M}(T) = \begin{pmatrix} \mathcal{M}(Tv_1) & \dots & \mathcal{M}(Tv_n) \end{pmatrix}$. Note that $\text{range } T = \text{span}(Tv_1, \dots, Tv_n)$.

Define $\mathcal{M} : \text{span}(Tv_1, \dots, Tv_n) \rightarrow \text{span}(\mathcal{M}(Tv_1), \dots, \mathcal{M}(Tv_n))$ as $w \mapsto \mathcal{M}(w)$.

1. \mathcal{M} is surjective: Note that

$$c_1\mathcal{M}(Tv_1) + \dots + c_n\mathcal{M}(Tv_n) = \mathcal{M}(c_1Tv_1 + \dots + c_nTv_n).$$

Since $c_1Tv_1 + \dots + c_nTv_n \in \text{range } T$, we know \mathcal{M} is surjective. \square

2. \mathcal{M} is injective: Let

$$\mathcal{M}(c_1Tv_1 + \dots + c_nTv_n) = 0. \tag{10}$$

We can reduce $c_1Tv_1 + \dots + c_nTv_n$ to a basis $Tv_{j_1}, \dots, Tv_{j_m}$. Then, Equation (10) becomes

$$\mathcal{M}(a_1Tv_{j_1} + \dots + a_mTv_{j_m}) = 0. \text{ By definition of matrix, we know } \begin{pmatrix} a_1 \\ \vdots \\ a_m \end{pmatrix} = 0. \text{ So, } a_1 = \dots = a_m = 0$$

and $a_1Tv_{j_1} + \dots + a_mTv_{j_m} = 0$. So, \mathcal{M} is injective. \square

Since \mathcal{M} is both surjective and injective, \mathcal{M} is a bijection. Thus, \mathcal{M} is an isomorphism between $\text{span}(Tv_1, \dots, Tv_n)$ and $\text{span}(\mathcal{M}(Tv_1), \dots, \mathcal{M}(Tv_n))$. In other words,

$$\text{span}(Tv_1, \dots, Tv_n) \cong \text{span}(\mathcal{M}(Tv_1), \dots, \mathcal{M}(Tv_n)).$$

Then, $\dim \text{span}(Tv_1, \dots, Tv_n) = \dim \text{span}(\mathcal{M}(Tv_1), \dots, \mathcal{M}(Tv_n))$. That is,

$$\dim \text{range } T = \text{column rank of } T.$$

■

Theorem 3.5.24 Row Rank Equals Column Rank

Suppose $A \in \mathbb{F}^{m,n}$. Then, the row rank of A equals the column rank of A .

Proof 17. Define $T : \mathbb{F}^{n,1} \rightarrow \mathbb{F}^{m,1}$ by $Tx = Ax$. Then, $\mathcal{M}(T) = A$, where $\mathcal{M}(T)$ is computed with respect to the standard basis of $\mathbb{F}^{n,1}$ and $\mathbb{F}^{m,1}$. Note that

$$\begin{aligned}
 \text{column rank of } A &= \text{column rank of } \mathcal{M}(T) \\
 &= \dim \text{range } T && \text{Theorem 3.5.23} \\
 &= \dim \text{range } T' && \text{Theorem 3.5.20(1)} \\
 &= \text{column rank of } \mathcal{M}(T') \\
 &= \text{column rank of } A^t && \text{Theorem 3.5.13} \\
 &= \text{row rank of } A
 \end{aligned}$$

■

Definition 3.5.25 (Rank). The *rank* of a matrix $A \in \mathbb{F}^{m,n}$ is the column rank of A , denoted as $\text{rank } A$.

3.6 Quotients of Vector Spaces

Definition 3.6.1 ($v + U$ /Affine Subset). Suppose $v \in V$ and U is a subspace of V . Then

$$v + U := \{v + u \mid u \in U\}.$$

An *affine subset* of V is a subset of V of the form $v + U$ for some $v \in V$ and some subspace U of V . The affine subset is said to be *parallel* to U .

Definition 3.6.2 (Quotient Space, V/U). Suppose U is a subspace of V . Then the quotient space V/U is the set of all affine subsets of V parallel to U . In other words,

$$V/U := \{v + U \mid v \in V\}.$$

Example 3.6.3 If $U = \{(x, 2x) \in \mathbb{R}^2 \mid x \in \mathbb{R}\}$, then \mathbb{R}^2/U is the set of all lines in \mathbb{R}^2 with slope of 2.

Theorem 3.6.4

Suppose U is a subspace of V and $v, w \in V$. Then, the following are equivalent:

1. $v - w \in U$
2. $v + U = w + U$
3. $(v + U) \cap (w + U) \neq \emptyset$

Proof 1.

1. We want to show (1) \implies (2). Suppose $v - w \in U$. Note that $v + u = w + ((v - w) + u)$. Since $v - w$ and $u \in U$, we have $(v - w) + u \in U$. So, $v + u \in w + U$. Similarly, we can show that $w + u \in v + U$. Then, we have $v + U = w + U$. \square
2. Now, we want to show (2) \implies (3): Suppose $v + U = w + U$. Then, we have $(v + U) \cap (w + U) \neq \emptyset$, which is evident from the assumption. \square
3. Finally, we will show (3) \implies (1). Suppose $(v + U) \cap (w + U) \neq \emptyset$. Then, $\exists u_1, u_2 \in U$ s.t. $v + u_1 = w + u_2$. So we have $v - w = u_2 - u_1 \in U$. \blacksquare

Definition 3.6.5 (Addition & Scalar Multiplication on V/U). Suppose U is a subspace of V . Then, *addition* and *scalar multiplication* is defined on V/U by

$$(v + U) + (w + U) = (v + w) + U$$

and

$$\lambda(v + U) = (\lambda v) + U$$

for $v, w \in U$ and $\lambda \in \mathbb{F}$.

Theorem 3.6.6

Suppose U is a subspace of V . Then, V/U , with the operations of addition and scalar multiplication defined above, is a vector space.

Proof2.

1. Addition on V/U makes sense.

Note the addition can be written in the language of mapping as $+: V/U \times V/U \rightarrow V/U$. So, we have $(v + U, w + U) \mapsto (v + w) + U$. Suppose $\exists \hat{v}, \hat{w} \in V$ s.t. $v + U = \hat{v} + U$ and $w + U = \hat{w} + U$. Note that $v - \hat{v} \in U$ and $w - \hat{w} \in U$ by Theorem 3.6.4. Then, $(v - \hat{v}) + (w - \hat{w}) \in U$. So, we have $(v + w) - (\hat{v} + \hat{w}) \in U$. Further, by Theorem 3.6.4, we have

$$(v + w) + U = (\hat{v} + \hat{w}) + U. \quad \square$$

2. Scalar multiplication on V/U makes sense.

We can write the scalar multiplication on V/U as a mapping: $\cdot : \mathbb{F} \times V/U \rightarrow V/U$ defined as $(\lambda, v + U) \mapsto \lambda v + U$. Suppose $\exists \hat{v} \in V$ s.t. $v + U = \hat{v} + U$. So we know $v - \hat{v} \in U$, and thus $\lambda(v - \hat{v}) = \lambda v - \lambda \hat{v} \in U$. By Theorem 3.6.4, we then have $(\lambda v) + U = (\lambda \hat{v}) + U$. Thus, the scalar multiplication makes sense. \square

3. additive identity: $0 + U = U$. \square

4. additive inverse: $(-v) + U$. \square

5. commutativity:

$$\begin{aligned} (v + U) + (w + U) &= (v + w) + U = (w + v) + U \\ &= (w + U) + (v + U). \end{aligned} \quad \square$$

6. associativity:

$$\begin{aligned} [(v + U) + (w + U)] + (x + U) &= [(v + w) + U] + (x + U) \\ &= [(v + w) + x] + U \\ &= [v + (w + x)] + U \\ &= (v + U) + [(w + x) + U] \\ &= (v + U) + [(x + U) + (w + U)]. \end{aligned} \quad \square$$

7. multiplicative identity: $1 \cdot (v + U) = (1 \cdot v) + U = v + U$. \square

8. distributivity:

$$\begin{aligned} a[(v + U) + (w + U)] &= a[(v + w) + U] \\ &= a(v + w) + U \\ &= (av + aw) + U \\ &= (av + U) + (aw + U) \\ &= a(v + U) + a(w + U). \end{aligned}$$

$$\begin{aligned}
(a+b)(v+U) &= (a+b)v + U \\
&= (av + bv) + U \\
&= (av + U) + (bv + U) \\
&= a(v+U) + b(v+U)
\end{aligned}$$

Definition 3.6.7 (Quotient Map). Suppose U is a subspace of V . The *quotient map* π is the linear map $\pi : V \rightarrow V/U$ defined by $\pi(v) := v + U \quad \forall v \in V$. ■

Remark. Here are some properties of the quotient map:

1. $\pi(v)$ is defined $\forall v \in V$. Thus, π is surjective.
2. $\text{null } \pi = \{v \in V \mid \pi(v) = 0\}$. If $\pi(v) = 0$, then $v + U = U = 0 + U$. So, $v - 0 \in U$ by Theorem 3.6.4. Then, $v \in U$. So, $\text{null } \pi \subseteq U$. Further, $\forall v \in U$, if $\pi(v) = 0$, then $v \in \text{null } \pi$, then $U \subseteq \text{null } \pi$. So, $U = \text{null } \pi$.
3. $\pi(v + w) = (v + w) + U = (v + U) + (w + U) = \pi(v) + \pi(w)$.
4. $\pi(\lambda v) = (\lambda v) + U = \lambda(v + U) = \lambda\pi(v)$.

Theorem 3.6.8

Suppose V is f - d and U is a subspace of V . Then

$$\dim V/U = \dim V - \dim U.$$

Proof 3. By Fundamental Theorem of Linear Map, we have

$$\dim V = \dim \text{null } \pi + \dim \text{range } \pi. \quad (11)$$

Since $\text{null } \pi = U$ from the Remark, we have $\dim \text{null } \pi = \dim U$. Further, since π is surjective as mentioned in the Remark, $\text{range } \pi = V/U$. Hence, $\dim \text{range } \pi = \dim V/U$. Therefore, Equation (11) becomes

$$\dim V = \dim U + \dim V/U,$$

or we have

$$\dim V/U = \dim V - \dim U$$

Definition 3.6.9 (\tilde{T}). Suppose $T \in \mathcal{L}(V, W)$. Define $\tilde{T} : V/(\text{null } T) \rightarrow W$ by $\tilde{T}(v + \text{null } T) = Tv$. ■

Proof 4.

1. This definition makes sense

Suppose $u, v \in V$ s.t. $u + \text{null } T = v + \text{null } T$. By Theorem 3.6.4, we know $u - v \in \text{null } T$. Then, $T(u - v) = 0$, or $Tu = Tv$. □

2. \tilde{T} is a linear map.

$$\begin{aligned}
\tilde{T}[(u + \text{null } T) + (v + \text{null } T)] &= \tilde{T}[(u + v) + \text{null } T] \\
&= T(u + v) \\
&= Tu + Tv = \tilde{T}(u + \text{null } T) + \tilde{T}(v + \text{null } T). \quad \square
\end{aligned}$$

$$\begin{aligned}
\tilde{T}[\lambda(u + \text{null } T)] &= \tilde{T}(\lambda u + \text{null } T) \\
&= T(\lambda u) \\
&= \lambda T u \\
&= \lambda T(u + \text{null } T).
\end{aligned}$$

■

Theorem 3.6.10

Suppose $T \in \mathcal{L}(V, W)$. Then,

1. \tilde{T} is injective.
2. $\text{range } \tilde{T} = \text{range } T$.
3. $V/(\text{null } T) \cong \text{range } T$.

Proof 5.

1. Suppose $v \in V$ and $\tilde{T}(v + \text{null } T) = 0$. Then, $Tv = 0$. So, $v \in \text{null } T$, or $v - 0 \in \text{null } T$. By Theorem 3.6.4, we then have $v + \text{null } T = 0 + \text{null } T$. Then, it implies $\text{null } \tilde{T} = 0$. So, \tilde{T} is injective. \square
2. By definition of \tilde{T} , it must be $\text{range } \tilde{T} = \text{range } T$. \square
3. Note that $\dim V/(\text{null } T) = \dim \text{null } \tilde{T} + \dim \text{range } \tilde{T} = 0 + \dim \text{range } T$. Then, by Theorem 3.4.9, we know two vector spaces are isomorphic if and only if their dimensions are equal. Then,

$$V/(\text{null } T) \cong \text{range } T.$$

■

4 Eigenvectors and Invariant Subspaces

4.1 Invariant Subspaces

Theorem 4.1.1

Suppose V is f - d with $\dim V = n \geq 1$. Then, \exists 1-dimensional subspaces U_1, \dots, U_n of V s.t.

$$V = U_1 \oplus \dots \oplus U_n.$$

Proof 1. Choose a basis v_1, \dots, v_n of V . Then, we know $V = \text{span}(v_1) + \dots + \text{span}(v_n)$. Also, $\forall v \in V$, we have $v = a_1 v_1 + \dots + a_n v_n$ with $a_j v_j \in \text{span}(v_j)$. Set $a_1 v_1 + \dots + a_n v_n = 0$. Since v_1, \dots, v_n is a basis, it must be $a_1 = \dots = a_n = 0$. Then,

$$V = \text{span}(v_1) \oplus \dots \oplus \text{span}(v_n).$$

■

Theorem 4.1.2

Suppose U_1, \dots, U_m are f - d subspaces of V s.t. $U_1 + \dots + U_m$ is a direct sum. Then, $U_1 \oplus \dots \oplus U_m$ is f - d and

$$\dim U_1 \oplus \dots \oplus U_m = \dim U_1 + \dots + \dim U_m.$$

Proof 2. Suppose $u_{k,1}, \dots, u_{k,j_k}$ is a basis of the subspace U_k . Then, any vector in $\bigoplus_{i=1}^m U_i$ is in the form of $u_1 + \dots + u_m$, $u_j \in U_j$. Also,

$$u_i = \sum_{k=1}^{j_i} a_{i,k} u_{i,k}.$$

So,

$$u_1 + \dots + u_m = \sum_{k=1}^{j_1} a_{1,k} u_{1,k} + \dots + \sum_{k=1}^{j_m} a_{m,k} u_{m,k}.$$

Then, $u_1 + \dots + u_m$ is a linear combination of $u_{1,1}, \dots, u_{j,m}$. So, the direct sum is f - d . □

Further, suppose

$$\sum_{k=1}^{j_1} a_{1,k} u_{1,k} + \dots + \sum_{k=1}^{j_m} a_{m,k} u_{m,k} = 0.$$

Since $U_1 + \dots + U_m$ is a direct sum, it must be

$$\sum_{k=1}^{j_1} a_{1,k} u_{1,k} = \dots = \sum_{k=1}^{j_m} a_{m,k} u_{m,k} = 0.$$

Since we selected bases, $a_{1,k} = \dots = a_{m,k} = 0$. So, $u_{1,1}, \dots, u_{j,m}$ is a basis of $U_1 \oplus \dots \oplus U_m$. Then,

$$\dim U_1 \oplus \dots \oplus U_m = \dim U_1 + \dots + \dim U_m.$$

■

Definition 4.1.3 (Invariant Subspace). Suppose $T \in \mathcal{L}(V)$. A subspace U of V is called *invariant* under T if $u \in U$ implies $Tu \in U$.

Example 4.1.4 Suppose $T \in \mathcal{L}(V)$. Show that each of the following subspaces of V is invariant under T :

1. $\{0\}$

Proof 3. $T0 = 0 \in \{0\}$ ■

2. V

Proof 4. $u \in V \implies Tu \in V$ ■

3. $\text{null } T$

Proof 5. $u \in \text{null } T \implies Tu = 0 \in \text{range } T$ ■

4. $\text{range } T$

Proof 6. $u \in \text{range } T \implies Tu \in \text{range } T$ ■

Example 4.1.5 Suppose $T \in \mathcal{L}(\mathcal{P}(\mathbb{R}))$ is defined by $Tp = p'$. Then, $\mathcal{P}_4(\mathbb{R})$ is invariant under T .

Proof 7. Note that $Tp_4 \in \mathcal{P}_4(\mathbb{R})$. Then, $\mathcal{P}_4(\mathbb{R})$ is invariant under T . ■

Definition 4.1.6 (Eigenvalue). Suppose $T \in \mathcal{L}(V)$. A number $\lambda \in \mathbb{F}$ is called an *eigenvalue* of T if $\exists v \in V$ s.t. $v \neq 0$ and $Tv = \lambda v$.

Corollary 4.1.7 T has a 1-dimensional invariant subspace if and only if T has an eigenvalue.

Proof 8.

(\implies) Suppose $\text{span}(v)$ is invariant under T . Let U be defined as $U = \{\lambda v \mid \lambda \in \mathbb{F}\} = \text{span}(v)$. Then, U is the invariant subspace under T and $\dim U = 1$. Then, $\forall v \in V$, we have $Tv \in U$. Hence, $\exists \lambda \in \mathbb{F}$ s.t. $Tv = \lambda v$. Then, λ is an eigenvalue. □

(\impliedby) Suppose $\lambda \in \mathbb{F}$ is an eigenvalue. Then, $Tv = \lambda v$. Hence, $\text{span}(v)$ is a 1-dimensional invariant subspace under T . ■

Theorem 4.1.8 Equivalent Conditions to be an Eigenvalue

Suppose V is f -d, $T \in \mathcal{L}(V)$, and $\lambda \in \mathbb{F}$. Then, the following are equivalent:

1. λ is an eigenvalue of T .
2. $T - \lambda I$ is not injective.
3. $T - \lambda I$ is not surjective.
4. $T - \lambda I$ is not invertible.

Proof 9.

1. (1) \implies (2): Suppose λ is an eigenvalue of T . Then, $\exists v \in V$ s.t. $v \neq 0$ and $Tv = \lambda v$. So, $Tv - \lambda v = (T - \lambda I)v = 0$. Since $v \neq 0$, $\text{null}(T - \lambda I) \neq \{0\}$, and thus T is not injective. □
2. Note that $T - \lambda I$ is an operator by itself. By Theorem 3.4.17, we know (2), (3), and (4) are equivalent.

3. (4) \implies (1): Suppose $T - \lambda I$ is not invertible. Then, it is not injective. So, $\exists v \neq 0$ s.t. $(T - \lambda I)v = 0$. That is, $Tv - \lambda Iv = Tv - \lambda v = 0$. So, $Tv = \lambda v$. Then, λ is an eigenvalue of T . ■

Definition 4.1.9 (Eigenvector). Suppose $T \in \mathcal{L}(V)$ and $\lambda \in \mathbb{F}$ is an eigenvalue of T . A vector $v \in V$ is called an *eigenvector* of T corresponding to λ if $v \neq 0$ and $Tv = \lambda v$.

Corollary 4.1.10 A vector $v \in V$ with $v \neq 0$ is an eigenvector of T with respect to λ if and only if $v \in \text{null}(T - \lambda I)$.

Proof 10. Note that $Tv = \lambda v$ if and only if $(T - \lambda I)v = 0$. ■

Example 4.1.11 Suppose $T \in \mathcal{L}(\mathbb{F}^2)$ is defined by $T(w, z) = (-z, w)$.

1. Find the eigenvalues and eigenvectors of T if $\mathbb{F} = \mathbb{R}$.

Solution 11.

Let $T(w, z) = \lambda(w, z)$. So, $(-z, w) = (\lambda w, \lambda z)$. Then, solve $\begin{cases} -z = \lambda w \\ w = \lambda z \end{cases}$.

Then, we have $\lambda^2 z + z = 0$. If $z \neq 0$, $\lambda^2 + 1 = 0$. This equation has no solutions on \mathbb{R} . So T has no eigenvalues. If $w = 0, z = 0$, then $T(w, z) = T(0, 0) = T0$. By definition, T has no eigenvalues. □

2. Find the eigenvalues and eigenvectors of T if $\mathbb{F} = \mathbb{C}$.

Solution 12.

Applying similar rational, $z \neq 0$ and solve $\lambda^2 + 1 = 0$. Then, we have $\lambda = \pm i$. If $\lambda = i$, then $-z = iw$. So, $v = (w, z) = (w, -iw)$. If $\lambda = -i$, then $-z = -iw$, or $z = iw$. So, $v = (w, iw)$. □

Theorem 4.1.12

Let $T \in \mathcal{L}(V)$. Suppose $\lambda_1, \dots, \lambda_m$ are distinct eigenvalues of T and v_1, \dots, v_m are corresponding eigenvectors. Then, v_1, \dots, v_m is L.I..

