

LINEAR ALGEBRA

INCALCULAS

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1 VECTOR SPACE

1.1 What is a Vector Space?

Vector space is a set with a binary operation

$$+ : V \times V \rightarrow V$$

Key properties of a vector space:

- i) *Commutativity*

$$A + B = B + A$$

- ii) *Associativity*

$$A + (B + C) = (A + B) + C$$

- iii) *Identity*

$$\exists 0 \in V$$

$$\text{s.t } v + 0 = v, \forall v \in V$$

- iv) *Inverse*

$$\forall v \in V, \exists v' \in V$$

$$\text{s.t } v + v' = 0$$

A set of scalars associated with a vector space is a Field

1.2 Definition of Fields

DEFINITION 1.1 (Fields)

$$(F, +, \cdot)$$

- $(F, +)$ Satisfies i) to iv) [an abelian group]
- $(F - \{0\}, \cdot)$ Satisfies i) to iv) [an abelian group]
- \cdot is distributive over $+$

EXAMPLE 1.2 (Binary field)

$$\{0, 1\}$$

Addition:

$$0 + 1 = 1 = 1 + 0$$

$$1 + 1 = 0$$

Multiplication:

$$1 \cdot 0 = 0 = 0 \cdot 1$$

$$1 \cdot 1 = 1$$

$$0 \cdot 0 = 0$$

What a field does to a vector in a vector space:

$$\gamma, \mu \in F, v, w \in V$$

$$\gamma \cdot (v + w) = (\gamma v + \gamma w)$$

$$(\gamma + \mu) v = \gamma v + \mu v$$

$$\mu(\gamma \cdot v) = (\mu\gamma)v$$

Properties of a vector space V over field F :

$u, v, w \in V$ and $a, b \in F$

- 1) $u + v = w = v + u$
- 2) $u + (v + w) = (u + v) + w$
- 3) $\exists 0 \in V, \text{s.t } 0 + v = v$
- 4) $\exists v' \in V, \text{s.t } v + v' = 0$
- 5) $\exists 1 \in F, \text{s.t } 1 \cdot v = v$
- 6) $(ab) \cdot v = a \cdot (bv)$
- 7) $a \cdot (v + w) = a \cdot v + a \cdot w$
- 8) $(a + b) \cdot v = a \cdot v + b \cdot v$

EXAMPLE 1.3 set $V = \{0\}$ over the field \mathbb{R}

EXAMPLE 1.4 set $\mathbb{R}, \mathbb{R}^2, \mathbb{R}^3 \dots \mathbb{R}^n$ over the field \mathbb{R}



If F is a field, then F is also a Vector space over itself

1.3 Definition of Vector Spaces

DEFINITION 1.6 (Vector Space)

$$(V, F, +, \cdot)$$

- $(V, +)$ is an Abelian group
- $\cdot : F \times V \rightarrow V$ is associative and follows distributivity

EXAMPLE 1.7

$\mathbb{Q}, \mathbb{R}, \mathbb{C}$ are all fields

PROPOSITION 1.8 Any field $F \subset \mathbb{R}$ contains \mathbb{Q}

Proof | We assume normal addition and multiplication

$$\forall a \in \mathbb{Q}, a = \frac{p}{q}$$

where $p, q \in \mathbb{Z}$

$0, 1 \in F$, as $(F, +)$ and $(F - \{0\}, \times)$ is an abelian groups. As $+$ is closed $1 + 1 = 2 \in F$ and $2 + 1 = 3 \in F$ and so on. By inverse property of $+$, we know $-1, -2, -3 \dots \in F$, therefore $\mathbb{Z} \in F$. By inverse property of \times , we know $\{1/a : a \in \mathbb{Z}\} \in F$. Since \times is closed, $S = \{a/b : a, b \in \mathbb{Z}\} \in F$, set S is just \mathbb{Q} . Therefore $\mathbb{Q} \in F$ if $F \subset \mathbb{R}$ is a field. ■

Properties of fields:

- 1) *Cancellation law*, If $a + b = a + c$ then $b = c$

- 2) Additive identity is unique
- 3) Additive inverse is unique
- 4) Multiplicative identity is unique
- 5) Multiplicative inverse is unique
- 6) if $a \cdot b = a \cdot c$ then $b = c$ if $a \neq 0$

Properties of Vector spaces:

- 1) *Cancellation law*, If $a + b = a + c$ then $b = c$
- 2) Additive identity is unique
- 3) Additive inverse is unique
- 4) $0 \cdot v = 0 \rightarrow$ is the null vector

Matrices as Vector spaces:

$$M_{n \times m}(\mathbb{R})$$

- Addition is entry wise
- $0_{n \times m}$ the additive identity
- Scaling is entry wise

$M_{n \times m}$ looks like $\mathbb{R}^{n \cdot m}$

1.4 Vector Subspaces

DEFINITION 1.9 (Vector Subspace) W is said to be a vector subspace of V if

- $W \subseteq V$
- W is a vector subspace

EXAMPLE 1.10 $P(\mathbb{R})$ is the set of all polynomials.
 $P_n(\mathbb{R})$ is the set of all polynomials of degree at most n .

- $P_0(\mathbb{R}) \subset P_1(\mathbb{R}) \subset P_2(\mathbb{R}) \subset P_3(\mathbb{R}) \subset \dots \subset P_n(\mathbb{R})$
- $\{a_0 + a_1x + a_2x^2 + \dots + a_nx^n : a_i \in \mathbb{R}\}$

EXAMPLE 1.11 $M_n(\mathbb{R})$ is the set of all $n \times n$ matrices

- Set of all symmetric matrices, $S = \{A : A \in M_n(\mathbb{R}), A = A^t\}$
- $T = \{A : A \in M_n(\mathbb{R}), \text{Tr}(A) = 0\}$

2 SPAN AND LINEAR INDEPENDENCE

2.1 Definition of Span

DEFINITION 2.1 (Span)

$$\text{span}(S) = \{\gamma_1 v_1 + \gamma_2 v_2 + \dots + \gamma_k v_k : v_i \in S, \gamma_i \in F\}$$

EXAMPLE 2.2

$$S = \{1, x, x^2\}$$

$$\text{span}(S) = P_2(\mathbb{R})$$

EXAMPLE 2.3

$$S = \{(1, 0, 0), (0, 1, 0), (0, 0, 1)\}$$

$$\text{span}(S) = \mathbb{R}^3$$


EXAMPLE 2.4

$$S = \left\{ \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}, \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \begin{pmatrix} 1 & 0 \\ 0 & 2 \end{pmatrix} \right\}$$

$$\text{span}(S) = M_2(\mathbb{R})_{\text{sym}}$$

Properties of Span:

- 1) $\text{span}(S)$ is always a subspace containing S as,
+ is closed and
Scaling operation is also closed.
- 2) For a subspace $S \subseteq W$, $S \subseteq \text{span}(S) \subseteq W$
- 3) $\text{span}(S)$ is the smallest subspace containing S .
That is, $\text{span}(S)$ is the intersection of all subspaces containing S .
- 4) $\text{span}(\emptyset) = \{0\}$
This is more of a convention, or you can arrive at this by following the above definition of Span.
- 5) $S_1 \subseteq S_2$ implies $\text{span}(S_1) \subseteq \text{span}(S_2)$
- 6) $\text{span}(\text{span}(S)) = \text{span}(S)$
- 7) $\text{span}(W) = W$ if and only if W is a subspace.
- 8) $\text{span}(S_1 \cup S_2) = \text{span}(S_1) + \text{span}(S_2)$
where $A + B = \{a + b : a \in A, b \in B\}$

 if V_1 and V_2 are subspaces then, $V_1 + V_2$ is also a subspace.

2.2 Linear (In)dependence

Given a non empty set S , consider $\text{span}(S)$. Is there an element $v \in S$ such that, $\text{span}(S) = \text{span}(S - \{v\})$?