Proof 13. Suppose for the sake of contradiction that v_1, \dots, v_m is linearly dependent. Let k be the smallest positive integer s.t. $v_k \in \text{span}(v_1, \dots, v_{k-1})$. Then, $v_k = a_1 v_1 + \dots + a_{k-1} v_{k-1}$. Applying T , we have

$$\lambda_k v_k = a_1 \lambda_1 v_1 + \dots + a_{k-1} \lambda_{k-1} v_{k-1}. \quad (12)$$

Since $v_k = a_1 v_1 + \dots + a_{k-1} v_{k-1}$, we also have

$$\lambda_k v_k = a_1 \lambda_k v_1 + \dots + a_{k-1} \lambda_k v_{k-1}. \quad (13)$$

So, by Equation (13)-(12), we have

$$0 = a_1 (\lambda_k - \lambda_1) v_1 + \dots + a_{k-1} (\lambda_k - \lambda_{k-1}) v_{k-1}.$$

By assumption, v_1, \dots, v_{k-1} is L.I.. Then, it must be that $a_1 = \dots = a_{k-1} = 0$ since $\lambda_1, \dots, \lambda_k$ are distinct eigenvalues. Therefore, $v_k = a_1 v_1 + \dots + a_{k-1} v_{k-1} = 0$. * This contradicts with the fact that v_k is an eigenvector, which cannot be 0. So, it must be that v_1, \dots, v_m are L.I. ■

Theorem 4.1.13

Suppose V is f - d . Then, each operator on V has at most $\dim V$ distinct eigenvalues.

Proof 14. Let $T \in \mathcal{L}(V)$. Suppose $\lambda_1, \dots, \lambda_m$ are distinct eigenvalues of T . Let v_1, \dots, v_m be corresponding eigenvectors. By Theorem 4.1.12, we know v_1, \dots, v_m is L.I.. Further by Theorem 2.3.5, we know $\dim \text{span}(v_1, \dots, v_m) \leq \dim V$. That is, $m \leq \dim V$ as desired. ■

4.2 Eigenvectors and Upper-Triangular Matrices

Definition 4.2.1 (T^m). Suppose $T \in \mathcal{L}(V)$ and m is a positive integer. Then, T^m is defined by

$$T^m := \underbrace{T \cdots T}_{m \text{ times}}.$$

Specially, T^0 is defined to be the identity operator I on V . Further, if T is invertible with inverse T^{-1} , then T^{-m} is defined by $T^{-m} := (T^{-1})^m$.

Theorem 4.2.2

$$T^m T^n = T^{m+n}; \quad (T^m)^n = T^{mn}.$$

Definition 4.2.3 ($p(T)$). Suppose $T \in \mathcal{L}(V)$ and $p \in \mathcal{P}(\mathbb{F})$ is a polynomial given by

$$p(z) = a_0 + a_1 z + a_2 z^2 + \cdots + a_m z^m, \quad z \in \mathbb{F}.$$

Then, $p(T)$ is the operator defined by

$$p(T) := a_0 I + a_1 T + a_2 T^2 + \cdots + a_m T^m.$$

Example 4.2.4 Suppose $D \in \mathcal{L}(\mathcal{P}(\mathbb{R}))$ is the differentiation operator defined by $Dq = q'$ and p is the polynomial defined by $p(x) = 7 - 3x + 5x^2$. Find $p(D)$ and $(p(D))q$.

Solution 1.

$$\begin{aligned} p(D) &= 7I - 3D + 5D^2 \\ (p(D))q &= (7I - 3D + 5D^2)q \\ &= 7Iq - 3Dq + 5D^2q \\ &= 7q - 3q' + 5q''. \end{aligned}$$

□

Theorem 4.2.5

If we fix an operator $T \in \mathcal{L}(V)$, then the function from $\mathcal{P}(\mathbb{F})$ to $\mathcal{L}(V)$ given by $p \mapsto p(T)$ is linear.

Proof 2. Suppose $f : \mathcal{P}(\mathbb{F}) \rightarrow \mathcal{L}(V)$ is defined by $p \mapsto p(T)$. Suppose

$$p = a_0 + a_1 z + \cdots + a_m z^m \mapsto a_0 I + a_1 T + \cdots + a_m T^m$$

and

$$q = b_0 + b_1 z + \cdots + b_m z^m \mapsto b_0 I + b_1 T + \cdots + b_m T^m.$$

Then,

$$\begin{aligned} f(p+q) &= (a_0 + b_0)I + (a_1 + b_1)T + \cdots + (a_m + b_m)T^m \\ &= (a_0 I + a_1 T + \cdots + a_m T^m) + (b_0 I + b_1 T + \cdots + b_m T^m) \\ &= f(p) + f(q). \end{aligned}$$

Further, suppose $\lambda \in \mathbb{F}$, then

$$\begin{aligned} f(\lambda p) &= \lambda a_0 I + \lambda a_1 T + \cdots + \lambda a_m T^m \\ &= \lambda(a_0 I + a_1 T + \cdots + a_m T^m) \\ &= \lambda f(p). \end{aligned}$$

Definition 4.2.6 (Product of Polynomials). If $p, q \in \mathcal{P}(\mathbb{F})$, then $pq \in \mathcal{P}(\mathbb{F})$ is the polynomial defined by $(pq)(z) := p(z)q(z)$ for $z \in \mathbb{F}$. ■

Remark. $(pq)(z) = p(z)q(z) = q(z)p(z) = (qp)(z)$ for $z \in \mathbb{F}$.

Theorem 4.2.7 Multiplicative Properties

Suppose $p, q \in \mathcal{P}(\mathbb{F})$ and $T \in \mathcal{L}(V)$. Then

1. $(pq)(T) = p(T)q(T)$
2. $p(T)q(T) = q(T)p(T)$

Proof 3.

1. Suppose $p(z) = \sum_{j=0}^m a_j z^j$ and $q(z) = \sum_{k=0}^n b_k z^k$. Then

$$(pq)(z) = p(z)q(z) = \sum_{j=0}^m a_j z^j \sum_{k=0}^n b_k z^k = \sum_{j=0}^m \sum_{k=0}^n a_j b_k z^{j+k}$$

So, by definition, we have

$$p(T)q(T) = \sum_{j=0}^m \sum_{k=0}^n a_j b_k T^{j+k} = \left(\sum_{j=0}^m a_j T^j \right) \cdot \left(\sum_{k=0}^n b_k T^k \right) = p(T)q(T). \quad \square$$

2. Similar to the Remark,

$$p(T)q(T) = (pq)(T) = (qp)(T) = q(T)p(T).$$

Theorem 4.2.8 Fundamental Theorem of Algebra

Every non-constant polynomial with complex coefficients has a zero. ■

Theorem 4.2.9 Existence of Eigenvalues

Every operator on a f -d, non-zero, complex vector space has an eigenvalue.

Proof 4. Let V be a complex vector space with dimension $n > 0$. Suppose $T \in \mathcal{L}(V)$. Choose $v \in V$ s.t. $v \neq 0$. Then, v, Tv, T^2v, \dots, T^nv is linearly dependent because $\dim V = n$ but the length of the list is $n + 1 > n$. Hence, $\exists a_0, a_1, \dots, a_n$ not all 0 $\in \mathbb{C}$ s.t.

$$0 = a_0 v + a_1 Tv + \cdots + a_n T^n v \tag{14}$$

By Fundamental Theorem of Algebra (Theorem 4.2.8), we have

$$a_0 + a_1z + \cdots + a_nz^n = c(z - \lambda_1) \cdots (z - \lambda_m)$$

with $c \in \mathbb{C}$, $c \neq 0$, and $\lambda_j \in \mathbb{C}$. Then, Equation (14) becomes

$$\begin{aligned} 0 &= a_0v + a_1Tv + \cdots + a_nT^n v \\ &= (a_0I + a_1T + \cdots + a_nT^n)v \\ &= c(T - \lambda_1I) \cdots (T - \lambda_mI)v \end{aligned}$$

Since $v \neq 0$ and $c \neq 0$, it must be some $T - \lambda_iI = 0$. Thus, $T = \lambda_iI$, and λ_i is an eigenvalue of T . ■

Definition 4.2.10 (Diagonal of a Matrix). The *diagonal of a square matrix* consists of the entries along the line from the upper left corner to the bottom right corner.

Definition 4.2.11 (Upper-Triangular Matrix). A matrix is called *upper-triangular* if all the entries below the diagonal equal 0. Typically, we present an upper triangular matrix in the form

$$\begin{pmatrix} \lambda_1 & & * \\ & \ddots & \\ 0 & & \lambda_n \end{pmatrix}.$$

Theorem 4.2.12 Conditions for Upper-Triangular Matrix

Suppose $T \in \mathcal{L}(V)$ and v_1, \dots, v_n is a basis of V . Then, the following are equivalent:

1. the matrix of T with respect to v_1, \dots, v_n is upper triangular.
2. $Tv_j \in \text{span}(v_1, \dots, v_j)$ for each $j = 1, \dots, n$
3. $\text{span}(v_1, \dots, v_j)$ is invariant under T for each $j = 1, \dots, n$.

Proof 5.

1. First, we will show (1) \iff (2).

Suppose $\mathcal{M}(T) = \begin{pmatrix} A_{1,1} & \cdots & A_{1,n} \\ & \ddots & \vdots \\ 0 & & A_{n,n} \end{pmatrix}$. Then,

$$\begin{aligned} Tv_1 &= A_{1,1}v_1 \\ Tv_2 &= A_{1,2}v_1 + A_{2,2}v_2 \\ &\vdots \\ Tv_j &= A_{1,j}v_1 + \cdots + A_{j,j}v_j. \end{aligned}$$

So, $Tv_j \in \text{span}(v_1, \dots, v_j)$. The reverse implication is trivial to prove. □

2. (3) \implies (2) is obvious and trivial to prove.

3. Lastly, we want to show (2) \implies (3).

Note that for each fixed $j = 1, \dots, n$, we have

$$\begin{aligned} Tv_1 &\in \text{span}(v_1) \subseteq \text{span}(v_1, \dots, v_j) \\ Tv_2 &\in \text{span}(v_1, v_2) \subseteq \text{span}(v_1, \dots, v_j) \\ &\vdots \\ Tv_j &\in \text{span}(v_1, \dots, v_j) \end{aligned}$$

Let $v \in \text{span}(v_1, \dots, v_j)$. Then, v is a linear combination of v_1, \dots, v_j , then

$$Tv \in \text{span}(v_1, \dots, v_j).$$

That is, $\text{span}(v_1, \dots, v_j)$ is invariant under T . ■

Definition 4.2.13 (Quotient Operator). Suppose $T \in \mathcal{L}(V)$ and U is a subspace of V invariant under T . The *quotient operator* $T/U \in \mathcal{L}(V/U)$ is defined by $(T/U)(v + U) := Tv + U$.

Proof 6. The definition makes sense, and here is the proof. If $v + U = w + U$, then $v - w \in U$. So, $T(v - w) \in U$ since U is invariant. That is, $Tv - Tw \in U$. Then, $Tv + U = Tw + U$. ■

Theorem 4.2.14

Suppose U is a subspace of V . Let $v_1 + U, \dots, v_m + U$ be a basis of V/U and u_1, \dots, u_n be a basis of U . Then, $v_1, \dots, v_m, u_1, \dots, u_n$ is a basis of V .

Proof 7. Let $v \in V$. Then $v + U \in V/U$. So, $v + U = a_1v_1 + \dots + a_mv_m + U$, uniquely. Then, by Theorem 3.6.4, we have $v - (a_1v_1 + \dots + a_mv_m) \in U$. Therefore, $v - (a_1v_1 + \dots + a_mv_m) = b_1u_1 + \dots + b_nu_n$, uniquely. So, $v = a_1v_1 + \dots + a_mv_m + b_1u_1 + \dots + b_nu_n$, uniquely. By definition, $v_1, \dots, v_m, u_1, \dots, u_n$ is a basis of V . ■

Theorem 4.2.15

Suppose V is a f - d complex vector space and $T \in \mathcal{L}(V)$. Then, T has an upper-triangular matrix with respect to some basis of V .

Proof 8.

Base Case When $\dim V = 1$, the implication holds.

Inductive Steps Suppose the implication is true for some complex vector space with dimension of $n - 1$. Let $\dim V = n$ and v_1 be any eigenvector of T . Suppose $U = \text{span}(v_1)$. Then, U is invariant under T . Note that $\dim V/U = \dim V - \dim U = n - 1$, so we can use the inductive hypothesis on the quotient operator $T/U \in \mathcal{L}(V/U)$. Then, \exists a basis $v_2 + U, \dots, v_n + U \in V/U$ s.t. T/U has an upper-triangular matrix. By Theorem 4.2.12, we have

$$(T/U)(v_j + U) \in \text{span}(v_2 + U, \dots, v_j + U) \quad \text{for } j \in \{2, \dots, n\}.$$

So, $Tv_j + U = (c_2v_2 + \dots + c_jv_j) + U$. Then,

$$Tv_j - (c_2v_2 + \dots + c_jv_j) \in U = \text{span}(v_1).$$

So, $Tv_j - (c_2v_2 + \dots + c_jv_j) = c_1v_1$ for some $c_1 \in \mathbb{F}$. Then, $Tv_j = c_1v_1 + c_2v_2 + \dots + c_jv_j$. So, $Tv_j \in \text{span}(v_1, \dots, v_j)$ for $j \in \{1, \dots, n\}$. Since by Theorem 4.2.14, v_1, \dots, v_n is a basis of V , further

by Theorem 4.2.12, T has an upper-triangular matrix with respect to v_1, \dots, v_n . So, the implication is true for $\dim V = n$.

Since the implication is true for $\dim V = 1$ and is true for $\dim V = n$ whenever it is hold for $\dim V = n - 1$, by the Principle of Mathematical Induction, the implication is true for all positive integers n . Hence, the proof is complete. ■

4.3 Eigenspaces and Diagonal Matrices

Definition 4.3.1 (Diagonal Matrix). A *diagonal matrix* is a square matrix that is 0 everywhere except possibly along the diagonal.

Definition 4.3.2 (Eigenspace, $E(\lambda, T)$). Suppose $T \in \mathcal{L}(V)$ and $\lambda \in \mathbb{F}$. The *eigenspace* of T corresponding to λ , denoted $E(\lambda, T)$, is defined by

$$E(\lambda, T) = \text{null}(T - \lambda I).$$

In other words, $E(\lambda, T)$ is the set of all eigenvectors of T corresponding to λ , along with the 0 vector.

Theorem 4.3.3 Sum of Eigenspaces is a Direct Sum

Suppose V is f - d and $T \in \mathcal{L}(V)$. Suppose also that $\lambda_1, \dots, \lambda_m$ are distinct eigenvalues of T . Then

$$E(\lambda_1, T) + \dots + E(\lambda_m, T)$$

is a direct sum. Further

$$\dim E(\lambda_1, T) + \dots + \dim E(\lambda_m, T) \leq \dim V.$$

Proof 1. Suppose $u_1 + \dots + u_m = 0$, where $u_j \in E(\lambda_j, T)$. If some $u_i \neq 0$, then $u_1 + \dots + u_m$ can never be 0 because u_1, \dots, u_m , as eigenvectors corresponding to distinct eigenvalues, is L.I.. Hence, the only way for $u_1 + \dots + u_m$ to be 0 is by taking $u_1 = \dots = u_m = 0$. Hence, we know $E(\lambda_1, T) + \dots + E(\lambda_m, T)$ is a direct sum. \square

By Theorem 4.1.2, we know

$$\begin{aligned} \dim E(\lambda_1, T) + \dots + \dim E(\lambda_m, T) &= \dim E(\lambda_1, T) \oplus \dots \oplus E(\lambda_m, T) \\ &\leq \dim V. \end{aligned}$$

■

Definition 4.3.4 (Diagonalizable). An operator $T \in \mathcal{L}(V)$ is called *diagonalizable* if the operator has a diagonal matrix with respect to some basis of V .

Theorem 4.3.5 Conditions Equivalent to Diagonalizability

Suppose V is f - d and $T \in \mathcal{L}(V)$. Let $\lambda_1, \dots, \lambda_m$ denote the distinct eigenvalues of T . Then, the following are equivalent:

1. T is diagonalizable.
2. V has a basis consisting of eigenvectors of T .
3. \exists 1-dimensional subspaces U_1, \dots, U_n of V , each invariant under T , s.t. $V = U_1 \oplus \dots \oplus U_n$.
4. $V = E(\lambda_1, T) \oplus \dots \oplus E(\lambda_m, T)$.
5. $\dim V = \dim E(\lambda_1, T) + \dots + \dim E(\lambda_m, T)$.

Remark. To prove this theorem, we will prove (1) \iff (2), (2) \iff (3), (2) \implies (4), (4) \implies (5), and (5) \implies (2).

Proof 2.

1. (1) \iff (2): By definition, we know T is diagonalizable if and only if \exists a basis v_1, \dots, v_n of T s.t.

$$\mathcal{M}(T) = \begin{pmatrix} \lambda_1 & & 0 \\ & \ddots & \\ 0 & & \lambda_n \end{pmatrix},$$

which holds if and only if we have $Tv_1 = \lambda_1 v_1, \dots, Tv_n = \lambda_n v_n$ i.e., v_1, \dots, v_n are eigenvectors of T . \square

2. (2) \implies (3): Suppose v_1, \dots, v_n is a basis of V . Then, for some $v \in V$, we have $v = a_1 v_1 + \dots + a_n v_n$. So, we know $V = \text{span}(v_1) + \dots + \text{span}(v_n)$. Further, let $a_1 v_1 + \dots + a_m v_m = 0$. Since v_1, \dots, v_n is a basis, it must be $a_1 = \dots = a_m = 0$. So, there is only one way to represent 0. So,

$$V = \text{span}(v_1) \oplus \dots \oplus \text{span}(v_n).$$

Now, we want to show each $\text{span}(v_j)$ is invariant. Consider $T(c_j v_j) = c_j T v_j = c_j \lambda_j v_j \in \text{span}(v_j)$. So, $\text{span}(v_j)$ is invariant. \square

3. (3) \implies (2): Suppose \exists 1-dimensional subspaces U_1, \dots, U_n of V , each invariant under T , s.t. $V = U_1 \oplus \dots \oplus U_n$. Then, $\forall v \in V$, we have $v = a_1 u_1 + \dots + a_n u_n$ uniquely. Then, u_1, \dots, u_n is a basis of V . Since U_1, \dots, U_n are 1-dimensional invariant subspaces, u_1, \dots, u_n are the eigenvalues. \square

4. (2) \implies (4): Suppose V has a basis consisting of eigenvectors of T . Then, $v = a_1 v_1 + \dots + a_n v_n$ is a linear combination of eigenvectors of T . By definition, $E(\lambda_j, T)$ contains the eigenvectors corresponding to λ_j . Further since $\lambda_1, \dots, \lambda_m$ is distinct, corresponding eigenvectors are L.I.. Then, $E(\lambda_j, T) \cap E(\lambda_i, T) = \{0\}$ if $i \neq j$. Then, we have

$$v = a_1 v_1 + \dots + a_n v_n \in E(\lambda_1, T) + \dots + E(\lambda_m, T).$$

Hence, $V = E(\lambda_1, T) + \dots + E(\lambda_m, T)$. Further by Theorem 4.3.3, we have

$$V = E(\lambda_1, T) \oplus \dots \oplus E(\lambda_m, T). \quad \square$$

5. (4) \implies (5): This conclusion can be deduced from Theorem 4.3.3 and its proof.
6. (5) \implies (2): Suppose $\dim V = \dim E(\lambda_1, T) + \dots + \dim E(\lambda_m, T)$. Select B_j , the basis of $E(\lambda_j, T)$ for $j = 1, \dots, m$. Denote $\dim V = n$. Then, if we put these bases together as B_1, \dots, B_m , we can write the collection as v_1, \dots, v_n . Suppose $a_1 v_1 + \dots + a_n v_n = 0$. Let u_j denote the sum of all the terms $a_k v_k$ s.t. $v_k \in E(\lambda_j, T)$. Then, the equation becomes $u_1 + \dots + u_m = 0$ and each $u_j \in E(\lambda_j, T)$. Since eigenvectors corresponding to distinct eigenvalues are L.I., it must be that $u_1 = \dots = u_m = 0$. Further, by definition of u_j , and since u'_k s are bases of $E(\lambda_j, T)$, it must be $a_1 = \dots = a_n = 0$. So, we know v_1, \dots, v_n is L.I.. Further, since $\text{len}(v_1, \dots, v_n) = n = \dim V$, we know that v_1, \dots, v_n is a basis of V . ■

Theorem 4.3.6

If $T \in \mathcal{L}(V)$ has $\dim V$ distinct eigenvalues, then T is diagonalizable.

Proof 3. Suppose $T \in \mathcal{L}(V)$ has $\dim V$ distinct eigenvalues: $\lambda_1, \dots, \lambda_{\dim V}$. Then, it has $v_1, \dots, v_{\dim V}$ as corresponding eigenvectors and is L.I.. Note that $\text{len}(v_1, \dots, v_{\dim V}) = \dim V$. So, $v_1, \dots, v_{\dim V}$ is a basis of V . By Theorem 4.3.5, with respect to this basis consisting of eigenvectors, T has a diagonal matrix. ■

Example 4.3.7 The *Fibonacci Sequence* F_1, F_2, \dots is defined by

$$F_1 = F_2 = 3 \quad \text{and} \quad F_n = F_{n-2} + F_{n-1} \quad \text{for } n \geq 3.$$

Define $T \in \mathcal{L}(\mathbb{R}^2)$ by $T(x, y) = (y, x + y)$.

1. Show that $T^n(0, 1) = (F_n, F_{n+1})$ for each $n \in \mathbb{Z}^+$.

Proof 4.

- Base Case: Note that $T(0, 1) = (1, 1) = (F_1, F_2)$.
- Inductive Process: Suppose $T^{n-1}(0, 1) = (F_{n-1}, F_n)$. Then,

$$\begin{aligned} T^n &= [T(T^{n-1})](0, 1) = T[T^{n-1}(0, 1)] \\ &= T(F_{n-1}, F_n) \\ &= (F_n, F_{n-1} + F_n) \\ &= (F_n, F_{n+1}). \end{aligned}$$

So, $T^n(0, 1) = (F_n, F_{n+1}) \quad \forall n \in \mathbb{Z}^+$ by Principle of Mathematical Induction. ■

2. Find the eigenvalues of T .

Solution 5.

Suppose $T(x, y) = \lambda(x, y)$. So, $(y, x + y) = (\lambda x, \lambda y)$. Solve $\begin{cases} y = \lambda x \\ x + y = \lambda y \end{cases}$. That is, $x + \lambda x = \lambda^2 x$, or $\lambda^2 x - \lambda x - x = 0$. It follows $x \neq 0$, so solving $\lambda^2 - \lambda - 1 = 0$, we get

$$\lambda_1 = \frac{1 + \sqrt{5}}{2} \quad \text{and} \quad \lambda_2 = \frac{1 - \sqrt{5}}{2}.$$

□

3. Since T has two eigenvalues, T should have a basis of \mathbb{R}^2 consisting of eigenvectors. Find the basis.

Solution 6.

When $\lambda_1 = \frac{1 + \sqrt{5}}{2}$, we have $y = \lambda x = \frac{1 + \sqrt{5}}{2}x$. So, $v_1 = \left(x, \frac{1 + \sqrt{5}}{2}x\right) = x\left(1, \frac{1 + \sqrt{5}}{2}\right)$.

That is,

$$v_1 = \left(1, \frac{1 + \sqrt{5}}{2}\right).$$

Similarly, we have

$$v_2 = \left(1, \frac{1 - \sqrt{5}}{2}\right).$$

Further, it follows that

$$\mathcal{M}(T, v_1, v_2) = \begin{pmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{pmatrix}.$$

□

4. Find F_n using an expression of n only.

Solution 7.

Note that $(0, 1) = \frac{1}{\sqrt{5}}(v_1 - v_2)$. So, we have

$$\begin{aligned} T^n(0, 1) &= T^n\left(\frac{1}{\sqrt{5}}(v_1 - v_2)\right) \\ &= \frac{1}{\sqrt{5}}T^n(v_1 - v_2) \\ &= \frac{1}{\sqrt{5}}(T^n v_1 - T^n v_2) \\ &= \frac{1}{\sqrt{5}}(\lambda_1^n v_1 - \lambda_2^n v_2) \\ &= \frac{1}{\sqrt{5}}\left(\left(\frac{1 + \sqrt{5}}{2}\right)^n \left(1, \frac{1 + \sqrt{5}}{2}\right) - \left(\frac{1 - \sqrt{5}}{2}\right)^n \left(1, \frac{1 - \sqrt{5}}{2}\right)\right) \\ &= \frac{1}{\sqrt{5}}\left(\left(\frac{1 + \sqrt{5}}{2}\right)^n - \left(\frac{1 - \sqrt{5}}{2}\right)^n, \left(\frac{1 + \sqrt{5}}{2}\right)^{n+1} - \left(\frac{1 - \sqrt{5}}{2}\right)^{n+1}\right) \\ &= (F_n, F_{n+1}). \end{aligned}$$

So, we have

$$F_n = \frac{1}{\sqrt{5}}\left(\left(\frac{1 + \sqrt{5}}{2}\right)^n - \left(\frac{1 - \sqrt{5}}{2}\right)^n\right).$$

□

5 Inner Product Spaces

5.1 Inner Products and Norms

Definition 5.1.1 (Dot Product). For $x, y \in \mathbb{R}^n$, the *dot product* of x and y , denoted $x \cdot y$, is defined by

$$x \cdot y = x_1y_1 + \cdots + x_ny_n,$$

where $x = (x_1, \dots, x_n)$ and $y = (y_1, \dots, y_n)$.

Theorem 5.1.2 Properties of dot Product

1. $x \cdot x = x_1^2 + \cdots + x_n^2 \geq 0 \quad \forall x \in \mathbb{R}^n$.
2. $x \cdot x = 0$ if and only if $x = 0$.
3. For $y \in \mathbb{R}^n$, define $f : \mathbb{R}^n \rightarrow \mathbb{R}$ as $x \mapsto x \cdot y$. Then, f is linear.
4. $\forall x, y \in \mathbb{R}^n, x \cdot y = y \cdot x$.

Proof 1. Properties #1, #2, and #4 are trivial to prove, so the proof is omitted. Here we complete a proof for property #3, linearity of dot product. Let $f : \mathbb{R}^n \rightarrow \mathbb{R}$ be defined as $x \mapsto x \cdot y$ for a fixed $y \in \mathbb{R}^n$. Note that

$$\begin{aligned} f(a + b) &= (a + b) \cdot y = (a_1 + b_1)y_1 + \cdots + (a_n + b_n)y_n \\ &= (a_1y_1 + \cdots + a_ny_n) + (b_1y_1 + \cdots + b_ny_n) \\ &= f(a) + f(b). \end{aligned}$$

Further, notice that

$$\begin{aligned} f(\lambda x) &= (\lambda x) \cdot y = (\lambda x_1)y_1 + \cdots + (\lambda x_n)y_n \\ &= \lambda(x_1y_1 + \cdots + x_ny_n) = \lambda f(x). \end{aligned}$$

■

Remark. For $w, z \in \mathbb{C}^n$, we define the *dot product* of w and z , denoted as $\langle w, z \rangle$, as

$$\langle w, z \rangle = w_1\overline{z_1} + \cdots + w_n\overline{z_n}.$$

Definition 5.1.3 (Inner Product). An *inner product* on V is a function that takes each ordered pair (u, v) of elements of V to a number $\langle u, v \rangle \in \mathbb{F}$ and has the following properties:

1. **positivity:** $\langle v, v \rangle \geq 0 \quad \forall v \in V$.
2. **definiteness:** $\langle v, v \rangle = 0$ if and only if $v = 0$.
3. **additivity in first slot:** $\langle u + v, w \rangle = \langle u, w \rangle + \langle v, w \rangle \quad \forall u, v, w \in V$.
4. **homogeneity in first slot:** $\langle \lambda u, v \rangle = \lambda \langle u, v \rangle \quad \forall \lambda \in \mathbb{F} \text{ and } \forall u, v \in V$.
5. **conjugate symmetry:** $\langle u, v \rangle = \overline{\langle v, u \rangle} \quad \forall u, v \in V$.

Example 5.1.4 Here, we offer some examples of inner product. Note that there might be multiple inner products over a vector space, as long as the following the definition and properties given in Definition 5.1.3.

1. Consider $\mathbb{C}[-1, 1]$, the set of continuous real-valued functions on the interval $[-1, 1]$. An inner product can be defined as $\langle f, g \rangle = \int_{-1}^1 f(x)g(x) \, dx$.

Proof 2.

$$(a) \quad \langle f, f \rangle = \int_{-1}^1 f^2(x) \, dx \geq 0.$$

$$(b) \quad \langle f, f \rangle = 0 \text{ if and only if } f(x) = 0.$$

(c) Note that

$$\begin{aligned} \langle f + g, h \rangle &= \int_{-1}^1 [f(x) + g(x)]h(x) \, dx \\ &= \int_{-1}^1 f(x)h(x) + g(x)h(x) \, dx \\ &= \int_{-1}^1 f(x)h(x) \, dx + \int_{-1}^1 g(x)h(x) \, dx \\ &= \langle f, h \rangle + \langle g, h \rangle. \end{aligned}$$

$$(d) \quad \langle \lambda f, g \rangle = \int_{-1}^1 \lambda f(x)g(x) \, dx = \lambda \int_{-1}^1 f(x)g(x) \, dx = \lambda \langle f, g \rangle.$$

$$(e) \quad \langle g, f \rangle = \int_{-1}^1 g(x)f(x) \, dx = \int_{-1}^1 f(x)g(x) \, dx = \langle f, g \rangle = \overline{\langle f, g \rangle}.$$

■

2. An inner product on $\mathcal{P}(\mathbb{R})$ can be defined as $\langle p, q \rangle = \int_0^\infty p(x)q(x)e^{-x} \, dx$

Proof 3. The definition makes sense. Consider the inner product as $\langle \cdot \rangle : \mathcal{P}(\mathbb{R}) \times \mathcal{P}(\mathbb{R}) \rightarrow \mathbb{R}$. Note that $\infty \notin \mathbb{R}$. So we need to show the improper integral converges to a finite number under any circumstances. Consider

$$\frac{x^2 p(x)q(x)}{e^x} = \frac{p(x)q(x)e^{-x}}{\frac{1}{x^2}}.$$

Note that

$$\lim_{x \rightarrow \infty} \frac{p(x)q(x)e^{-x}}{\frac{1}{x^2}} = 0$$

Further since $\int_0^\infty \frac{1}{x^2} \, dx$ converges as it is a p -series with $p = 2 > 1$, we know it must be $\int_0^\infty p(x)q(x)e^{-x} \, dx$ converges as well, by the comparison test. The remaining job is to show this definition of $\langle \cdot \rangle$ indeed retain the five properties as required in Definition 5.1.3, which is trivial and so is omitted. ■

Definition 5.1.5 (Inner Product Space). An *inner product space* is a vector space V along with an inner product on V .

Example 5.1.6 Euclidean Inner Product on \mathbb{F}^n is defined as

$$\langle (w_1, \dots, w_n), (z_1, \dots, z_n) \rangle = w_1 \overline{z_1} + \dots + w_n \overline{z_n},$$

where $(w_1, \dots, w_n), (z_1, \dots, z_n) \in \mathbb{F}^n$.

Notation 5.1.7. For the rest of this Chapter, without otherwise specification, V denotes an inner product space over \mathbb{F} .

Remark. If not explicitly defined, the inner product is the Euclidean inner product as defined in Example 5.1.6.

Theorem 5.1.8 Basic Properties of an Inner Product

1. For each fixed $u \in V$, the function that takes v to $\langle v, u \rangle$ is a linear map from V to \mathbb{F} .
2. $\langle 0, u \rangle = 0$ for every $u \in V$.
3. $\langle u, 0 \rangle = 0$ for every $u \in V$.
4. $\langle u, v + w \rangle = \langle u, v \rangle + \langle u, w \rangle$ for all $u, v, w \in V$.
5. $\langle u, \lambda v \rangle = \overline{\lambda} \langle u, v \rangle \quad \forall \lambda \in \mathbb{F} \text{ and } u, v \in V$.

Proof 4.

1. Define $f : V \rightarrow \mathbb{F}$ as $v \mapsto \langle v, u \rangle$ for some fixed $u \in V$. Then,

$$f(v + w) = \langle v + w, u \rangle = \langle v, u \rangle + \langle w, u \rangle = f(v) + f(w).$$

$$f(\lambda v) = \langle \lambda v, u \rangle = \lambda \langle v, u \rangle = \lambda f(v). \quad \square$$

2. Since f is a linear map, then $f(0) = \langle 0, u \rangle = 0$. \square

3. Note that $\langle u, 0 \rangle = \overline{\langle 0, u \rangle} = \overline{0} = 0$. \square

4. Notice

$$\begin{aligned} \langle u, v + w \rangle &= \overline{\langle v + w, u \rangle} = \overline{\langle v, u \rangle + \langle w, u \rangle} \\ &= \overline{\langle v, u \rangle} + \overline{\langle w, u \rangle} \\ &= \langle u, v \rangle + \langle u, w \rangle. \end{aligned} \quad \square$$

5. Observe that

$$\begin{aligned} \langle u, \lambda v \rangle &= \overline{\langle \lambda v, u \rangle} = \overline{\lambda \langle v, u \rangle} \\ &= \overline{\lambda} \cdot \overline{\langle v, u \rangle} = \overline{\lambda} \langle u, v \rangle. \end{aligned}$$

■

Definition 5.1.9 (Norm). Suppose V is a vector space. Then, the *norm* of v is a real-valued function $\| \cdot \| : V \rightarrow \mathbb{R}$ satisfying the following properties:

1. $\|v\| \geq 0$ and $\|v\| = 0$ if and only if $v = 0$.
2. $\|\alpha v\| = |\alpha|\|v\| \quad \forall \alpha \in \mathbb{F} \text{ and } v \in V$.
3. triangle inequality: $\|u + v\| \leq \|u\| + \|v\| \quad \forall u, v \in \mathbb{F}$.

Definition 5.1.10 (Norm Induced by An Inner Product). For $v \in V$, $\|v\| = \sqrt{\langle v, v \rangle}$ is a *norm* on V .

Remark. We will prove Definition 5.1.10 is indeed a definition of norm that satisfies the conditions indicated by Definition 5.1.9 throughout the rest of this section.

Theorem 5.1.11 Basic Properties of Norms

Let $v \in V$. Then,

1. $\|v\| = 0$ if and only if $v = 0$.
2. $\|\lambda v\| = |\lambda|\|v\| \quad \forall \lambda \in \mathbb{F}$.

Proof 5.

1. $\|v\| = 0$ if and only if $\sqrt{\langle v, v \rangle} = 0$, which is equivalent to $\langle v, v \rangle = 0$. By properties of an inner product, $\langle v, v \rangle = 0$ if and only if $v = 0$. So, the proof is complete. \square
2. Consider

$$\|\lambda v\|^2 = \langle \lambda v, \lambda v \rangle = \lambda \cdot \bar{\lambda} \langle v, v \rangle = |\lambda|^2 \langle v, v \rangle.$$

$$\text{So, } \|\lambda v\| = \sqrt{|\lambda|^2 \langle v, v \rangle} = |\lambda| \|v\|.$$

■

Definition 5.1.12 (Orthogonal). Two vectors $u, v \in V$ are called *orthogonal* if $\langle u, v \rangle = 0$.

Theorem 5.1.13 Orthogonality and 0

1. 0 is orthogonal to every vector in V .
2. 0 is the only vector in V that is orthogonal to itself.

Proof 6.

1. As $\langle 0, u \rangle = 0 \quad \forall u \in V$, the proof is complete. \square
2. Note that $\langle v, v \rangle = 0$ if and only if $v = 0$, so we complete the proof. \square

■

Theorem 5.1.14 Pythagorean Theorem

Suppose u and v are orthogonal vectors in V , then

$$\|u + v\|^2 = \|u\|^2 + \|v\|^2.$$

Proof 7. Note that

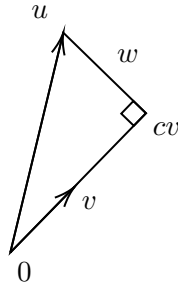
$$\begin{aligned}\|u + v\|^2 &= \langle u + v, u + v \rangle \\ &= \langle u, u + v \rangle + \langle v, u + v \rangle \\ &= \langle u, u \rangle + \langle u, v \rangle + \langle v, u \rangle + \langle v, v \rangle.\end{aligned}$$

Since u and v are orthogonal, $\langle u, v \rangle = \langle v, u \rangle = 0$. So, $\|u + v\|^2 = \langle u, u \rangle + \langle v, v \rangle = \|u\|^2 + \|v\|^2$. ■

Theorem 5.1.15 An Orthogonal Decomposition

Suppose $u, v \in V$, with $v \neq 0$. Set $c = \frac{\langle u, v \rangle}{\|v\|^2}$ and $w = u - \frac{\langle u, v \rangle}{\|v\|^2}v$. Then, $\langle w, v \rangle = 0$ and $u = cv + w$.

Proof 8.



The idea is to find c, w s.t. $\langle v, w \rangle = 0$ and $w = u - cv$. That is, $u = w + cv$. Since $\langle v, w \rangle = 0$, then we have

$$\langle v, u - cv \rangle = 0 = \langle u - cv, v \rangle = \langle u, v \rangle - c\|v\|^2.$$

So,

$$c = \frac{\langle u, v \rangle}{\|v\|^2}$$

and

$$w = u - cv = u - \frac{\langle u, v \rangle}{\|v\|^2}v.$$

■

Theorem 5.1.16 Cauchy-Schwarz Inequality

Suppose $u, v \in V$. Then,

$$|\langle u, v \rangle| \leq \|u\|\|v\|.$$

This inequality is an equality if and only if one of u, v is a scalar multiple of the other.

Proof 9. If $v = 0$, then $|\langle u, v \rangle| = 0 = \|u\|\|v\|$. So, we can assume $v \neq 0$. Consider the orthogonal decomposition,

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

Then, by the Pythagorean Theorem, we have

$$\begin{aligned}\|u\|^2 &= \left\| \frac{\langle u, v \rangle}{\|v\|^2} \cdot v \right\|^2 + \|w\|^2 = \frac{|\langle u, v \rangle|^2}{\|v\|^4} \|v\|^2 + \|w\|^2 \\ &= \frac{|\langle u, v \rangle|^2}{\|v\|^2} + \|w\|^2 \geq \frac{|\langle u, v \rangle|^2}{\|v\|^2}\end{aligned}$$

As $\|v\|^2 > 0$, we have $\|u\|^2\|v\|^2 \geq |\langle u, v \rangle|^2$. Further since $\|u\| \geq 0$, $\|v\| \geq 0$, and $|\langle u, v \rangle| \geq 0$, then

$$|\langle u, v \rangle| \leq \|u\|\|v\|.$$

The equality holds if and only if $\|w\|^2 = 0$. That is, $w = 0$ from the orthogonal decomposition. In other words, u and v are linearly dependent. ■

Theorem 5.1.17 Triangle Inequality

Suppose $u, v \in V$. Then

$$\|u + v\| \leq \|u\| + \|v\|.$$

This inequality is an equality if and only if one of u, v is a non-negative multiple of the other.

Proof 10. Note that

$$\begin{aligned} \|u + v\|^2 &= \langle u + v, u + v \rangle \\ &= \langle u, u \rangle + \langle u, v \rangle + \langle v, u \rangle + \langle v, v \rangle \\ &= \langle u, u \rangle + \langle v, v \rangle + \langle u, v \rangle + \overline{\langle u, v \rangle} \\ &= \|u\|^2 + \|v\|^2 + 2 \operatorname{Re}(\langle u, v \rangle) \\ &\leq \|u\|^2 + \|v\|^2 + 2|\langle u, v \rangle| \\ &\leq \|u\|^2 + \|v\|^2 + 2\|u\|\|v\| \quad \text{Cauchy-Schwarz Inequality} \\ &= (\|u\| + \|v\|)^2. \end{aligned}$$

Since $\|u + v\| \geq 0$, $\|u\| \geq 0$, and $\|v\| \geq 0$, we have

$$\|u + v\| \leq \|u\| + \|v\|.$$

The equality holds if and only if $\langle u, v \rangle = \|u\|\|v\|$. That is, when u and v are linearly dependent to each other. ■

Remark. After proving this triangle inequality, we finally, and officially, complete our proof to show the norm induced by an inner product as stated in Definition 5.1.10 is indeed a norm satisfying the formal definition of norms as stated in Definition 5.1.9.