Then S is linearly dependent.

EXAMPLE 2.6

$$S = \{(0, 0, 0), (0, 1, 0), (0, 0, e)\}$$

$$\text{span}(S) = \{(0, a, b) : a, b \in \mathbb{R}\} = \text{span}(S - \{(0, 0, 0)\})$$

For $\text{span}(S) = \text{span}(S - \{v\})$, there exists $v_1, v_2, \dots, v_k \in S - \{v\}$ and scalars $\gamma_1, \gamma_2, \dots, \gamma_k \in F$ such that,

$$v = \sum_{i=1}^k \gamma_i v_i$$

as $0 \notin S$, not all γ_i can be 0.

DEFINITION 2.7 (Linear Dependence) A subset $S \subseteq V$ is said to be linearly dependent if there exists scalars, $\gamma_1, \gamma_2, \dots, \gamma_k \in F$ such that for $v_1, v_2, \dots, v_k \in S$

$$\gamma_1 v_1 + \gamma_2 v_2 + \dots + \gamma_k v_k = 0$$

Where not all $\gamma_i = 0$ and v_i are all distinct.

DEFINITION 2.8 (Linear Independence) A subset $S \subseteq V$ is said to be linearly independent if there exists no scalars, $\gamma_1, \gamma_2, \dots, \gamma_k \in F$ such that for $v_1, v_2, \dots, v_k \in S$


$$\gamma_1 v_1 + \gamma_2 v_2 + \dots + \gamma_k v_k = 0$$

Where not all $\gamma_i = 0$ and v_i are all distinct.

EXAMPLE 2.9 $V = P(\mathbb{R}), S = \{1+x, 1-x, x^2, 2x^2-1\}$

$$\frac{1}{2}(1+x) + \frac{1}{2}(1-x) + (2x^2-1) + (-2)x^2 = 0$$

$$S' = \{1+x, 1-x, x^2\}$$

 if S is linearly dependent, then $\exists v \in S$ such that $\text{span}(S) = \text{span}(S - \{v\})$

PROPOSITION 2.11 if S is linearly independent and $\exists v \notin \text{span}(S)$ then $S \cup \{v\}$ is linearly independent.

Proof | let $\gamma, \gamma_1, \dots, \gamma_k \in F$ and $v_1, \dots, v_k \in S$

$$\gamma_1 v_1 + \dots + \gamma_k v_k + \gamma v = 0$$

case 1: $\gamma = 0$,

$$\gamma_1 v_1 + \dots + \gamma_k v_k = 0$$

as S is linearly independent $\gamma_i = 0$ therefore,

$$\gamma_1, \gamma_2, \dots, \gamma_k, \gamma = 0$$

therefore $S \cup \{v\}$ is linearly independent.

case 2: $\gamma \neq 0$,

$$v = \frac{-\gamma_1}{\gamma} v_1 + \dots + \frac{-\gamma_k}{\gamma} v_k$$

but $v \notin \text{span}(S)$, therefore this case is not possible. ■

3 BASIS AND DIMENSION OF A VECTOR SPACE

3.1 Basis and Dimension

DEFINITION 3.1 (Basis) set $\beta \subseteq V$ is called the basis of V if

- 1) β is linearly independent.
- 2) β spans V

DEFINITION 3.2 (Dimension) For β being a basis of V , $\dim_F V = |\beta|$

3.2 Replacement Theorem

THEOREM 3.3 (Replacement Theorem) Let $S \subseteq V$ be a finite set which spans V and let $L \subseteq V$ be a finite linearly independent subset, then,

- 1) $|L| \leq |S|$
- 2) $\exists T \subseteq S$ (T is of size $|S| - |L|$) such that $T \cup L$ spans V