Theorem 5.1.18 Parallelogram Equality

Suppose $u, v \in V$. Then

$$\|u + v\|^2 + \|u - v\|^2 = 2(\|u\|^2 + \|v\|^2).$$

Proof 11. Note that

$$\begin{aligned} \|u + v\|^2 + \|u - v\|^2 &= \langle u + v, u + v \rangle + \langle u - v, u - v \rangle \\ &= \langle u, u \rangle + \langle v, v \rangle + \langle u, v \rangle + \langle v, u \rangle + \langle u, u \rangle + \langle v, v \rangle - \langle u, v \rangle - \langle v, u \rangle \\ &= \|u\|^2 + \|u\|^2 + \|v\|^2 + \|v\|^2 \\ &= 2(\|u\|^2 + \|v\|^2). \end{aligned}$$

■

Theorem 5.1.19

Suppose V is a real inner product space. Then,

$$\langle u, v \rangle = \frac{\|u + v\|^2 - \|u - v\|^2}{4}.$$

Proof 12. Note that

$$\begin{aligned} \|u + v\|^2 - \|u - v\|^2 &= \langle u + v, u + v \rangle - \langle u - v, u - v \rangle \\ &= \|u\|^2 + \|v\|^2 + 2\langle u, v \rangle - (\|u\|^2 + \|v\|^2 - 2\langle u, v \rangle) \\ &= 4\langle u, v \rangle. \end{aligned}$$

So, we have

$$\langle u, v \rangle = \frac{\|u + v\|^2 - \|u - v\|^2}{4}.$$

■

Theorem 5.1.20

Suppose V is a complex inner product space. Then,

$$\langle u, v \rangle = \frac{\|u + v\|^2 - \|u - v\|^2 + \|u + iv\|^2 - \|u - iv\|^2}{4}.$$

Proof 13. Note that

$$\begin{aligned} &\langle u + v, u + v \rangle - \langle u - v, u - v \rangle + \langle u + iv, u + iv \rangle - \langle u - iv, u - iv \rangle \\ &= 2\langle u, v \rangle + 2\langle v, u \rangle + (2\langle u, iv \rangle + 2\langle iv, u \rangle)i \\ &= 2\langle u, v \rangle + 2\langle v, u \rangle + (-2i\langle u, v \rangle + 2i\langle v, u \rangle)i \\ &= 2\langle u, v \rangle + 2\langle v, u \rangle + 2\langle u, v \rangle - 2\langle v, u \rangle \\ &= 4\langle u, v \rangle. \end{aligned}$$

so, we have

$$\langle u, v \rangle = \frac{\|u + v\|^2 - \|u - v\|^2 + \|u + iv\|^2 - \|u - iv\|^2}{4}.$$

■

Theorem 5.1.21

Let U be a vector space. If $\| \cdot \|$ is a norm on U satisfying the parallelogram equality, then there is an inner product $\langle \cdot, \cdot \rangle$ on U s.t. $\|u\| = \sqrt{\langle u, u \rangle} \quad \forall u \in U$.

5.2 Orthonormal Bases

Definition 5.2.1 (Orthonormal). A list of vectors is called *orthonormal* if each vector in the list has norm 1 and is orthogonal to all the other vectors in the list. In other words, a list e_1, \dots, e_m of vectors in V is orthonormal if

$$\langle e_j, e_k \rangle = \begin{cases} 1 & \text{if } j = k \\ 0 & \text{if } j \neq k \end{cases}.$$

Theorem 5.2.2

If e_1, \dots, e_m is an orthonormal list of vectors in V , then

$$\|a_1 e_1 + \dots + a_m e_m\|^2 = |a_1|^2 + \dots + |a_m|^2 \quad \forall a_1, \dots, a_m \in \mathbb{F}.$$

Proof 1. Note that

$$\langle a_1 e_1, a_2 e_2 + \dots + a_m e_m \rangle = \langle a_1 e_1, a_2 e_2 \rangle + \dots + \langle a_1 e_1, a_m e_m \rangle = 0.$$

So, by the Pythagorean Theorem, we have

$$\begin{aligned} \|a_1 e_1 + \dots + a_m e_m\|^2 &= \|a_1 e_1\|^2 + \|a_2 e_2 + \dots + a_m e_m\|^2 \\ &= \|a_1 e_1\|^2 + \|a_2 e_2\|^2 + \dots + \|a_m e_m\|^2 \\ &= |a_1|^2 + |a_2|^2 + \dots + |a_m|^2. \end{aligned}$$

■

Theorem 5.2.3

Every orthonormal list of vectors is L.I..

Proof 2. Suppose e_1, \dots, e_m is an orthonormal list of vectors in V . Then, $\|a_1 e_1 + \dots + a_m e_m\|^2 = 0$. By Theorem 5.2.2, it is equivalent to $|a_1|^2 + \dots + |a_m|^2 = 0$. Since each $|a_j| \geq 0$, it must be $a_j = 0$ for all $j = 1, \dots, m$. Therefore, the orthonormal list is L.I.. ■

Definition 5.2.4 (Orthonormal Basis). An *orthonormal basis* of V is an orthonormal list of vectors in V that is also a basis of V .

Theorem 5.2.5

Every orthonormal list of vectors in V with length $\dim V$ is an orthonormal basis of V .

Proof 3. By Theorem 5.2.3, any orthonormal list of vectors must be L.I.. Further since it has length $\dim V$, it is a basis of V . So, by definition, it is an orthonormal basis of V . ■

Theorem 5.2.6

Suppose e_1, \dots, e_n is an orthonormal basis of V and $v \in V$. Then, $v = \langle v, e_1 \rangle e_1 + \dots + \langle v, e_n \rangle e_n$, and $\|v\|^2 = |\langle v, e_1 \rangle|^2 + \dots + |\langle v, e_n \rangle|^2$.

Proof 4. Suppose $v \in V$ and $v = a_1 e_1 + \dots + a_n e_n$. Then,

$$\langle v, e_j \rangle = \langle a_1 e_1 + \dots + a_n e_n, e_j \rangle = \langle a_j e_j, e_j \rangle = a_j.$$

So, we have

$$v = \langle v, e_1 \rangle e_1 + \cdots + \langle v, e_n \rangle e_n.$$

Further, by Theorem 5.2.2, we have

$$\|v\|^2 = |\langle v, e_1 \rangle|^2 + \cdots + |\langle v, e_n \rangle|^2.$$

Theorem 5.2.7 Gram-Schmidt Procedure

Suppose v_1, \dots, v_m is L.I. list of vectors in V . Let $e_1 = \frac{v_1}{\|v_1\|}$. For $j = 2, \dots, m$, define e_j inductively by

$$e_j = \frac{v_j - \langle v_j, e_1 \rangle e_1 - \cdots - \langle v_j, e_{j-1} \rangle e_{j-1}}{\|v_j - \langle v_j, e_1 \rangle e_1 - \cdots - \langle v_j, e_{j-1} \rangle e_{j-1}\|}. \quad (15)$$

Then, e_1, \dots, e_m is an orthonormal list of vectors in V s.t. $\text{span}(v_1, \dots, v_j) = \text{span}(e_1, \dots, e_j)$ for $j = 1, \dots, m$.

Proof5. To prove that Gram-Schmidt Procedure indeed produces an orthonormal list of vectors in V , we will use prove by mathematical induction.

Base Case Suppose $j = 1$, then $\text{span}(v_1) = \text{span}(e_1)$ since v_1 is a positive multiple of e_1 . So, the conclusion holds when $j = 1$.

Inductive Steps Suppose for some $1 < j < m$, we have $\text{span}(v_1, \dots, v_{j-1}) = \text{span}(e_1, \dots, e_{j-1})$. Since v_1, \dots, v_m is L.I., we know $v_j \notin \text{span}(v_1, \dots, v_{j-1})$. That is, $v_j \notin \text{span}(e_1, \dots, e_{j-1})$. (If $v_j \in \text{span}(e_1, \dots, e_{j-1})$, then $v_j = \langle v_j, e_1 \rangle e_1 + \cdots + \langle v_j, e_{j-1} \rangle e_{j-1}$.) Then, we are dividing by 0 in Equation (15). So, we are not dividing by 0 in Equation (15). Dividing a vector by its norm produces a new vector with norm 1, so $\|e_j\| = 1$. Now, we want to verify e_j is orthogonal to e_1, \dots, e_{j-1} . Pick some k s.t. $1 \leq k < j$. Then

$$\begin{aligned} \langle e_j, e_k \rangle &= \left\langle \frac{v_j - \langle v_j, e_1 \rangle e_1 - \cdots - \langle v_j, e_{j-1} \rangle e_{j-1}}{\|v_j - \langle v_j, e_1 \rangle e_1 - \cdots - \langle v_j, e_{j-1} \rangle e_{j-1}\|}, e_k \right\rangle \\ &= \frac{\langle v_j - \langle v_j, e_1 \rangle e_1 - \cdots - \langle v_j, e_{j-1} \rangle e_{j-1}, e_k \rangle}{\|v_j - \langle v_j, e_1 \rangle e_1 - \cdots - \langle v_j, e_{j-1} \rangle e_{j-1}\|} \\ &= \frac{\langle v_j, e_k \rangle - \langle v_j, e_k \rangle}{\|v_j - \langle v_j, e_1 \rangle e_1 - \cdots - \langle v_j, e_{j-1} \rangle e_{j-1}\|} \\ &= 0 \end{aligned}$$

Then, e_1, \dots, e_j is an orthonormal basis, and $v_j \in \text{span}(e_1, \dots, e_j)$ since v_j is a linear combination of e_1, \dots, e_j by Equation (15). Further, we have

$$\dim \text{span}(v_1, \dots, v_j) = \dim \text{span}(e_1, \dots, e_j)$$

and

$$\text{span}(v_1, \dots, v_j) \subseteq \text{span}(e_1, \dots, e_j).$$

That is, exactly, $\text{span}(v_1, \dots, v_j) = \text{span}(e_1, \dots, e_j)$.

Theorem 5.2.8

Every f - d inner product space has an orthonormal basis.

Proof 6. Suppose V is f - d , and select a basis of V . Apply Gram-Schmidt Procedure (Theorem 5.2.7) to this basis, we then have an orthonormal basis of V . ■

Theorem 5.2.9

Suppose V is f - d . Then, every orthonormal list of vectors in V can be extended to an orthonormal basis of V .

Proof 7. Suppose e_1, \dots, e_m is an orthonormal list of vectors in V . Then, e_1, \dots, e_m is L.I. and can be extended to a basis $e_1, \dots, e_m, v_1, \dots, v_n$ of V . Apply Gram-Schmidt Procedure to this basis, we get an orthonormal list $e_1, \dots, e_m, f_1, \dots, f_n$. Here, e_1, \dots, e_m is unchanged since they are already orthonormal. Then, $e_1, \dots, e_m, f_1, \dots, f_n$ is an orthonormal basis of V . ■

Theorem 5.2.10

Suppose $T \in \mathcal{L}(V)$. If T has an upper-triangular matrix with respect to some basis of V , then T has an upper-triangular matrix with respect to some orthonormal basis of V .

Proof 8. Suppose $\mathcal{M}(T)$ is upper-triangular with respect to a basis v_1, \dots, v_n of V . Then, we know $\text{span}(v_1, \dots, v_j)$ is invariant under T for $j = 1, \dots, n$. Apply Gram-Schmidt Procedure to v_1, \dots, v_n , we will get an orthonormal basis e_1, \dots, e_n of V . Further, since $\text{span}(e_1, \dots, e_j) = \text{span}(v_1, \dots, v_j)$ for $j = 1, \dots, n$, we know $\text{span}(e_1, \dots, e_j)$ is invariant under T . Therefore, T has an upper-triangular matrix with respect to the orthonormal basis e_1, \dots, e_n . ■

Theorem 5.2.11 Schur's Theorem

Suppose V is a f - d complex vector space and $T \in \mathcal{L}(V)$. Then, T has an upper-triangular matrix with respect to some orthonormal basis of V .

Proof 9. Since V is a f - d complex vector space, T must have an upper-triangular matrix with respect to some basis of V . Further, by Theorem 5.2.10, T must have an upper-triangular matrix with respect to an orthonormal basis of V . ■

Example 5.2.12 The function $\varphi : \mathbb{F}^3 \rightarrow \mathbb{F}$ defined by

$$\varphi(z_1, z_2, z_3) = 2z_1 - 5z_2 + z_3$$

is a linear functional on \mathbb{F}^3 . We could write this linear functional in the form $\varphi(z) = \langle z, u \rangle$ for every $z \in \mathbb{F}^3$, where $u = \langle 2, -5, 1 \rangle$.

Theorem 5.2.13 Riesz Representation Theorem

Suppose V is f - d and φ is a linear functional on V . Then, there is a unique vector $u \in V$ s.t. $\varphi(v) = \langle v, u \rangle$ for every $v \in V$.

Proof 10. Let e_1, \dots, e_n be an orthonormal basis of V . Then, for all $v \in V$, we have

$$v = \langle v, e_1 \rangle e_1 + \dots + \langle v, e_n \rangle e_n.$$

So,

$$\begin{aligned} \varphi(v) &= \varphi(\langle v, e_1 \rangle e_1 + \dots + \langle v, e_n \rangle e_n) \\ &= \langle v, e_1 \rangle \varphi(e_1) + \dots + \langle v, e_n \rangle \varphi(e_n) \\ &= \langle v, \overline{\varphi(e_1)} e_1 \rangle + \dots + \langle v, \overline{\varphi(e_n)} e_n \rangle \\ &= \langle v, \overline{\varphi(e_1)} e_1 + \dots + \overline{\varphi(e_n)} e_n \rangle. \end{aligned}$$

Suppose $\exists u_1, u_2 \in V$ s.t. $\varphi(v) = \langle v, u_1 \rangle = \langle v, u_2 \rangle$. Then, $\langle v, u_1 \rangle - \langle v, u_2 \rangle = \langle v, u_1 - u_2 \rangle = 0$. Let $v = u_1 - u_2$, then we have $\langle u_1 - u_2, u_1 - u_2 \rangle = 0$. So, it must be $u_1 = u_2$. Therefore, \exists a unique $u \in V$ and

$$u = \overline{\varphi(e_1)} e_1 + \dots + \overline{\varphi(e_n)} e_n \text{ s.t. } \varphi(v) = \langle v, u \rangle \quad \forall v \in V.$$

■

Example 5.2.14 Find $u \in \mathcal{P}_2(\mathbb{R})$ s.t. $\int_{-1}^1 p(t)(\cos(\pi t)) dt = \int_{-1}^1 p(t)u(t) dt$ for every $p \in \mathcal{P}_2(\mathbb{R})$.

Remark. Define an inner product on $\mathcal{P}_2(\mathbb{R})$ as $\langle p, q \rangle = \int_{-1}^1 p(x)q(x) dx$ to solve this problem.

Solution 11.

Let $\varphi \in \mathcal{L}(\mathcal{P}_2(\mathbb{R}), \mathbb{R})$ be defined as $\varphi(t) = \int_{-1}^1 p(t)(\cos(\pi t)) dt$. Note that $1, x, x^2$ is a basis of $\mathcal{P}_2(\mathbb{R})$. To find an orthonormal basis of $\mathcal{P}_2(\mathbb{R})$, apply Gram-Schmidt Procedure, we have

$$e_1 = \frac{1}{\|1\|} = \frac{1}{\sqrt{\int_{-1}^1 1 \cdot 1 dt}} = \sqrt{\frac{1}{2}}.$$

Since $x - \langle x, e_1 \rangle e_1 = x - \int_{-1}^1 x \sqrt{\frac{1}{2}} dx \cdot \sqrt{\frac{1}{2}} = x$, and $\|x\| = \sqrt{\int_{-1}^1 x^2 dx} = \sqrt{\frac{2}{3}}$, we have

$$e_2 = \frac{x}{\sqrt{\frac{2}{3}}} = \sqrt{\frac{3}{2}}x.$$

Further, consider

$$\begin{aligned} x^2 - \langle x^2, e_1 \rangle e_1 - \langle x^2, e_2 \rangle e_2 &= x^2 - \int_{-1}^1 x^2 \sqrt{\frac{1}{2}} dx \cdot \sqrt{\frac{1}{2}} - \int_{-1}^1 x^2 \sqrt{\frac{3}{2}} x dx \cdot \sqrt{\frac{3}{2}} x \\ &= x^2 - \frac{1}{3}, \end{aligned}$$

and note that

$$\left\|x^2 - \frac{1}{3}\right\| = \sqrt{\int_{-1}^1 \left(x^2 - \frac{1}{3}\right)^2 dx} = \sqrt{\int_{-1}^1 x^4 - \frac{2}{3}x^2 + \frac{1}{9} dx} = \sqrt{\frac{8}{45}}.$$

So, we have

$$e_3 = \frac{x^2 - \frac{1}{3}}{\sqrt{\frac{8}{45}}} = \sqrt{\frac{45}{8}} \left(x^2 - \frac{1}{3}\right).$$

That is, $e_1 = \sqrt{\frac{1}{2}}$, $e_2 = \sqrt{\frac{3}{2}}x$, $e_3 = \sqrt{\frac{45}{8}} \left(x^2 - \frac{1}{3}\right)$ is an orthonormal basis of $\mathcal{P}_2(\mathbb{R})$. Then, we have

$$\varphi(e_1) = \int_{-1}^1 \sqrt{\frac{1}{2}} \cos(\pi t) dt = \sqrt{\frac{1}{2}} \int_{-1}^1 \cos(\pi t) dt = 0$$

$$\varphi(e_2) = \int_{-1}^1 \sqrt{\frac{3}{2}} t \cos(\pi t) dt = \sqrt{\frac{3}{2}} \int_{-1}^1 t \cos(\pi t) dt = 0$$

$$\begin{aligned} \varphi(e_3) &= \int_{-1}^1 \sqrt{\frac{45}{8}} \left(t^2 - \frac{1}{3}\right) \cos(\pi t) dt \\ &= \sqrt{\frac{45}{8}} \int_{-1}^1 t^2 \cos(\pi t) dt - \sqrt{\frac{45}{8}} \cdot \frac{1}{3} \underbrace{\int_{-1}^1 \cos(\pi t) dt}_0 \\ &= \sqrt{\frac{45}{8}} \int_{-1}^1 t^2 \cos(\pi t) dt \\ &= \sqrt{\frac{45}{8}} \left(-\frac{4}{\pi^2}\right). \end{aligned}$$

So, by Theorem 5.2.15 and its proof, we know

$$\begin{aligned} u &= \varphi(e_1)e_1 + \varphi(e_2)e_2 + \varphi(e_3)e_3 = 0 + 0 + \sqrt{\frac{45}{8}} \left(-\frac{4}{\pi^2}\right) \sqrt{\frac{45}{8}} \left(x^2 - \frac{1}{3}\right) \\ &= \frac{45}{8} \left(-\frac{4}{\pi^2}\right) \left(x^2 - \frac{1}{3}\right) \\ &= -\frac{45}{2\pi^2} \left(x^2 - \frac{1}{3}\right). \end{aligned}$$

□

5.3 Orthogonal Complements and Minimization Problems

Definition 5.3.1 (Orthogonal Complement, U^\perp). If U is a subset of V , then the *orthogonal complement* of U , denoted U^\perp , is the set of all vectors in V that are orthogonal to every vector in U :

$$U^\perp = \{v \in V \mid \langle v, u \rangle = 0 \quad \forall u \in U\}.$$

Theorem 5.3.2 Basic Properties of Orthogonal Complements

1. If U is a subset of V , then U^\perp is a subspace of V .
2. $\{0\}^\perp = V$.
3. $V^\perp = \{0\}$.
4. If U is a subset of V , then $U \cap U^\perp \subseteq \{0\}$.
5. If U and W are subsets of V and $U \subseteq W$, then $W^\perp \subseteq U^\perp$.

Proof 1.

1. Let $v, w \in U^\perp$. Then $\langle v + w, u \rangle = \langle v, u \rangle + \langle w, u \rangle = 0 + 0 = 0$. So, $v + w \in U^\perp$. Further, suppose $\lambda \in \mathbb{F}$. Then $\langle \lambda v, u \rangle = \lambda \langle v, u \rangle = \lambda \cdot 0 = 0$. So, $\lambda v \in U^\perp$. Finally since $\langle 0, u \rangle = 0$, we know $0 \in U^\perp$. Then, U^\perp is a subspace of V . \square
2. Since $\langle v, 0 \rangle = 0 \quad \forall v \in V$, we know $\{0\}^\perp = V$. \square
3. Suppose $v \in V^\perp$. Then, $\langle v, v \rangle = 0$. By property of an inner product, it must be that $v = 0$. So, $V^\perp = \{0\}$. \square
4. Suppose U is a subset of V . Let $v \in U \cap U^\perp$. Then, $v \in U$ and $v \in U^\perp$. So, $\langle v, v \rangle = 0$. Then, it must be that $v = 0$. So, $U \cap U^\perp \subseteq \{0\}$. \square
5. Suppose U and W are subsets of V with $U \subseteq W$. Suppose $v \in W^\perp$. Then, $\langle v, u \rangle = 0 \quad \forall u \in W$. Since $U \subseteq W$, we have $\langle v, u \rangle = 0 \quad \forall u \in U$. That is, $v \in U^\perp$. Then, we have $W^\perp \subseteq U^\perp$. \blacksquare

Theorem 5.3.3

Suppose U is a f - d subspace of V . Then, $V = U \oplus U^\perp$.

Proof 2. Suppose $u \in U$ and $w \in U^\perp$. Then, $\forall v \in V$, we have $v = cu + w$ for some $c \in \mathbb{F}$ and $\langle u, w \rangle = 0$. Then, we have $V = U + U^\perp$. Further, by Theorem 5.3.2(4), $U \cap U^\perp = \{0\}$ since U and U^\perp are all subspaces of V . Hence, $V = U \oplus U^\perp$. \blacksquare

Corollary 5.3.4 Suppose V is f - d and U is a subspace of V . Then, $\dim U^\perp = \dim V - \dim U$.

Theorem 5.3.5

Suppose U is a f - d subspace of V . Then, $U = (U^\perp)^\perp$.

Proof 3.

(\subseteq). Suppose $u \in U$. Then, $\langle u, v \rangle = 0 \quad \forall v \in U^\perp$. Then, $u \in (U^\perp)^\perp$. That is, $U \subseteq (U^\perp)^\perp$. \square

(\supseteq). Suppose $v \in (U^\perp)^\perp$. Then, $v = u + w$ for some $u \in U$ and $w \in U^\perp$. Then, $w = v - u \in (U^\perp)^\perp$. Since $U \subseteq (U^\perp)^\perp$, we know $u \in U^\perp$. Then, $v - u \in (U^\perp)^\perp$. Hence, $v - u \in U^\perp \cap (U^\perp)^\perp$. That is, $v - u$ is orthogonal to itself. So, it must be that $v - u = 0$ or $v = u$. Since $u \in U$ and $v \in U$, we have shown that $(U^\perp)^\perp \subseteq U$. ■

Definition 5.3.6 (Orthogonal Projection, P_U). Suppose U is a f - d subspace of V . Then orthogonal projection of V onto U is the operator $P_U \in \mathcal{L}(V)$ defined as follows: For $v \in V$, write $v = u + w$, where $u \in U$ and $w \in U^\perp$. Then, $P_U v = u$.

Remark. By Theorem 5.3.3, $V = U \oplus U^\perp$, which ensures each $v \in V$ can be uniquely represented in the form of $u + w$ with $u \in U$ and $w \in U^\perp$, and thus P_U is well-defined.

Example 5.3.7 Suppose $x \in V$ with $x \neq 0$ and $U = \text{span}(x)$. Show that

$$P_U v = \frac{\langle v, x \rangle}{\|x\|^2} x \quad \forall v \in V.$$

Proof 4. Suppose $v \in V$. Then,

$$v = \frac{\langle v, x \rangle}{\|x\|^2} x + \left(v - \frac{\langle v, x \rangle}{\|x\|^2} x \right),$$

where $\frac{\langle v, x \rangle}{\|x\|^2} x \in \text{span}(x)$ and $v - \frac{\langle v, x \rangle}{\|x\|^2} x \in U^\perp$. Thus, $P_U v = \frac{\langle v, x \rangle}{\|x\|^2} x$. ■

Theorem 5.3.8 Properties of Orthogonal Projections

Suppose U is a f - d subspace of V and $v \in V$. Then,

1. $P_U \in \mathcal{L}(V)$.
2. $P_U u = u \quad \forall u \in U$.
3. $P_U w = 0 \quad \forall w \in U^\perp$.
4. $\text{range } P_U = U$.
5. $\text{null } P_U = U^\perp$.
6. $v - P_U v \in U^\perp$.
7. $P_U^2 = P_U$.
8. $\|P_U v\| \leq \|v\|$.
9. for every orthonormal basis e_1, \dots, e_m of U ,

$$P_U v = \langle v, e_1 \rangle e_1 + \dots + \langle v, e_m \rangle e_m.$$

Proof 5.

1. Suppose $v_1 = u_1 + w_1$ and $v_2 = u_2 + w_2$, where $v_1, v_2 \in V$, $u_1, u_2 \in U$, and $w_1, w_2 \in U^\perp$. Then,

$v_1 + v_2 = (u_1 + u_2) + (w_1 + w_2)$, where $u_1 + u_2 \in U$ and $w_1 + w_2 \in U^\perp$. So,

$$P_U(v_1 + v_2) = u_1 + u_2 = P_U v_1 + P_U v_2.$$

Additionally, suppose $\lambda \in \mathbb{F}$. Then, $\lambda v_1 = \lambda u_1 + \lambda w_1$, where $\lambda u_1 \in U$ and $\lambda w_1 \in U^\perp$. Then,

$$P_U(\lambda v_1) = \lambda u_1 = \lambda P_U(v_1). \quad \square$$

2. Suppose $u \in U$. Then, $u = u + 0$, where $u \in U$ and $0 \in U^\perp$. So, $P_U u = u$. \square

3. Suppose $w \in U^\perp$. Then, $w = 0 + w$, where $0 \in U$ and $w \in U^\perp$. So, $P_U w = 0$. \square

4. By definition of P_U , we have $\text{range } P_U \subseteq U$. By Theorem 5.3.8(2), we know $U \subseteq \text{range } P_U$. So, $\text{range } P_U = U$. \square

5. By Theorem 5.3.8(3), we have $U^\perp \subseteq \text{null } P_U$. Further note if $v \in \text{null } P_U$, then $v = 0 + v$ with $0 \in U$ and $v \in U^\perp$. So, $\text{null } P_U \subseteq U^\perp$. That is, $\text{null } P_U = U^\perp$. \square

6. If $v = u + w$ with $u \in U$ and $w \in U^\perp$, then

$$v - P_U v = v - u = w \in U^\perp. \quad \square$$

7. If $v = u + w$ with $u \in U$ and $w \in U^\perp$, then

$$(P_U^2)v = P_U(P_U v) = P_U u = u = P_U v.$$

So, $P_U^2 = P_U$. \square

8. If $v = u + w$ with $u \in U$ and $w \in U^\perp$, then we have

$$\|P_U v\|^2 = \|u\|^2 \leq \|u\|^2 + \|w\|^2 = \|v\|^2$$

by the Pythagorean Theorem. \square

9. If $v = u + w$ with $u \in U$ and $w \in U^\perp$, then

$$v = u + w = \langle v, e_1 \rangle e_1 + \cdots + \langle v, e_m \rangle e_m + (v - \langle v, e_1 \rangle e_1 - \cdots - \langle v, e_m \rangle e_m).$$

Since e_1, \dots, e_m is an orthonormal basis of U , we have $\langle v, e_1 \rangle e_1 + \cdots + \langle v, e_m \rangle e_m \in U$. Now, consider

$$\begin{aligned} \langle \langle v, e_1 \rangle e_1 + \cdots + \langle v, e_m \rangle e_m, v - \langle v, e_1 \rangle e_1 - \cdots - \langle v, e_m \rangle e_m \rangle &= \langle \langle v, e_1 \rangle e_1 + \cdots + \langle v, e_m \rangle e_m, v \rangle - \|u\|^2 \\ &= \langle v, e_1 \rangle \langle e_1, v \rangle + \cdots + \langle v, e_m \rangle \langle e_m, v \rangle - \|u\|^2 \\ &= \langle v, e_1 \rangle \overline{\langle v, e_1 \rangle} + \cdots + \langle v, e_m \rangle \overline{\langle v, e_m \rangle} - \|u\|^2 \\ &= |\langle v, e_1 \rangle|^2 + \cdots + |\langle v, e_m \rangle|^2 - \|u\|^2 \\ &= \|u\|^2 - \|u\|^2 = 0 \quad (\text{By Theorem 5.2.2}) \end{aligned}$$

Then, $v - \langle v, e_1 \rangle e_1 - \cdots - \langle v, e_m \rangle e_m \in U^\perp$. So, we have $P_U v = \langle v, e_1 \rangle e_1 + \cdots + \langle v, e_m \rangle e_m$. ■

Theorem 5.3.9 Minimizing the Distance to a Subspace

Suppose U is a f - d subspace of V , $v \in V$, and $u \in U$. Then, $\|v - P_U v\| \leq \|v - u\|$. The inequality is an equality if and only if $u = P_U v$.

Proof 6. Note that $\|v - P_U v\|^2 \leq \|v - P_U v\|^2 + \|P_U v - u\|^2$ since $\|P_U v - u\|^2 \geq 0$. Further, since $v - P_U v \in U^\perp$ by Theorem 5.3.8(6) and $P_U v - u \in U$ by the Pythagorean Theorem, we have

$$\|v - P_U v\|^2 + \|P_U v - u\|^2 = \|v - P_U v + P_U v - u\|^2 = \|v - u\|^2.$$

Then, $\|u - P_U v\|^2 \leq \|v - P_U v\|^2 + \|P_U v - u\|^2 = \|v - u\|^2$. Since $\|v - P_U v\|^2 \geq 0$ and $\|v - u\|^2 \geq 0$, we have $\|v - P_U v\| \leq \|v - u\|$. The equality holds if and only if $\|P_U v - u\|^2 = 0$. That is, $\|P_U v - u\| = 0$, $P_U v - u = 0$, or $P_U v = u$. ■

Example 5.3.10 In \mathbb{R}^4 , set $U = \text{span}((1, 1, 0, 0), (1, 1, 1, 2))$. Find $u \in U$ s.t. $\|u - (1, 2, 3, 4)\|$ is as small as possible.

Solution 7.

By Theorem 5.3.9, we need to find $P_U v = \langle v, e_1 \rangle e_1 + \langle v, e_2 \rangle e_2$. Thus, we need to use Gram-Schmidt Procedure to find e_1 and e_2 :

$$e_1 = \frac{1}{\sqrt{2}}(1, 1, 0, 0) \quad \text{and} \quad e_2 = \frac{1}{\sqrt{5}}(0, 0, 1, 2).$$

Set $v = (1, 2, 3, 4)$, we have

$$\begin{aligned} P_U v &= \langle (1, 2, 3, 4), \frac{1}{\sqrt{2}}(1, 1, 0, 0) \rangle \frac{1}{\sqrt{2}}(1, 1, 0, 0) + \langle (1, 2, 3, 4), \frac{1}{\sqrt{5}}(0, 0, 1, 2) \rangle \frac{1}{\sqrt{5}}(0, 0, 1, 2) \\ &= \left(\frac{3}{2}, \frac{3}{2}, \frac{11}{5}, \frac{22}{5} \right). \end{aligned}$$

□

6 Operators on Inner Product Spaces

6.1 Self-Adjoint and Normal Operators

Definition 6.1.1 (Adjoint, T^*). Suppose $T \in \mathcal{L}(V, W)$. The *adjoint* of T is the function $T^* : W \rightarrow V$ s.t.

$$\langle Tv, w \rangle = \langle v, T^*w \rangle$$

for every $v \in V$ and every $w \in W$.

Theorem 6.1.2

If $T \in \mathcal{L}(V, W)$, then $T^* \in \mathcal{L}(W, V)$.

Proof 1.

1. The definition of adjoint makes sense.

Suppose $T \in \mathcal{L}(V, W)$. Fix $w \in W$. Let $f : V \rightarrow \mathbb{F}$ be defined as $v \mapsto \langle Tv, w \rangle$. Then, f is a linear functional on V . Note that

$$\begin{aligned} f(au + bv) &= \langle T(au + bv), w \rangle = \langle aTu + bTv, w \rangle \\ &= a\langle Tu, w \rangle + b\langle Tv, w \rangle \\ &= af(u) + b(fv). \end{aligned}$$

By Riesz Representation Theorem, we know $f(v) = \langle v, \Delta \rangle$ for some $\Delta \in V$. We call this unique Δ as T^*w . That is, for each $w \in W$, \exists unique $T^*w \in V$. So, T^* is well-defined as a function from W to V . \square

2. Adjoint is a linear map.

Suppose $w_1, w_2 \in W$. If $v \in V$, then

$$\begin{aligned} \langle v, T^*(w_1 + w_2) \rangle &= \langle Tv, w_1 + w_2 \rangle = \langle Tv, w_1 \rangle + \langle Tv, w_2 \rangle \\ &= \langle v, T^*w_1 \rangle + \langle v, T^*w_2 \rangle \\ &= \langle v, T^*w_1 + T^*w_2 \rangle. \end{aligned}$$

So, $T^*(w_1 + w_2) = T^*w_1 + T^*w_2$. \square

Now fix $w \in W$ and $\lambda \in \mathbb{F}$. If $v \in V$, then

$$\begin{aligned} \langle v, T^*(\lambda w) \rangle &= \langle Tv, \lambda w \rangle = \overline{\lambda} \langle Tv, w \rangle \\ &= \overline{\lambda} \langle v, T^*w \rangle \\ &= \langle v, \lambda T^*w \rangle. \end{aligned}$$

So, we know $T^*(\lambda w) = \lambda T^*w$. \square

Thus, we've shown T^* is a linear map as desired. ■

Example 6.1.3 Define $T : \mathbb{R}^3 \rightarrow \mathbb{R}^2$ by $T(x_1, x_2, x_3) = (x_2 + 3x_3, 2x_1)$. Find a formula for T^* .

Solution 2.

Define $T^* : \mathbb{R}^2 \rightarrow \mathbb{R}^3$. Let $y = (y_1, y_2) \in \mathbb{R}^2$. Then,

$$\begin{aligned}\langle x, T^*y \rangle &= \langle Tx, y \rangle = y_1x_2 + 3y_1x_3 + 2x_1y_2 \\ &= \langle (x_1, x_2, x_3), (2y_2, y_1, 3y_1) \rangle.\end{aligned}$$

Thus, $T^* : \mathbb{R}^2 \rightarrow \mathbb{R}^3$ is defined as $T^*(y_1, y_2) = (2y_2, y_1, 3y_1)$. □

Example 6.1.4 Fix $u \in V$ and $x \in W$. Define $T \in \mathcal{L}(V, W)$ by $Tv = \langle v, u \rangle x$ for every $v \in V$. Find a formula for T^* .

Solution 3.

Define $T^* \in \mathcal{L}(W, V)$. Consider

$$\begin{aligned}\langle v, T^*w \rangle &= \langle Tv, w \rangle = \langle \langle v, u \rangle x, w \rangle \\ &= \langle v, u \rangle \langle x, w \rangle \\ &= \langle v, \langle w, x \rangle u \rangle.\end{aligned}$$

So, we have $T^*w = \langle w, x \rangle u$. □

Theorem 6.1.5 Properties of the Adjoint

1. $(S + T)^* = S^* + T^* \quad \forall S, T \in \mathcal{L}(V, W)$.
2. $(\lambda T)^* = \bar{\lambda} T^* \quad \forall \lambda \in \mathbb{F} \text{ and } T \in \mathcal{L}(V, W)$.
3. $(T^*)^* = T \quad \forall T \in \mathcal{L}(V, W)$.
4. $I^* = I$, where I is the identity operator on V .
5. $(ST)^* = T^* S^* \quad \forall T \in \mathcal{L}(V, W) \text{ and } S \in \mathcal{L}(W, U)$.

Proof 4.

1. Consider

$$\begin{aligned}\langle v, (S + T)^*w \rangle &= \langle (S + T)v, w \rangle = \langle Sv, w \rangle + \langle Tv, w \rangle \\ &= \langle v, S^*w \rangle + \langle v, T^*w \rangle \\ &= \langle v, S^*w + T^*w \rangle \\ &= \langle v, (S^* + T^*)w \rangle.\end{aligned}$$

So, we have $(S + T)^*w = (S^* + T^*)w \quad \forall w \in W$. □

2. Note that

$$\begin{aligned}\langle v, (\lambda T)^*w \rangle &= \langle (\lambda T)v, w \rangle = \lambda \langle Tv, w \rangle \\ &= \lambda \langle v, T^*w \rangle \\ &= \langle v, \bar{\lambda} T^*w \rangle.\end{aligned}$$

So, we get $(\lambda T)^*w = \bar{\lambda}T^*w \quad \forall w \in W.$ \square

3. Consider

$$\begin{aligned}\langle v, (T^*)^*w \rangle &= \langle T^*v, w \rangle = \overline{\langle w, T^*v \rangle} \\ &= \overline{\langle Tw, v \rangle} \\ &= \langle v, Tw \rangle.\end{aligned}$$

So, it is $(T^*)^*w = Tw \quad \forall w \in W.$ \square

4. Note we have

$$\langle v, I^*w \rangle = \langle Iv, w \rangle = \langle v, w \rangle.$$

So, $I^*w = w \quad \forall w \in W.$ That is, $I^* = I.$ \square

5. We have

$$\begin{aligned}\langle v, (ST)^*w \rangle &= \langle (ST)v, w \rangle = \langle S(Tv), w \rangle \\ &= \langle Tv, S^*w \rangle \\ &= \langle v, T^*(S^*w) \rangle.\end{aligned}$$

So, $(ST)^*w = T^*(S^*w) = (T^*S^*)w \quad \forall w \in W.$

Theorem 6.1.6 Null Space and Range of T^*

Suppose $T \in \mathcal{L}(V, W).$ Then,

1. $\text{null } T^* = (\text{range } T)^\perp.$
2. $\text{range } T = (T^*)^\perp.$
3. $\text{null } T = (\text{range } T^*)^\perp.$
4. $\text{range } T^* = (\text{null } T)^\perp.$

Proof 5.

1. Suppose $w \in \text{null } T^*.$ Then, $T^*w = 0.$ So, $\langle v, T^*w \rangle = 0.$ That is, $\langle Tv, w \rangle = 0 \quad \forall v \in V.$ Then, w is orthogonal to any $Tv.$ That is, $w \in (\text{range } T)^\perp.$ Conversely, if $w \in (\text{range } T)^\perp,$ we have $\langle Tv, w \rangle = 0,$ and thus $\langle v, T^*w \rangle = 0,$ or $T^*w = 0.$ That is, $w \in \text{null } T^*.$ Hence, $\text{null } T^* = (\text{range } T)^\perp.$ \square
2. Note that $(\text{null } T^*)^\perp = ((\text{range } T)^\perp)^\perp = \text{range } T.$ \square
3. Suppose $v \in \text{null } T.$ Then, $Tv = 0,$ and $\langle Tv, w \rangle = 0.$ So, $\langle v, T^*w \rangle = 0 \quad \forall w \in W.$ Then, v is orthogonal to every vectors in $T^*W.$ So, $v \in (\text{range } T^*)^\perp.$ In the other way around, if we assume $v \in (\text{range } T^*)^\perp,$ then $\langle v, T^*w \rangle = \langle Tv, w \rangle = 0.$ So, $Tv = 0,$ and thus $v \in \text{null } T.$ Hence, we have $\text{null } T = (\text{range } T^*)^\perp.$ \square
4. Consider $(\text{null } T)^\perp = ((\text{range } T^*)^\perp)^\perp = \text{range } T^*.$

Definition 6.1.7 (Conjugate Transpose). The *conjugate transpose* of an $m \times n$ matrix is the $n \times m$ matrix obtained by interchanging the rows and columns and then taking the conjugate of each entry.

Theorem 6.1.8

Let $T \in \mathcal{L}(V, W)$. Suppose e_1, \dots, e_n is an orthonormal basis of V and f_1, \dots, f_m is an orthonormal basis of W . Then, $\mathcal{M}(T^*, (f_1, \dots, f_m), (e_1, \dots, e_m))$ is the conjugate transpose of $\mathcal{M}(T, (e_1, \dots, e_n), (f_1, \dots, f_m))$.

Proof 6. Suppose $\mathcal{M}(T)$ denote the matrix $\mathcal{M}(T, (e_1, \dots, e_n), (f_1, \dots, f_m))$ and let $\mathcal{M}(T^*)$ denote the matrix $\mathcal{M}(T^*, (f_1, \dots, f_m), (e_1, \dots, e_m))$. Then, note that $Te_k = \langle Te_k, f_1 \rangle f_1 + \dots + \langle Te_k, f_m \rangle f_m$. So,

$$(\mathcal{M}(T))_{j,k} = \langle Te_k, f_j \rangle.$$

Further, consider $T^*f_k = \langle T^*f_k, e_1 \rangle e_1 + \dots + \langle T^*f_k, e_n \rangle e_n$. That is,

$$\begin{aligned} (\mathcal{M}(T^*))_{j,k} &= \langle T^*f_k, e_j \rangle = \overline{\langle e_j, T^*f_k \rangle} \\ &= \overline{\langle Te_j, f_k \rangle} \\ &= \overline{(\mathcal{M}(T))_{k,j}} \end{aligned}$$

So, we've shown that $\mathcal{M}(T^*)$ is the conjugate transpose of $\mathcal{M}(T)$. ■

Definition 6.1.9 (Self-Adjoint). An operator $T \in \mathcal{L}(V)$ is called *self-adjoint* if $T = T^*$. In other words, $T \in \mathcal{L}(V)$ is self-adjoint if and only if $\langle Tv, w \rangle = \langle v, Tw \rangle \quad \forall v, w \in V$.

Theorem 6.1.10

The sum of two self-adjoint operators is self-adjoint, and the product of a real scalar and a self-adjoint operator is self-adjoint.

Proof 7.