Proof |

$$L = \{u_1, \dots, u_m\}$$

$$S = \{v_1, \dots, v_n\}$$

$$u_m \in V = \text{span}(S)$$

therefore,

$$u_m = a_1 v_1 + \dots + a_n v_n$$

as u_m is in L a linearly independent set, u_m cannot be 0, therefore, all of a_i cannot be zero as well. Let $a_n \neq 0$.

$$v_n = \frac{1}{a_n} u_m + \frac{-a_1}{a_n} v_1 + \dots + \frac{-a_{n-1}}{a_n} v_{n-1}$$

$$v_n \in \text{span}\{v_1, \dots, v_{n-1}, u_m\} = \text{span}(S) = V$$

similarly,

$$u_{m-1} \in V = \text{span}\{v_1, \dots, v_{n-1}, u_m\}$$

therefore,

$$u_{m-1} = a_1 v_1 + \dots + a_{n-1} v_{n-1} + b_m u_m$$

as u_{m-1} and u_m are linearly independent, therefore all of a_i cannot be 0

$$v_{n-1} = \frac{1}{a_{n-1}} u_{m-1} + \frac{-b_m}{a_{n-1}} u_m + \frac{-a_1}{a_{n-1}} v_1 \dots + \frac{-a_{n-2}}{a_{n-1}} v_{n-2}$$

$$v_{n-1} \in \text{span}\{v_1, \dots, v_{n-1}, u_{m-1}, u_m\} = \text{span}(S) = V$$

Now iterate this process to get,

$$S' = \{v_1, \dots, v_{n-m}, u_1, \dots, u_m\}$$

Where S' spans V ,

$$\text{span}(S') = V$$

If $n < m$ then, there will be a point when iterating the steps where a proper subset of L will span V , which would not be possible since this breaks the linear independence of L .

The set T from the theorem is,

$$T = S' - L$$

■



If $S \subseteq V$ spans V and $L \subseteq V$ is an linearly independent subset, then $|L| \leq |S|$.

COROLLARY 3.5 Given 2 basis of the same vector space V , β and β' .

$$|\beta| = |\beta'|$$

Proof | Set $S = \beta$ and $L = \beta'$. β spans V by definition of basis and β' is linearly independent by definition of basis.

Now according to 1) of replacement theorem, we get.

$$|\beta| \leq |\beta'|$$

Similarly, we can swap S and L to get,

$$|\beta| \geq |\beta'|$$

$$\therefore |\beta| = |\beta'|$$

■

💡 Going back to the definition of dimension, we can see that basis need not be unique but the dimension of a vector space is unique regardless of which basis we use to find the dimension

COROLLARY 3.7 Let V be a vector space of finite dimension n , then

- 1) Any finite spanning set S , $|S| \geq n$, if $|S| = n$ then S is a basis.
- 2) Any linearly independent set L , $|L| \leq n$, if $|L| = n$, then L spans V .
- 3) Any linearly independent set L can be extended to form a basis of V .

COROLLARY 3.8 Let V be a finite dimensional vector space over the field F and let $W \subseteq V$ be a subspace, then,

$$\dim_F(W) \leq \dim_F(V)$$

If equality holds, then, $V = W$.

Proof | Let β be a basis of V of size n . Now look at $\text{span}\{\emptyset\} = \{0\}$, if it is W then we are done, if not, we choose $u_1 \in W$ which is non zero, $L_1 = \{u_1\} \subseteq W$ is linearly independent. We check again if $\text{span}(L_1) = W$, if it is then we are done, if it isn't then we choose $u_2 \in W \setminus \text{span}(L_1)$. We iterate this process until we get $\beta_\circ = \{u_1, \dots, u_k\}$ which spans W . This set is linearly independent by construction (refer to proposition 2.11). Using 1) from replacement theorem, using β as S and β_\circ as L , we get,

$$|\beta_\circ| \leq |\beta|$$

which is the same as,

$$\dim_F(W) \leq \dim_F(V)$$

And using corollary 3.8 we can say that the equality implies $V = W$.