1. Suppose $T, S \in \mathcal{L}(V)$ are self-adjoint. Then,

$$(S + T)^* = S^* + T^* = S + T.$$

So, $S + T$ is self-adjoint. □

2. Let $\lambda \in \mathbb{R}$. Then,

$$(\lambda T)^* = \lambda T^* = \lambda T.$$

So, λT is self-adjoint. ■

Theorem 6.1.11

Every eigenvalue of a self-adjoint operator is real.

Proof 8. Suppose T is a self-adjoint operator on V . Let λ be an eigenvalue of T , and let v be a non-zero vector in V s.t. $Tv = \lambda v$. Then,

$$\lambda \|v\|^2 = \langle \lambda v, v \rangle = \langle Tv, v \rangle = \langle v, Tv \rangle = \langle v, \lambda v \rangle = \bar{\lambda} \|v\|^2.$$

So, it must be $\lambda = \bar{\lambda}$, which means λ is real. ■

Theorem 6.1.12

Suppose V is a complex inner product space and $T \in \mathcal{L}(V)$. Suppose $\langle Tv, v \rangle = 0 \quad \forall v \in V$. Then, $T = 0$.

Proof 9. Note that

$$\begin{aligned} \langle Tu, w \rangle &= \frac{1}{4} \left[\langle T(u+w), u+w \rangle - \langle T(u-w), u-w \rangle \right] \\ &\quad + \frac{i}{4} \left[\langle T(u+iw), u+iw \rangle - \langle T(u-iw), u-iw \rangle \right] \\ &= 0 \quad \forall u, w \in V. \end{aligned}$$

Let $w = Tu \in V$. Then, $\langle Tu, Tu \rangle = 0$. That is, $Tu = 0 \quad \forall u \in V$. So, $T = 0$. ■

Theorem 6.1.13

Suppose V is a complex inner product space and $T \in \mathcal{L}(V)$. Then, T is self-adjoint if and only if $\langle Tv, v \rangle \in \mathbb{R} \quad \forall v \in V$.

Proof 10.

(\Rightarrow) Let $v \in V$. Then,

$$\begin{aligned} \langle Tv, v \rangle - \overline{\langle Tv, v \rangle} &= \langle Tv, v \rangle - \langle v, Tv \rangle \\ &= \langle Tv, v \rangle - \langle T^*v, v \rangle \\ &= \langle (T - T^*)v, v \rangle \end{aligned} \tag{16}$$

If $\langle Tv, v \rangle \in \mathbb{R} \quad \forall v \in V$, then Equation (16) = 0. That is, $\langle (T - T^*)v, v \rangle = 0 \quad \forall v \in V$. So, $T - T^* = 0$, or $T = T^*$. That is, T is self-adjoint. □

(\Leftarrow) Conversely, if T is self-adjoint, then Equation (16) = 0. That is, $\langle Tv, v \rangle = \overline{\langle Tv, v \rangle} = 0$, or we have $\langle Tv, v \rangle = \overline{\langle Tv, v \rangle}$. This is equivalent to the conclusion $\langle Tv, v \rangle \in \mathbb{R}$. ■

Theorem 6.1.14

Suppose T is a self-adjoint operator on V s.t. $\langle Tv, v \rangle = 0 \quad \forall v \in V$. Then, $T = 0$.

Proof 11. We've already shown this to be true under a complex inner product space. Thus, we can assume V is a real inner product space. If $u, w \in V$, then

$$\begin{aligned} \langle Tu, w \rangle &= \frac{1}{4} \langle T(u+w), u+w \rangle - \langle T(u-w), u-w \rangle \\ &= 0 \quad \forall u, w \in V. \end{aligned}$$

Let $w = Tu$. Then, $\langle Tu, Tu \rangle = 0$, or $Tu = 0 \quad \forall u \in V$. So, $T = 0$. ■

Definition 6.1.15 (Normal Operator). An operator on an inner product space is called *normal* if it commutes with its adjoint. In other words, $T \in \mathcal{L}(V)$ is normal if $TT^* = T^*T$.

Example 6.1.16 Let T be the operator on \mathbb{F}^2 whose matrix with respect to the standard basis is

$$\begin{pmatrix} 2 & -3 \\ 3 & 2 \end{pmatrix}.$$

Show that T is not self-adjoint but is still normal.

Proof 12. Since $\mathcal{M}(T) = \begin{pmatrix} 2 & -3 \\ 3 & 2 \end{pmatrix}$ and $\mathcal{M}(T^*) = \begin{pmatrix} 2 & 3 \\ -3 & 2 \end{pmatrix}$, then $\mathcal{M}(T) \neq \mathcal{M}(T^*)$, and thus it is not self-adjoint. However, note that

$$\begin{pmatrix} 2 & -3 \\ 3 & 2 \end{pmatrix} \begin{pmatrix} 2 & 3 \\ -3 & 2 \end{pmatrix} = \begin{pmatrix} 13 & 0 \\ 0 & 13 \end{pmatrix}$$

and

$$\begin{pmatrix} 2 & 3 \\ -3 & 2 \end{pmatrix} \begin{pmatrix} 2 & -3 \\ 3 & 2 \end{pmatrix} = \begin{pmatrix} 13 & 0 \\ 0 & 13 \end{pmatrix}.$$

So, by definition, T is normal. ■

Theorem 6.1.17

An operator $T \in \mathcal{L}(V)$ is normal if and only if $\|Tv\| = \|T^*v\| \quad \forall v \in V$.

Proof 13. Note that

$$\begin{aligned} T \text{ is normal} &\iff T^*T - TT^* = 0 \\ &\iff \langle (T^*T - TT^*)v, v \rangle = 0 \quad \forall v \in V \\ &\iff \langle T^*Tv, v \rangle = \langle TT^*v, v \rangle \quad \forall v \in V \\ &\iff \langle Tv, Tv \rangle = \langle T^*v, T^*v \rangle \quad \forall v \in V \\ &\iff \|Tv\|^2 = \|T^*v\|^2 \quad \forall v \in V. \end{aligned}$$

Since $\|Tv\| \geq 0$ and $\|T^*v\| \geq 0$, it is equivalent to

$$\|Tv\| = \|T^*v\| \quad \forall v \in V. \quad \text{■}$$

Theorem 6.1.18

Suppose $T \in \mathcal{L}(V)$ is normal and $v \in V$ is an eigenvector of T with eigenvalue λ . Then, v is also an eigenvector of T^* with eigenvalue $\bar{\lambda}$.

Proof 14. Note that $(T - \lambda I)^* = T^* - \bar{\lambda}I$. Consider $(T - \lambda I)(T - \lambda I)^* = TT^* - \bar{\lambda}T - \lambda T^* + \lambda\bar{\lambda}$ and $(T - \lambda I)^*(T - \lambda I) = T^*T - \bar{\lambda}T - \lambda T^* + \lambda\bar{\lambda}$. Since, T is normal, $TT^* = T^*T$. So,

$$(T - \lambda I)(T - \lambda I)^* = (T - \lambda I)^*(T - \lambda I).$$

That is, $T - \lambda I$ is also normal. So, by Theorem 6.1.17, we have

$$\|(T - \lambda I)v\| = \|(T^* - \bar{\lambda}I)v\| = 0.$$

That is, $T^*v = \bar{\lambda}v$, or v is an eigenvector of T^* with eigenvalue $\bar{\lambda}$. ■

Theorem 6.1.19

Suppose $T \in \mathcal{L}(V)$ is normal. Then, eigenvectors of T corresponding to distinct eigenvalues are orthogonal.

Proof 15. Suppose α, β are distinct eigenvalues of T , with corresponding eigenvectors u, v . Then, $Tu = \alpha u$ and $Tv = \beta v$. By Theorem 6.1.18, we have $T^*v = \bar{\beta}v$. So, we have

$$\begin{aligned} (\alpha - \beta)\langle u, v \rangle &= \langle \alpha u, v \rangle - \langle u, \bar{\beta}v \rangle \\ &= \langle Tu, v \rangle - \langle u, T^*v \rangle \\ &= \langle Tu, v \rangle - \langle Tu, v \rangle \\ &= 0. \end{aligned}$$

Since $\alpha \neq \beta$, it must be $\langle u, v \rangle = 0$. So, u and v are orthogonal. ■

6.2 The Spectral Theorem

Theorem 6.2.1 Complex Spectral Theorem

Suppose $\mathbb{F} = \mathbb{C}$ and $T \in \mathcal{L}(V)$. Then, the following are equivalent:

1. T is normal.
2. V has an orthonormal basis consisting of eigenvectors of T .
3. T has a diagonal matrix with respect to some orthonormal basis of V .

Proof 1. Note that (2) \iff (3) is obvious by Theorem 4.3.5. Now we need to show (3) \iff (1) to complete the proof. \square

Suppose (3). Then, $\mathcal{M}(T)$ is diagonal. That is, $\mathcal{M}(T^*)$ is also diagonal. Then, $\mathcal{M}(T)\mathcal{M}(T^*) = \mathcal{M}(T^*)\mathcal{M}(T)$. That is $\mathcal{M}(TT^*) = \mathcal{M}(T^*T)$, or $TT^* = T^*T$. So, T is normal. \square

Suppose (1). That is, T is normal. Then, by Schur's Theorem, \exists an orthonormal basis e_1, \dots, e_n of V s.t. $\mathcal{M}(T, (e_1, \dots, e_n))$ is an upper triangular matrix. Suppose

$$\mathcal{M}(T, (e_1, \dots, e_n)) = \begin{pmatrix} a_{1,1} & \cdots & a_{1,n} \\ & \ddots & \vdots \\ 0 & & a_{n,n} \end{pmatrix}.$$

Then,

$$\mathcal{M}(T^*, (e_1, \dots, e_n)) = \begin{pmatrix} \overline{a_{1,1}} & & 0 \\ \vdots & \ddots & \\ \overline{a_{1,n}} & \cdots & \overline{a_{n,n}} \end{pmatrix}.$$

Then, $Te_1 = a_{1,1}e_1$ and $T^*e_1 = \overline{a_{1,1}}e_1 + \cdots + \overline{a_{1,n}}e_n$. Further, note that $\|Te_1\|^2 = |a_{1,1}|^2$ and $\|T^*e_1\|^2 = |a_{1,1}|^2 + \cdots + |a_{1,n}|^2$. Since $\|Te_1\|^2 = \|T^*e_1\|^2$, we have $|a_{1,1}|^2 = |a_{1,1}|^2 + \cdots + |a_{1,n}|^2$. Then, it must be that $|a_{1,2}|^2 + \cdots + |a_{1,n}|^2 = 0$. Applying this procedure to $\|Te_2\|^2 = \|T^*e_2\|^2, \dots, \|Te_n\|^2 = \|T^*e_n\|^2$, we have $|a_{j,k}| = 0$ when $j \neq k$. So, $\mathcal{M}(T)$ is a diagonal matrix. \blacksquare

Lemma 6.2.2 Invertible Quadratic Expressions Suppose $T \in \mathcal{L}(V)$ is self-adjoint and $b, c \in \mathbb{R}$ are s.t. $b^2 < 4c$. Then, $T^2 + bT + cI$ is invertible.

Proof 2. Let $v \in V$ s.t. $v \neq 0$. Note that

$$\begin{aligned} \langle (T^2 + bT + cI)v, v \rangle &= \langle T^2v, v \rangle + b\langle Tv, v \rangle + c\langle v, v \rangle \\ &= \langle Tv, Tv \rangle + b\langle Tv, v \rangle + c\|v\|^2 && T \text{ is self-adjoint} \\ &\geq \|Tv\|^2 - |b|\|Tv\|\|v\| + c\|v\|^2 && \text{Cauchy-Schwarz} \\ &= \left(\|Tv\| - \frac{|b|\|v\|}{2} \right)^2 + \left(c - \frac{b^2}{4} \right) \|v\|^2 \\ &> 0 && b^2 < 4c \end{aligned}$$

Then, $\forall v \neq 0$, $\langle (T^2 + bT + cI)v, v \rangle > 0$. So, it must be that $(T^2 + bT + cI)v = 0$ if and only if $v = 0$. Then, $\text{null}(T^2 + bT + cI) = \{0\}$. Thus, $T^2 + bT + cI$ is injective, and thus it is invertible. \blacksquare

Lemma 6.2.3 Suppose $V \neq \{0\}$ and $T \in \mathcal{L}(V)$ is a self-adjoint operator. Then, T has an eigenvalue.

Proof 3. Let $m = \dim V$ and choose $v \in V$. Then, $v, Tv, \dots, T^m v$ cannot be L.I. because we have $m + 1 > \dim V$ vectors in the list. So, $\exists a_0, \dots, a_m \in \mathbb{R}$ s.t. $a_0v + a_1Tv + \cdots + a_mT^m v = 0$. Make the a 's the

coefficient of a polynomial then

$$a_0 + a_1x + \cdots + a_nx^n = c(x^2 + b_1x + c_1) \cdots (x^2 + b_Mx + c_M)(x - \lambda_1) \cdots (x - \lambda_m),$$

where c is a non-zero real number, each $b_j, c_j, \lambda_j \in \mathbb{R}$, each $b_j < 4c_j$, and $m + M \geq 1$. Then, we have

$$\begin{aligned} 0 &= a_0v + a_1Tv + \cdots + a_nT^n v \\ &= (a_0I + a_1T + \cdots + a_nT^n)v \\ &= c(T^2 + b_1T + c_1I) \cdots (T^2 + b_MT + c_MI)(T - \lambda_1I) \cdots (T - \lambda_mI). \end{aligned}$$

By Lemma 6.2.2, $T^2 + b_jT + c_jI$ is invertible. Since $c \neq 0$, it must be that $0 = (T - \lambda_1I) \cdots (T - \lambda_mI)$. Hence, $T - \lambda_jI$ is not injective for at least one j . So, T has at least one eigenvalue. ■

Definition 6.2.4 (Restriction Operator, $T|_U$). Suppose $T \in \mathcal{L}(V)$ and U is an invariant subspace of V under T . Then, the *restriction operator*, $T|_U \in \mathcal{L}(U)$, is defined as $T|_U(u) = Tu$ for $u \in U$.

Theorem 6.2.5

Suppose $T \in \mathcal{L}(V)$ is self-adjoint and U is a subspace of V that is invariant under T . Then,

1. U^\perp is invariant under T ;
2. $T|_U \in \mathcal{L}(U)$ is self-adjoint;
3. $T|_{U^\perp} \in \mathcal{L}(U^\perp)$ is self-adjoint.

Proof 4.

1. Suppose $v \in U^\perp$ and $u \in U$. Then, $\langle v, Tu \rangle = \langle Tv, u \rangle = 0$ since U is invariant under T (and hence $Tu \in U$) and $v \in U^\perp$. Then, we have $Tv \in U^\perp \quad \forall v \in U^\perp$, proving U^\perp is an invariant subspace under T . □

2. Note that if $u, v \in U$, then

$$\langle (T|_U)u, v \rangle = \langle Tu, v \rangle = \langle u, Tv \rangle = \langle u, (T|_U)v \rangle.$$

Therefore, $T|_U$ is self-adjoint. □

3. Replace U with U^\perp in (2) and apply the conclusion from (1), and we complete the proof. ■

Theorem 6.2.6 Real Spectral Theorem

Suppose $\mathbb{F} = \mathbb{R}$ and $T \in \mathcal{L}(V)$. Then, the following are equivalent:

1. T is self-adjoint;
2. V has an orthonormal basis consisting of eigenvectors of T .
3. T has a diagonal matrix with respect to some orthonormal basis of V .

Proof 5. Similar to the complex case, (2) \iff (3) is obvious. So, we will show (3) \implies (1) and (1) \implies (2) to complete the proof. □

Suppose (3) holds. Then, $\mathcal{M}(T)$ is diagonal. So, we have $\mathcal{M}(T)^t = \mathcal{M}(T)$. That is, $T = T^*$, and thus T is self-adjoint. \square

Suppose (1) holds. We will use mathematical induction on $\dim V$. **Base Case** When $\dim V = 1$. Clearly, (1) \implies (2). **Inductive Steps** Assume $\dim V > 1$ and (1) \implies (2) holds for all cases with dimension $\dim V - 1$. Let u be an eigenvector of T with $\|u\| = 1$. Let $U = \text{span}(u)$. Then, $\dim U = 1$. Since $V = U \oplus U^\perp$, we know $\dim U^\perp = \dim V - \dim U = \dim V - 1$. So, (1) \implies (2) holds on U^\perp . That is, \exists an orthonormal basis of U^\perp consisting of eigenvectors of $T|_{U^\perp}$. Now, add u to this orthonormal basis, we get a basis of V . Further since $u \in U$, this basis is an orthonormal basis of V consisting of eigenvectors of T . \blacksquare

6.3 Positive Operators and Isometries

Definition 6.3.1 (Positive Operator). An operator $T \in \mathcal{L}(V)$ is called *positive* if T is self-adjoint and $\langle Tv, v \rangle \geq 0 \quad \forall v \in V$.

Definition 6.3.2 (Square Root). An operator R is called a *square root* of an operator T if $R^2 = T$.

Example 6.3.3 Suppose $T \in \mathcal{L}(\mathbb{R}^3)$ and $R \in \mathcal{L}(\mathbb{R}^3)$ be defined as $T(z_1, z_2, z_3) = (z_3, 0, 0)$ and $R(z_1, z_2, z_3) = (z_2, z_3, 0)$. Then, R is a square root of T .

Proof 1. Since $R^2(z_1, z_2, z_3) = R(z_2, z_3, 0) = (z_3, 0, 0) = T(z_1, z_2, z_3)$, R is a square root of T . ■

Theorem 6.3.4 Characterization of Positive Operators

Let $T \in \mathcal{L}(V)$. Then, the following are equivalent:

1. T is positive;
2. T is self-adjoint and all the eigenvalues of T are non-negative;
3. T has a positive square root;
4. T has a self-adjoint square root;
5. \exists an operator $R \in \mathcal{L}(V)$ s.t. $T = R^*R$.

Proof 2.

(1) \implies (2): Since T is positive, then T is self-adjoint. Let λ be an eigenvalue of T . Then, $Tv = \lambda v$ for some $v \in V$. Then, $\langle Tv, v \rangle = \langle \lambda v, v \rangle = \lambda \langle v, v \rangle = \lambda \|v\|^2$. Since T is positive, $\langle Tv, v \rangle \geq 0$. Further since $\|v\|^2 \geq 0$, it must also be $\lambda \geq 0$. So, we complete the proof. □

(2) \implies (3): Suppose T is self-adjoint and all the eigenvalues of T are non-negative. By the Spectrum Theorem, \exists an orthonormal basis e_1, \dots, e_n , where e_1, \dots, e_n are eigenvectors of T . Let $\lambda_1, \dots, \lambda_n$ be the corresponding eigenvalues, where $\lambda_j \geq 0$. Let $R \in \mathcal{L}(V)$ s.t. $Re_j = \sqrt{\lambda_j}e_j$. Then

$$\begin{aligned} \langle Rv, v \rangle &= \left\langle a_1 \sqrt{\lambda_1} e_1 + \dots + a_n \sqrt{\lambda_n} e_n, a_1 e_1 + \dots + a_n e_n \right\rangle \\ &= |a_1|^2 \sqrt{\lambda_1} + \dots + |a_n|^2 \sqrt{\lambda_n} \geq 0. \end{aligned}$$

Further, we can verify R is self-adjoint (proof omitted). So, R is positive by definition. Note that

$$R^2 e_j = R(\sqrt{\lambda_j} e_j) = \sqrt{\lambda_j} \sqrt{\lambda_j} e_j = \lambda_j e_j = T e_j.$$

So, R is a square root of T . □

(3) \implies (4): Suppose T has a positive square root. By definition, positive operators are self-adjoint. □

(4) \implies (5): Suppose T has a self-adjoint square root. Then, we have $R \in \mathcal{L}(V)$ s.t. $R^* = R$ and $R^2 = T$. That is, $T = R^2 = RR = R^*R$. □

(5) \implies (1): Suppose \exists an operator $R \in \mathcal{L}(V)$ s.t. $T = R^*R$. Then,

$$T^* = (R^*R)^* = R^*(R^*)^* = R^*R = T.$$

So, T is self-adjoint. Now, since

$$\langle Tv, v \rangle = \langle R^* R v, v \rangle = \langle R v, R v \rangle = \|R v\|^2 \geq 0,$$

we have T is a positive operator. ■

Theorem 6.3.5

Each positive operator on V has a unique positive square root.

Proof 3. Let T be a positive operator on V . Select v to be an eigenvector of T with corresponding eigenvalue of λ . Then, we have $Tv = \lambda v$. Let R be a positive square root of T . Apply Spectrum Theorem to R , then \exists an orthonormal basis e_1, \dots, e_n , where e_1, \dots, e_n are eigenvectors of R . Then, $\exists \lambda_1, \dots, \lambda_n \geq 0$ s.t. $Re_j = \sqrt{\lambda_j} e_j$. Suppose $v \in V$ and $v = a_1 e_1 + \dots + a_n e_n$. Then,

$$Rv = a_1 \sqrt{\lambda_1} e_1 + \dots + a_n \sqrt{\lambda_n} e_n \quad \text{and} \quad R^2 v = a_1 \lambda_1 e_1 + \dots + a_n \lambda_n e_n.$$

Further, $Tv = \lambda v = \lambda a_1 e_1 + \dots + \lambda a_n e_n$. Since $R^2 v = Tv$, we know

$$a_1(\lambda_1 - \lambda) e_1 + \dots + a_n(\lambda_n - \lambda) e_n = 0.$$

Since e_1, \dots, e_n is an orthonormal basis, for each $j = 1, \dots, n$, we have $a_j(\lambda_j - \lambda) = 0$. So, it must be $a_j = 0$ or $\lambda_j = \lambda$. If $a_j = 0$, then we can delete it from the representation of v . So,

$$v = \sum_{\{j|\lambda_j=\lambda\}} a_j e_j$$

Hence,

$$Rv = \sum_{\{j|\lambda_j=\lambda\}} a_j \sqrt{\lambda} e_j = \sqrt{\lambda} v.$$

Definition 6.3.6 (Isometry). An operator $S \in \mathcal{L}(V)$ is called an *isometry* if $\|Sv\| = \|v\| \quad \forall v \in V$. In other words, an operator is an isometry if it preserves norms. ■

Example 6.3.7 Let $\lambda_1, \dots, \lambda_n \in \mathbb{F}$ with $|\lambda_j| = 1$ and $S \in \mathcal{L}(V)$ s.t. $Se_j = \lambda_j e_j$ for some orthonormal bases e_1, \dots, e_n of V . Then, S is an isometry.

Proof 4. Let $v \in V$. Then, $v = \langle v, e_1 \rangle e_1 + \dots + \langle v, e_n \rangle e_n$. So, $\|v\|^2 = |\langle v, e_1 \rangle|^2 + \dots + |\langle v, e_n \rangle|^2$. Further, $Sv = \lambda_1 \langle v, e_1 \rangle e_1 + \dots + \lambda_n \langle v, e_n \rangle e_n$, and thus $\|Sv\|^2 = |\lambda_1|^2 |\langle v, e_1 \rangle|^2 + \dots + |\lambda_n|^2 |\langle v, e_n \rangle|^2$. Since $|\lambda_j| = 1$, we know

$$\|Sv\|^2 = |\langle v, e_1 \rangle|^2 + \dots + |\langle v, e_n \rangle|^2 = \|v\|^2.$$

So, $\|Sv\| = \|v\|$ since $\|Sv\| \geq 0$ and $\|v\| \geq 0$. That is, by definition, S is an isometry. ■

Theorem 6.3.8 Characterization of Isometries

Suppose $S \in \mathcal{L}(V)$. Then, the following are equivalent:

1. S is an isometry.
2. $\langle Su, Sv \rangle = \langle u, v \rangle \quad \forall u, v \in V$;
3. Se_1, \dots, Se_n is orthonormal for every orthonormal list of vectors e_1, \dots, e_n in V ;
4. \exists an orthonormal basis e_1, \dots, e_n of V s.t. Se_1, \dots, Se_n is orthonormal;
5. $S^*S = I$;
6. $SS^* = I$;
7. S^* is an isometry;
8. S is invertible and $S^{-1} = S^*$.

Proof 5.

(1) \implies (2): Note that

$$\begin{aligned} \langle Su, Sv \rangle &= \frac{\|Su + Sv\|^2 - \|Su - Sv\|^2}{4} = \frac{\|S(u + v)\|^2 - \|S(u - v)\|^2}{4} \\ &= \frac{\|u + v\|^2 - \|u - v\|^2}{4} \\ &= \langle u, v \rangle \quad \square \end{aligned}$$

(2) \implies (3): We have

$$\langle Se_i, Se_j \rangle = \langle e_i, e_j \rangle = \begin{cases} 1 & \text{if } i = j \\ 0 & \text{if } i \neq j \end{cases}$$

So, Se_1, \dots, Se_n are orthonormal. \square

(3) \implies (4): Suppose e_1, \dots, e_m is orthonormal. We can extend it to a basis of V : $e_1, \dots, e_m, v_{m+1}, \dots, v_n$. Then, apply the Gram-Schmidt Procedure, we get an orthonormal basis, $e_1, \dots, e_m, e_{m+1}, \dots, e_n$ of V .

\square

(4) \implies (5): Suppose e_1, \dots, e_n is an orthonormal basis of V . Then,

$$\langle S^*Se_j, e_k \rangle = \langle Se_j, Se_k \rangle = \langle e_j, e_k \rangle.$$

Suppose $u, v \in V$ s.t. $u = a_1e_1 + \dots + a_ne_n$ and $v = b_1e_1 + \dots + b_ne_n$. Then,

$$\begin{aligned} \langle S^*Su, v \rangle &= \langle Su, Sv \rangle = \langle S(a_1e_1 + \dots + a_ne_n), S(b_1e_1 + \dots + b_ne_n) \rangle \\ &= \langle a_1Se_1 + \dots + a_nSe_n, b_1Se_1 + \dots + b_nSe_n \rangle \\ &= \langle a_1Se_1, b_1Se_1 \rangle + \dots + \langle a_nSe_n, b_nSe_n \rangle \\ &= a_1\overline{b_1}\|Se_1\|^2 + \dots + a_n\overline{b_n}\|Se_n\|^2 \\ &= a_1\overline{b_1} + \dots + a_n\overline{b_n} \\ &= \langle u, v \rangle. \end{aligned}$$

So, $S^*Su = u$, or $S^*S = I$. \square

(5) \implies (6): Suppose $S^*S = I$. Then, $S = S^*$. So, $SS^* = I$. \square

(6) \implies (7): Suppose $S^*S = I$. Then,

$$\|S^*v\|^2 = \langle S^*v, S^*v \rangle = \langle SS^*v, v \rangle = \langle v, v \rangle = \|v\|^2. \quad \square$$

(7) \implies (8): Suppose S^* is an isometry. Then, we know $S^*S = I$ and $SS^* = I$ by the proofs done above. So, S is invertible, and $S^{-1} = S^*$. \square

(8) \implies (1): Finally, suppose S is invertible and $S^{-1} = S^*$. Then, $S^*S = I$. Note that

$$\|Sv\|^2 = \langle Sv, Sv \rangle = \langle S^*Sv, v \rangle = \langle v, v \rangle = \|v\|^2.$$

Theorem 6.3.9

Suppose V is a complex inner product space and $S \in \mathcal{L}(V)$. Then, S is an isometry if and only if \exists an orthonormal basis of V consisting of eigenvectors of S whose corresponding eigenvalues all have absolute value of 1.

Proof 6.

(\implies): By the Spectrum Theorem, \exists an orthonormal basis e_1, \dots, e_n , where e_1, \dots, e_n are eigenvectors of S . Suppose $\lambda_1, \dots, \lambda_n$ are the corresponding eigenvalues. Then, we have

$$\|Se_j\| = \|\lambda_j e_j\| = |\lambda_j|.$$

Since S is an isometry, $\|Se_j\| = \|e_j\| = 1$. So, $|\lambda_j| = \|Se_j\| = 1$. \square

(\impliedby): This direction is proven in Example 6.3.7. \blacksquare

6.4 Polar Decomposition and SVD

Notation 6.4.1. If T is a positive operator, then \sqrt{T} denotes the unique positive square root of T .

Remark. We want to verify that the definition of $\sqrt{T^*T}$ is reasonable: $\langle T^*Tv, v \rangle = \langle Tv, Tv \rangle \geq 0$. Also, $(T^*T)^* = T^*T$. So, T^*T is a positive operator, and thus $\sqrt{T^*T}$ is well-defined.

Theorem 6.4.2 Polar Decomposition

Suppose $T \in \mathcal{L}(V)$. Then, \exists an isometry $S \in \mathcal{L}(V)$ s.t. $T = S\sqrt{T^*T}$.

Proof 1.

Step 1 Characteristics of range $\sqrt{T^*T}$: Note that

$$\begin{aligned} \|Tv\|^2 &= \langle Tv, Tv \rangle = \langle T^*Tv, v \rangle \\ &= \langle \sqrt{T^*T}\sqrt{T^*T}v, v \rangle \\ &= \langle \sqrt{T^*T}v, \sqrt{T^*T}v \rangle \\ &= \|\sqrt{T^*T}v\|^2. \end{aligned}$$

So, $\forall v \in V$, we have $\|Tv\| = \|\sqrt{T^*T}v\|$. Define $S_1 : \text{range } \sqrt{T^*T} \rightarrow \text{range } T$ as $S_1(\sqrt{T^*T}v) = Tv$. Then, we have $\|S_1\sqrt{T^*T}v\| = \|Tv\|$.

1. Now, we want to verify that S_1 is well-defined. Suppose $v_1, v_2 \in V$ s.t. $\sqrt{T^*T}v_1 = \sqrt{T^*T}v_2$. Then,

$$\begin{aligned} \|Tv_1 - Tv_2\| &= \|T(v_1 - v_2)\| = \|\sqrt{T^*T}(v_1 - v_2)\| \\ &= \|\sqrt{T^*T}v_1 - \sqrt{T^*T}v_2\| \\ &= 0. \end{aligned}$$

So, S_1 is well-defined.

2. Further, we want to show S_1 is linear. By using the linearity of T , we can easily prove that S_1 is also linear.

3. Additionally, S_1 is surjective by definition of S_1 .

4. Also, S_1 is isometry. Note that $\forall u \in \text{range } \sqrt{T^*T}$, we have $\|S_1u\| = \|u\|$ since $\|\sqrt{T^*T}v\| = \|Tv\|$.

5. Hence, S_1 is injective: Note that $\|S_1v\| = 0$ if and only if $\|v\| = 0$, which is equivalent to $v = 0$. So, $\text{null } S_1 = \{0\}$. \square

Step 2 Extend S_1 to an isometry on V . Note that we have $\dim \text{range } \sqrt{T^*T} = \dim \text{range } T$. So, we know $\dim (\text{range } \sqrt{T^*T})^\perp = \dim (\text{range } T)^\perp$. Select an orthonormal basis e_1, \dots, e_m of $(\text{range } \sqrt{T^*T})^\perp$ and an orthonormal basis f_1, \dots, f_m of $(\text{range } T)^\perp$. Now, let's define $S_2 : (\text{range } \sqrt{T^*T})^\perp \rightarrow (\text{range } T)^\perp$ as $S_1(a_1e_1 + \dots + a_me_m) = a_1f_1 + \dots + a_mf_m$. We can then not only show S_2 is well-defined but also S_2

is linear. Moreover, $\forall w \in \left(\text{range } \sqrt{T^*T}\right)^\perp$, if $w = a_1e_1 + \cdots + a_me_m$, we have

$$\begin{aligned}\|S_2w\|^2 &= \|S_2(a_1e_1 + \cdots + a_me_m)\|^2 = \|a_1f_1 + \cdots + a_mf_m\|^2 \\ &= |a_1|^2 + \cdots + |a_m|^2 \\ &= \|a_1e_1 + \cdots + a_me_m\|^2 \\ &= \|w\|^2.\end{aligned}$$

So, $\|S_2w\| = \|w\|$. Now, we define

$$Sv = \begin{cases} S_1v, & v \in \text{range } \sqrt{T^*T} \\ S_2v, & v \in \left(\text{range } \sqrt{T^*T}\right)^\perp \end{cases}$$

Note that since $V = \text{range } \sqrt{T^*T} \oplus \left(\text{range } \sqrt{T^*T}\right)^\perp$, we can uniquely represent $v \in V$ as $v = u + w$ for some $u \in \text{range } \sqrt{T^*T}$ and $w \in \left(\text{range } \sqrt{T^*T}\right)^\perp$. Hence, we can also write the definition of S as $Sv = S_1u + S_2w$. If we select $\sqrt{T^*T}v \in \text{range } \sqrt{T^*T}$, then we have $S(\sqrt{T^*T}v) = S_1(\sqrt{T^*T}v) = Tv$. Therefore, $T = S\sqrt{T^*T} \quad \forall v \in V$. \square

Finally, we will show S is an isometry. Note that $v = u + w$. So, by Pythagorean Theorem,

$$\begin{aligned}\|Sv\|^2 &= \|S_1u + S_2w\|^2 = \|S_1u\|^2 + \|S_2w\|^2 \\ &= \|u\|^2 + \|w\|^2 \\ &= \|v\|^2.\end{aligned}$$

■

Definition 6.4.3 (Singular Values). Suppose $T \in \mathcal{L}(V)$. The *singular values* of T are the eigenvalues of $\sqrt{T^*T}$, with each eigenvalue λ repeated $\dim E(\lambda, \sqrt{T^*T})$ times.

Example 6.4.4 Define $T \in \mathcal{L}(\mathbb{F}^4)$ by

$$T(z_1, z_2, z_3, z_4) = (0, 3z_1, 2z_2, -3z_4).$$

Find the singular values of T .

Solution 2.

Suppose $v = (z_1, z_2, z_3, z_4) \in \mathbb{F}^4$ and $w = (y_1, y_2, y_3, y_4) \in \mathbb{F}^4$. Consider

$$\begin{aligned}\langle v, T^*w \rangle &= \langle Tv, w \rangle \\ &= \langle (0, 3z_1, 2z_2, -3z_4), (y_1, y_2, y_3, y_4) \rangle \\ &= 3z_1\overline{y_2} + 2z_2\overline{y_3} - 3z_4\overline{y_4} \\ &= \langle (z_1, z_2, z_3, z_4), (3y_2, 2y_3, 0, -3y_4) \rangle.\end{aligned}$$

So, $T^*w = T^*(y_1, y_2, y_3, y_4) = (3y_2, 2y_3, 0, -3y_4)$. Then, $T^*T(z_1, z_2, z_3, z_4) = (9z_1, 4z_2, 0, 9z_4)$. Then, $\sqrt{T^*T}(z_2, z_2, z_3, z_4) = (3z_1, 2z_2, 0, 3z_4)$. So, the eigenvalues of $\sqrt{T^*T}$ are 3, 2, and 0. Also,

$$\dim E(3, \sqrt{T^*T}) = 2, \quad \dim E(2, \sqrt{T^*T}) = \dim E(0, \sqrt{T^*T}) = 1.$$

So, the singular values are 3, 3, 2, 0. □

Theorem 6.4.5 Singular Value Decomposition (SVD)

Suppose $T \in \mathcal{L}(V)$ has singular values s_1, \dots, s_n . Then, \exists orthonormal bases e_1, \dots, e_n and f_1, \dots, f_n of V s.t.

$$Tv = s_1 \langle v, e_1 \rangle f_1 + \dots + s_n \langle v, e_n \rangle f_n$$

for every $v \in V$.

Remark. *Relevant Theorem used in proving SVD: Spectrum Theorem, Characterization and Properties of Isometry, and Polar Decomposition.*

Proof3. Apply the Spectrum Theorem to $\sqrt{T^*T}$, we know \exists an orthonormal basis e_1, \dots, e_n of V s.t.

$$\sqrt{T^*T}e_j = s_j e_j \quad \forall j = 1, \dots, n.$$

Note that $\forall v \in V$, we have

$$v = \langle v, e_1 \rangle e_1 + \dots + \langle v, e_n \rangle e_n \tag{17}$$

Apply $\sqrt{T^*T}$ to Equation (17) we have

$$\sqrt{T^*T}v = s_1 \langle v, e_1 \rangle e_1 + \dots + s_n \langle v, e_n \rangle e_n. \tag{18}$$

By Polar Decomposition, \exists an isometry $S \in \mathcal{L}(V)$ s.t. $T = S\sqrt{T^*T}$. Apply S to Equation (18), we get

$$S(\sqrt{T^*T}v) = s_1 \langle v, e_1 \rangle Se_1 + \dots + s_n \langle v, e_n \rangle Se_n.$$

By the characteristics of isometry, since e_1, \dots, e_n is an orthonormal basis, Se_1, \dots, Se_n is also an orthonormal basis. Let $f_j = Se_j$. Then,

$$Tv = S\sqrt{T^*T}v = s_1 \langle v, e_1 \rangle f_1 + \dots + s_n \langle v, e_n \rangle f_n.$$

■

Theorem 6.4.6

Suppose $T \in \mathcal{L}(V)$. Then, the singular values of T are the non-negative square roots of the eigenvalues of T^*T , with each eigenvalue λ repeated $\dim E(\lambda, T^*T)$ times.

Proof4. By the Spectrum Theorem, \exists an orthonormal basis e_1, \dots, e_n and non-negative number $\lambda_1, \dots, \lambda_n$ s.t. $T^*Te_j = \lambda_j e_j \quad \forall j = 1, \dots, n$. Then, we have $\sqrt{T^*T}e_j = \sqrt{\lambda_j}e_j \quad \forall j = 1, \dots, n$, which completes the proof. ■

7 Operators on Complex Vector Spaces

7.1 Generalized Eigenvectors, Nilpotent Operators

Theorem 7.1.1

Suppose $T \in \mathcal{L}(V)$. Then,

$$\{0\} \subseteq \text{null } T^0 \subseteq \text{null } T^1 \subseteq \cdots \subseteq \text{null } T^k \subseteq \text{null } T^{k+1} \subseteq \cdots$$

Proof 1. Let $k \in \mathbb{N}^+$. Let $v \in \text{null } T^k$. Then, $T^k v = 0$. Then, we know $T(T^k v) = T^{k+1} v = 0$. So, $v \in \text{null } T^{k+1}$. That is, $\text{null } T^k \subseteq \text{null } T^{k+1}$ as desired. ■

Theorem 7.1.2

Suppose $T \in \mathcal{L}(V)$. Suppose m is a non-negative integer s.t. $\text{null } T^m = \text{null } T^{m+1}$. Then,

$$\text{null } T^m = \text{null } T^{m+1} = \text{null } T^{m+2} = \text{null } T^{m+3} = \cdots$$

Proof 2. Let $k \in \mathbb{N}$. We've already shown $\text{null } T^{m+k} \subseteq \text{null } T^{m+k+1}$ in Theorem 7.1.1. Now, let $v \in \text{null } T^{m+k+1}$. So, $T^{m+k+1}(v) = 0$. That is, $T^{m+1}(T^k v) = 0$. So, $T^k v \in \text{null } T^{m+1} = \text{null } T^m$. In other words, $T^m(T^k v) = T^{m+k}(v) = 0$. So, $v \in \text{null } T^{m+k}$. Then, $\text{null } T^{m+k+1} \subseteq \text{null } T^{m+k}$. Hence,

$$\text{null } T^{m+k} = \text{null } T^{m+k+1}.$$

Theorem 7.1.3

Suppose $T \in \mathcal{L}(V)$. Let $n = \dim V$. Then,

$$\text{null } T^n = \text{null } T^{n+1} = \text{null } T^{n+2} = \cdots$$

Proof 3. Suppose for the sake of contradiction that $\text{null } T^n \neq \text{null } T^{n+1}$. Then,

$$\text{null } T^0 \subsetneq \text{null } T \subsetneq \text{null } T^2 \subsetneq \cdots \subsetneq \text{null } T^n \subsetneq \text{null } T^{n+1}.$$

As the symbol \subsetneq means “contained in but not equal to,” at each of the strict inclusions in the chain above, the dimension increases by at least 1. That is, $\dim \text{null } T^{n+1} \geq n + 1$. * This is a contradiction because a subspace of V ($\text{null } T^{n+1}$) cannot be a dimension larger than $\dim V = n$. So, it must be that our assumption is wrong, and $\text{null } T^n = \text{null } T^{n+1}$. ■

Theorem 7.1.4

Suppose $T \in \mathcal{L}(V)$. Let $n = \dim V$. Then,

$$V = \text{null } T^n \oplus \text{range } T^n.$$

Proof 4. Note that $\dim V = \dim \text{null } T^n + \dim \text{range } T^n$ by the Fundamental Theorem of Linear Maps. So, we only need to prove $(\text{null } T^n) \cap (\text{range } T^n) = \{0\}$. Let $v \in (\text{null } T^n) \cap (\text{range } T^n)$. Then, $\exists u \in V$ s.t. $v = T^n u$. Since $v \in \text{null } T^n$, $T^n v = T^n(T^n u) = 0$. That is, $T^{2n} u = T^n v = 0$. Therefore, $u \in \text{null } T^{2n} = \text{null } T^n$. So, we now have $T^n u = 0$. Hence, $v = T^n u = 0$. Then, $(\text{null } T^n) \cap (\text{range } T^n) = \{0\}$, and thus $V = \text{null } T^n \oplus \text{range } T^n$. ■

Definition 7.1.5 (Generalized Eigenvector). Suppose $T \in \mathcal{L}(V)$ and λ is an eigenvalue of T . A vector $v \in V$ is called a *generalized eigenvector* of T corresponding to λ if $v \neq 0$ and $(T - \lambda I)^j v = 0$ for some positive integer j .