■

💡 Given subspace W of vector space V , with β_\circ as the basis of W , we can extend the basis β_\circ to β as a basis for V

3.3 Direct Sum

Let W_1 and W_2 be subspaces of a finite dimensional vector space V . Then $W_1 + W_2$ is also a subspace.

Case A: $W_1 \cap W_2 = \{0\}$

DEFINITION 3.10 (Direct Sum) Given subspaces W_1 and W_2 of a finite dimensional vector space V , if $W_1 \cap W_2 = \{0\}$ then the vector subspace $W_1 + W_2$ is known as the direct sum.

Case B: $W_1 \cap W_2 \neq \{0\}$

$$\dim_F (W_1 + W_2) = \dim_F (W_1) + \dim_F (W_2) - \dim_F (W_1 \cap W_2)$$

Proof | Start with basis of $W_1 \cap W_2$, $\beta_\circ = \{u_1, \dots, u_k\}$. Now extend this basis to a basis of W_1 , $\beta_1 = \{u_1, \dots, u_k, w_1, \dots, w_l\}$ and similarly for W_2 , $\beta_2 = \{u_1, \dots, u_k, w_1', \dots, w_m'\}$

$$\beta = \beta_1 \cup \beta_2$$

$$\beta = \{u_1, \dots, u_k, w_1, \dots, w_l, w_1', \dots, w_m'\}$$

As any element in $W_1 + W_2$ can be represented by a linear combination of elements of β , β spans $W_1 + W_2$. To show that β is linearly independent,

$$c_1 u_1 + \dots + c_k u_k + d_1 w_1 + \dots + d_l w_l + \gamma_1 w_1' + \dots + \gamma_m w_m' = 0$$

$$\Rightarrow c_1 u_1 + \dots + c_k u_k + d_1 w_1 + \dots + d_l w_l = -\gamma_1 w_1' - \dots - \gamma_m w_m' = v$$

Clearly $v \in W_1$ and $v \in W_2$, therefore $v \in W_1 \cap W_2$, therefore v can be written as,

$$v = c_1' u_1 + \dots + c_k' u_k$$

$$\Rightarrow c_1 u_1 + \dots + c_k u_k + d_1 w_1 + \dots + d_l w_l = -\gamma_1 w_1' - \dots - \gamma_m w_m' = v = c_1' u_1 + \dots + c_k' u_k$$

From these 2 equations, we are able to determine that β is linearly independent,

We have,

$$-\gamma_1 w_1' - \dots - \gamma_m w_m' = c_1' u_1 + \dots + c_k' u_k$$

$\{u_1, \dots, u_k, w_1', \dots, w_m'\}$ is a linear independent set, therefore,

$$\gamma_1 = \dots = \gamma_m' = c_1' = \dots = c_k' = 0$$

Similarly, we have,

$$c_1 u_1 + \dots + c_k u_k + d_1 w_1 + \dots + d_l w_l = c_1' u_1 + \dots + c_k' u_k$$

We know $c_1' = \dots = c_k' = 0$, therefore,

$$c_1 u_1 + \dots + c_k u_k + d_1 w_1 + \dots + d_l w_l = 0$$

$\{u_1, \dots, u_k, w_1, \dots, w_l\}$ is a linear independent set, therefore,

$$\gamma_1 = \dots = \gamma_m' = c_1 = \dots = c_l = 0$$

Therefore the only solution for

$$c_1 u_1 + \dots + c_k u_k + d_1 w_1 + \dots + d_l w_l + \gamma_1 w_1' + \dots + \gamma_m w_m' = 0$$

is all the scalars being equal to zero, which implies linear independence of β . Therefore β is both linearly independent and spans $W_1 + W_2$, which makes it a basis for $W_1 + W_2$.

$$\dim_F (W_1) = |\beta_1| = k + l$$

$$\dim_F (W_2) = |\beta_2| = k + m$$

$$\dim_F (W_1 + W_2) = |\beta| = k + l + m$$

$$\dim_F (W_1 \cap W_2) = |\beta_\circ| = k$$

$$\therefore \dim_F (W_1 + W_2) = \dim_F (W_1) + \dim_F (W_2) - \dim_F (W_1 \cap W_2)$$

■

PROPOSITION 3.11 If V is the direct sum, $W_1 + W_2$ then $v \in V$ can be uniquely expressed as $w_1 + w_2$ where $w_1 \in W_1$ and $w_2 \in W_2$.