Definition 7.1.6 (Generalized Eigenspace, $G(\lambda, T)$). Suppose $T \in \mathcal{L}(V)$ and $\lambda \in \mathbb{F}$. The *generalized eigenspace* of T corresponding to λ , denoted $G(\lambda, T)$, is defined to be the set of all generalized eigenvectors of T corresponding to λ , along with the 0 vector.

Theorem 7.1.7

Suppose $T \in \mathcal{L}(V)$ and $\lambda \in \mathbb{F}$. Then,

$$G(\lambda, T) = \text{null } (T - \lambda I)^{\dim V}.$$

Proof 5.

■

7.2 Decomposition of an Operator

7.3 Characteristic and Minimal Polynomials

7.4 Jordan Form

8 Operators on Real Vectors Spaces

8.1 Complexification

8.2 Operators on Real Inner Product Spaces

9 Trace and Determinant

9.1 Trace

9.2 Determinant

10 Exercises

10.1 Span and Linear Independence

1. Suppose v_1, v_2, v_3, v_4 spans V . Prove that the list $v_1 - v_2, v_2 - v_3, v_3 - v_4, v_4$ also spans V .
2. Prove that if \mathbb{C} is a vector space on \mathbb{R} , then the list $1 + i, 1 - i$ is L.I..
3. Prove that if \mathbb{C} is a vector space on \mathbb{C} , then the list $1 + i, 1 - i$ is linearly dependent.
4. Prove or give a counterexample: Suppose v_1, v_2, \dots, v_m is L.I. in V and $\lambda \in \mathbb{F}$ with $\lambda \neq 0$. Then $\lambda v_1, \lambda v_2, \dots, \lambda v_m$ is L.I..
5. Suppose v_1, \dots, v_m is L.I. in V and $w \in V$. Prove that if $v_1 + w, \dots, v_m + w$ is linearly dependent, then $w \in \text{span}(v_1, \dots, v_m)$.

10.2 Bases

1. Find all the vectors spaces that consist of only one basis.

Hint. $\{0\}$.

2. Suppose U is a subspace of \mathbb{R}^5 s.t. $U = \{(x_1, x_2, x_3, x_4, x_5) \in \mathbb{R}^5 \mid x_1 = 3x_2, x_3 = 7x_4\}$. Find a basis of U . Extend this basis into a basis of \mathbb{R}^5 . Then, find a subspace W of \mathbb{R}^5 s.t. $\mathbb{R}^5 = U \oplus W$.
3. Suppose v_1, v_2, v_3, v_4 is a basis of V . Prove that $v_1 + v_2, v_2 + v_3, v_3 + v_4, v_4$ is also a basis of V .
4. **Prove** or disprove: $\mathcal{P}_3(\mathbb{F})$ has a basis p_0, p_1, p_2, p_3 s.t. no one from p_0, p_1, p_2, p_3 has a degree of 2.

Hint. Use the conclusion from #3.

5. Prove or **give a counterexample**: If v_1, v_2, v_3, v_4 is a basis of V and U is a subspace of V s.t. $v_1, v_2 \in U, v_3 \notin U, v_4 \notin U$, then v_1, v_2 is basis of U .

10.3 Dimension

1. Suppose V is f - d and U is a subspace of V s.t. $\dim U = \dim V$. Prove that $U = V$.
2. Prove that the subspaces of \mathbb{R}^2 are exactly the following: $\{0\}, \mathbb{R}^2$, and all the lines passing through the origin in \mathbb{R}^2 .
3. Suppose v_1, \dots, v_m is L.I. in V and $w \in V$. Prove $\dim \text{span}(v_1 + w, \dots, v_m + w) \geq m - 1$.
4. Suppose $p_0, p_1, \dots, p_m \in \mathcal{P}(\mathbb{F})$ s.t. $\deg p_j = j$. Prove p_0, p_1, \dots, p_m is a basis of $\mathcal{P}_m(\mathbb{F})$.
5. Suppose U and W are subspaces of \mathbb{R}^8 s.t. $\dim U = 3, \dim W = 5$, and $U + W = \mathbb{R}^8$. Prove that $\mathbb{R}^8 = U \oplus W$.
6. Suppose U and W are 5-dimensional subspaces of \mathbb{R}^9 . Prove $U \cap W \neq \{0\}$.
7. Suppose U and W are 4-dimensional subspaces of \mathbb{C}^6 . Prove that \exists two vectors in $U \cap W$ s.t. any one of which is not a scalar multiple of another one.

8. Suppose U_1, \dots, U_m are f - d vector spaces of V . Prove that $U_1 + \dots + U_m$ is f - d and

$$\dim(U_1 + \dots + U_m) \leq \dim U_1 + \dots + \dim U_m.$$

9. Suppose V is f - d and $\dim V = n \geq 1$. Prove that \exists 1-dimensional subspaces of V , U_1, \dots, U_n s.t.

$$V = U_1 \oplus \dots \oplus U_n.$$

10. Suppose U_1, \dots, U_m are f - d vector subspaces of V s.t. $U_1 + \dots + U_m$ is a direct sum. Prove that $U_1 \oplus \dots \oplus U_m$ is f - d and

$$\dim U_1 \oplus \dots \oplus U_m = \dim U_1 + \dots + \dim U_m.$$

Hint. Use mathematical induction.

Remark. This problem deepens the analogy between direct sums of subspaces and disjoint unions of subsets. Specifically, compare this problem to the following obvious statement: if a set is written as a disjoint union of finite subsets, then the number of elements in the set equals the sum of the numbers of elements in the disjoint subsets.

11. Prove or give a counter example:

$$\begin{aligned} \dim(U_1 + U_2 + U_3) &= \dim U_1 + \dim U_2 + \dim U_3 \\ &\quad - \dim(U_1 \cap U_2) - \dim(U_1 \cap U_3) - \dim(U_2 \cap U_3) \\ &\quad + \dim(U_1 \cap U_2 \cap U_3). \end{aligned}$$

Hint. Consider $U_1 = \{(x, 0) \mid x \in \mathbb{R}\}$, $U_2 = \{(0, y) \mid y \in \mathbb{R}\}$, $U_3 = \{(x, x) \mid x \in \mathbb{R}\}$.

10.4 The Vector Space of Linear Maps

1. Suppose $T \in \mathcal{L}(V, W)$ and v_1, \dots, v_m is a vector list in V s.t. Tv_1, \dots, Tv_m is L.I. in W . Prove that v_1, \dots, v_m is L.I.
2. Prove that $\mathcal{L}(V, W)$ is a vector space.
3. Prove the algebraic properties of products of linear maps.
4. Show that every linear map from a 1-dimensional vector space to itself is multiplication by some scalar. More precisely, prove that if $\dim V = 1$ and $T \in \mathcal{L}(V, V)$, then $\exists \lambda \in \mathbb{F}$ s.t. $Tv = \lambda v \quad \forall v \in V$.

10.5 Null Spaces and Range

1. Suppose V is a vector space and $S, T \in \mathcal{L}(V, V)$ s.t. $\text{range } S \subset \text{null } T$. Prove that $(ST)^2 = 0$.
2. Prove that \nexists a linear map $T : \mathbb{R}^5 \rightarrow \mathbb{R}^5$ s.t. $\text{range } T = \text{null } T$.
3. Suppose $T \in \mathcal{L}(V, W)$ is injective and v_1, \dots, v_n is L.I. in V . Prove that Tv_1, \dots, Tv_n is L.I. in W .

4. Suppose v_1, \dots, v_n spans V and $T \in \mathcal{L}(V, W)$. Prove that Tv_1, \dots, Tv_n spans $\text{range } T$.
5. Suppose U is a 3-dimensional subspace of \mathbb{R}^8 and T is a linear map from \mathbb{R}^8 to \mathbb{R}^5 s.t. $\text{null } T = U$. Prove that T is surjective.
6. Suppose V and W are f -d. Prove that \exists an injective linear map from V to $W \iff \dim V \leq \dim W$.
7. Suppose U and V are f -d vector spaces, $S \in \mathcal{L}(V, W)$, and $T \in \mathcal{L}(U, V)$. Prove

$$\dim \text{null } ST \leq \dim \text{null } S + \dim \text{null } T.$$

8. Suppose U and V are f -d vector spaces, $S \in \mathcal{L}(V, W)$, and $T \in \mathcal{L}(U, V)$. Prove

$$\dim \text{range } ST \leq \min \{ \dim \text{range } S, \dim \text{range } T \}.$$

9. Suppose $D \in \mathcal{L}(\mathcal{P}(\mathbb{R}), \mathcal{P}(\mathbb{R}))$ s.t. $\deg Dp = (\deg p) - 1 \forall$ non-constant polynomial $p \in \mathcal{P}(\mathbb{R})$.

Remark. The notation D is used above to remind you of the differentiation map that sends a polynomial p to p' . Without knowing the formula for the derivative of a polynomial (except that it reduces the degree by 1), you can use the exercise above to show that for every polynomial $q \in \mathcal{P}(\mathbb{R})$, \exists a polynomial $p \in \mathcal{P}(\mathbb{R})$ s.t. $p' = q$.

10. Suppose $p \in \mathcal{P}(\mathbb{R})$. Prove that $\exists q \in \mathcal{P}(\mathbb{R})$ s.t. $5q'' + 3q' = p$.

Remark. This problem can be solved without using knowledge in Linear Algebra, but it is more interesting to solve with Linear Algebra.

11. Suppose $T \in \mathcal{L}(V, W)$ and let w_1, \dots, w_m be a basis of $\text{range } T$. Prove that $\exists \varphi_1, \dots, \varphi_m \in \mathcal{L}(V, \mathbb{F})$ s.t. $Tv = \varphi_1(v)w_1 + \dots + \varphi_m(v)w_m \quad \forall v \in V$.

10.6 Matrices

1. Suppose V and W are f -d and $T \in \mathcal{L}(V, W)$. Prove that for any basis in V and W , the matrix for T has at least $\dim \text{range } T$ non-zero entries.
2. If $S, T \in \mathcal{L}(V, W)$, then $\mathcal{M}(S + T) = \mathcal{M}(S) + \mathcal{M}(T)$.
3. Suppose $\lambda \in \mathbb{F}$ and $T \in \mathcal{L}(V, W)$. Then, $\mathcal{M}(\lambda T) = \lambda \mathcal{M}(T)$.

10.7 Invertibility and Isomorphism

1. Suppose $T \in \mathcal{L}(U, V)$ and $S \in \mathcal{L}(V, W)$ are invertible linear maps. Prove that $ST \in \mathcal{L}(U, W)$ is invertible and $(ST)^{-1} = T^{-1}S^{-1}$.
2. Suppose V is f -d and $\dim V > 1$. Prove that the set of non-invertible operators on V is not a subspace of $\mathcal{L}(V)$.
3. Suppose V is f -d and U is a subspace of V . Let $S \in \mathcal{L}(U, V)$. Prove that \exists invertible operator $T \in \mathcal{L}(V)$ s.t. $Tu = Su \quad \forall u \in U \iff S$ is injective.

4. Suppose W is f - d and $T_1, T_2 \in \mathcal{L}(V, W)$. Prove that $\text{null } T_1 = \text{null } T_2 \iff \exists$ invertible operator $S \in \mathcal{L}(W)$ s.t. $T_1 = ST_2$.
5. Suppose V is f - d and $T_1, T_2 \in \mathcal{L}(V, W)$. Prove that $\text{range } T_1 = \text{range } T_2 \iff \exists$ invertible operator $S \in \mathcal{L}(V)$ s.t. $T_1 = T_2S$.
6. Suppose V is f - d and $S, T \in \mathcal{L}(V)$. Prove that ST is invertible \iff both S and T are invertible.
7. Suppose V is f - d and $S, T \in \mathcal{L}(V)$. Prove $ST = I \iff TS = I$.
8. Suppose V is f - d and $S, T, U \in \mathcal{L}(V)$ s.t. $STU = I$. Prove T is invertible and $T^{-1} = US$.
9. Suppose V is f - d and $R, S, T \in \mathcal{L}(V)$ s.t. RST is a surjection. Prove that S is an injection.
10. Suppose v_1, \dots, v_n is a basis of V . Define a linear map $T : V \rightarrow \mathbb{F}^{n,1}$ as $Tv = \mathcal{M}(v)$, where $\mathcal{M}(v)$ is the matrix of $v \in V$ with respect to the basis v_1, \dots, v_n . Prove that T is an isomorphism from V to $\mathbb{F}^{n,1}$.
11. Prove that $V \cong \mathcal{L}(\mathbb{F}, V)$.

10.8 Duality

1. Let V be f - d and U is a subspace of V s.t. $U \neq V$. Prove that $\exists \varphi \in V'$ s.t. $\forall u \in U, \varphi(u) = 0$ but $\varphi \neq 0$.
2. Suppose V is f - d , $v_1, \dots, v_m \in V$. Define a linear map $\Gamma : V' \rightarrow \mathbb{F}^m$ as follows:

$$\Gamma(\varphi) = (\varphi(v_1), \dots, \varphi(v_m)).$$
 - (a) Prove that v_1, \dots, v_m spans V if and only if Γ is injective.
 - (b) Prove that v_1, \dots, v_m is L.I. if and only if Γ is surjective.
3. Suppose v_1, \dots, v_n is a basis of V and $\varphi_1, \dots, \varphi_n$ is the corresponding dual basis of v' . Suppose $\psi \in V'$. Prove that

$$\psi = \psi(v_1)\varphi_1 + \dots + \psi(v_n)\varphi_n.$$
4. Suppose W is f - d and $T \in \mathcal{L}(V, W)$. Prove that $T' = 0$ if and only if $T = 0$.
5. Suppose V and W are f - d . Prove that the linear map from $T \in \mathcal{L}(V, W)$ to $T' \in \mathcal{L}(W', V')$ is an isomorphism between $L(V, W)$ and $L(W', V')$.
6. Suppose V is f - d and $U \subset V$. Prove that $U = \{0\}$ if and only if $U^0 = V'$.
7. Suppose V is f - d and U is a subspace of V . Prove that $U = V$ if and only if $U^0 = \{0\}$.
8. Suppose U and V are subsets of V with $U \subset W$. Prove that $W^0 \subset U^0$.
9. Suppose V is f - d and U and W are subspaces of V with $W^0 \subset U^0$. Prove that $U \subseteq W$.
10. Suppose U and W are subspaces of V . Prove that $(U + W)^0 = U^0 \cap W^0$.
11. Suppose V is f - d and U and W are subspaces of V . Prove that $(U \cap W)^0 = U^0 + W^0$.

10.9 Quotient Space

1. Suppose $v, x \in V$ and U and W are subspaces of V s.t. $v + U = x + W$. Prove that $U = W$.

10.10 Invariant Spaces

1. Suppose $T \in \mathcal{L}(V)$ and U is the subspace of V .
 - (a) Prove that if $U \subset \text{null } T$, then U is invariant under T .
 - (b) Prove that if $\text{range } T \subset U$ then U is invariant under T .
2. Suppose $S, T \in \mathcal{L}(V)$ s.t. $ST = TS$. Prove that $\text{null } S$ is invariant under T .
3. Suppose $S, T \in \mathcal{L}(V)$ s.t. $ST = TS$. Prove that $\text{range } S$ is invariant under T .
4. Suppose $T \in \mathcal{L}(V)$ and U_1, \dots, U_m are invariant subspaces of V under T . Prove that $U_1 + \dots + U_m$ are invariant under T .
5. Suppose $T \in \mathcal{L}(V)$. Prove that the intersection of any collection of invariant subspaces of V under T is also invariant under T .
6. Prove or give a counterexample: If V is f -d and U is a subspace of V s.t. U is invariant under every operators of V , then $U = \{0\}$ or $U = V$.
7. Define $T \in \mathcal{L}(\mathbb{R}^2)$ as $T(x, y) = (-3y, x)$. Find the eigenvalues of T .
8. Define $T \in \mathcal{L}(\mathbb{F}^2)$ as $T(w, z) = (z, w)$. Find all the eigenvalues and eigenvectors of T .
9. Define $T \in \mathcal{L}(\mathbb{F}^3)$ as $T(z_1, z_2, z_3) = (2z_2, 0, 5z_3)$, Find all the eigenvalues and eigenvectors of T .
10. Suppose $T \in \mathcal{L}(V)$. Let $S \in \mathcal{L}(V)$ is invertible.
 - (a) Prove that T and $S^{-1}TS$ have identical eigenvalues.
 - (b) What is the relationship between the eigenvectors of T and the eigenvectors of $S^{-1}TS$?
11. Define $T \in \mathcal{L}(\mathbb{C}^\infty)$ as $T(z_1, z_2, \dots) = (0, z_1, z_2, \dots)$. Prove that T has no eigenvalues.
12. Suppose $T \in \mathcal{L}(V)$ is invertible.
 - (a) Suppose $\lambda \in \mathbb{F}$ and $\lambda \neq 0$. Prove that λ is an eigenvalue of T if and only if $\frac{1}{\lambda}$ is an eigenvalue of T^{-1} .
 - (b) Prove that T and T^{-1} have identical eigenvectors.
13. Suppose $T \in \mathcal{L}(V)$ and \exists nonzero $v, w \in V$ s.t. $Tv = 3w$ and $Tw = 3v$. Prove that 3 or -3 is an eigenvalue of T .
14. Suppose V is f -d and $S, T \in \mathcal{L}(V)$. Prove that ST and TS have identical eigenvalues.

10.11 Eigenvalues and Upper-Triangular Matrices

- Suppose $T \in \mathcal{L}(V)$ and $\exists n \in \mathbb{Z}^+$ s.t. $T^n = 0$.
 - Prove that $(I - T)$ is invertible and $(I - T)^{-1} = I + T + \cdots + T^{n-1}$.
 - Give a rationale of coming up with the formula above.
- Suppose $T \in \mathcal{L}(V)$ and $(T - 2I)(T - 3I)(T - 4I) = 0$. Suppose λ is an eigenvalue of T . Prove that $\lambda = 2$, $\lambda = 3$, or $\lambda = 4$.
- Suppose $T \in \mathcal{L}(V)$, $T^2 = I$, and -1 is not an eigenvalue of T . Prove that $T = I$.
- Suppose $P \in \mathcal{L}(V)$ and $P^2 = P$. Prove that $V = \text{null } P \oplus \text{range } P$.
- Suppose $T \in \mathcal{L}(V)$. Prove that 9 is an eigenvalue of T^2 if and only if 3 or -3 is an eigenvalue of T .
- Find a $T \in \mathcal{L}(\mathbb{R}^2)$ s.t. $T^4 = -I$.
- Suppose $T \in \mathcal{L}(V)$ and v is the eigenvector of T corresponding to the eigenvalue λ . Let $p \in \mathcal{P}(\mathbb{F})$. Prove that $p(T)v = p(\lambda)v$.

10.12 Eigenspace and Diagonal Matrices

- Suppose $T \in \mathcal{L}(V)$ is diagonalizable. Prove that $V = \text{null } T \oplus \text{range } T$.
- Suppose V is f - d and $T \in \mathcal{L}(V)$. Prove that the following conditions are equivalent:
 - $V = \text{null } T \oplus \text{range } T$;
 - $V = \text{null } T + \text{range } T$;
 - $\text{null } T \cap \text{range } T = \{0\}$.
- Suppose V is f - d , $T \in \mathcal{L}(V)$ has $\dim V$ distinct eigenvalues, and $S \in \mathcal{L}(V)$ has identical eigenvectors with T (but not necessarily corresponding to the same eigenvalues). Prove that $ST = TS$.
- Suppose $T \in \mathcal{L}(V)$ has a diagonal matrix corresponding to some basis of V , denoted as A . Let $\lambda \in \mathbb{F}$. Prove that λ will appear on the diagonal of A exactly $\dim E(\lambda, T)$ times.
- Suppose $T \in \mathcal{L}(\mathbb{F}^5)$ and $\dim E(8, T) = 4$. Prove that $(T - 2I)$ or $(T - 6I)$ is invertible.
- Suppose $T \in \mathcal{L}(V)$ is invertible. Prove that for every nonzero $\lambda \in \mathbb{F}$, we have $E(\lambda, T) = \left(\frac{1}{\lambda}, T^{-1}\right)$.
- Suppose V is f - d and $T \in \mathcal{L}(V)$. Let $\lambda_1, \dots, \lambda_m$ be distinct nonzero eigenvalues. Prove that

$$\dim E(\lambda_1, T) + \cdots + \dim E(\lambda_m, T) \leq \dim \text{range } T.$$