Proof | Let, $v = w_1 + w_2 = w_1' + w_2'$ then, $w_1 - w_1' = w_2 - w_2' = x$. therefore $x \in W_1 \cap W_2$ and by definition of direct sum, $x \in \{0\}$, therefore $x = 0$. Which gives us, $w_1 = w_1'$ and $w_2 = w_2'$. ■

4 QUOTIENT SPACES

4.1 Quotient Spaces

Goal is to create a new vector space out of $W \subseteq V$, define an equivalence relation \sim_W on V . $v_1 \sim_W v_2$ if and only if $v_1 - v_2 \in W$

- *Reflexive* Yes, if $0 \in W$.
- *Symmetric* Yes, if whenever, $v_1 - v_2 \in W$ implies $v_2 - v_1 \in W$, ie, $-(v_1 - v_2) \in W$.
- *transitivity* Yes, if whenever $v_1 - v_2 \in W$ and $v_2 - v_3 \in W$ implies $v_1 - v_3 = (v_1 - v_2) + (v_2 - v_3) \in W$.

Starting with any arbitrary subset of V we end with a subspace of V due to the conditions that needs to be satisfied for \sim_W to be an equivalence relation.

For any equivalence relation \sim on an arbitrary set S , an equivalence class is given by.

$$[s] = \{s' : s' \in S, s' \sim s\}$$

Equivalence relations are disjointed and partition the set. that is either $[s] \cap [s'] = \emptyset$ or $[s] = [s']$.

For \sim_W ,

$$\begin{aligned} [v] &= \{v_1 : v_1 - v \in W\} \\ [v] &= \{v_1 = v + w : w \in W\} \\ [v] &= v + W \end{aligned}$$

$[v_1] = [v_2]$ we translate via W ,

$$\begin{aligned} v_1 + W &= v_2 + W \\ v_1 &= v_2 + w \\ v_1 - v_2 &= w \in W \end{aligned}$$

Therefore $[v_1] = [v_2]$ if and only if $v_1 - v_2 \in W$.

We can create a new vector space, where each element is an equivalence class of the equivalence relation \sim_W . Consider the set of all equivalence class of the relation \sim_W , V/W .

Addition under the vector space V/W ,

$$+ : V/W \times V/W \rightarrow V/W$$

$$[v_1] + [v_2] = [v_1 + v_2]$$

Scaling,

$$\times : F \times V/W \rightarrow V/W$$

$$(\gamma, [v]) \rightarrow [\gamma v]$$

5 LINEAR MAPS

5.1 Linear Maps

Given vector spaces V, W (over the same field F) and linear map T .

$$T : V \rightarrow W$$

T should be compatible with the structures of the vector spaces $\forall v_1, v_2, v \in V$ and $\forall \gamma \in F$.


- $T(v_1 + v_2) = Tv_1 + Tv_2$
- $T(\gamma v) = \gamma Tv$

EXAMPLE 5.1 (Scaling Linear Map)

$$T : \mathbb{R} \rightarrow \mathbb{R}, x \rightarrow \gamma \circ x$$

$$T(x + y) = \gamma \circ (x + y) = \gamma \circ x + \gamma \circ y = Tx + Ty$$

$$T(\gamma y) = \gamma \circ (\gamma y) = \gamma(\gamma \circ y) = \gamma(Tx)$$

 $T(0_v) = 0_w$

EXAMPLE 5.3 (Dilation)

$$T : V \rightarrow V, v \rightarrow 2v (= v + v)$$

$$\gamma v \rightarrow 2(\gamma v) = \gamma(2v) = \gamma(Tv)$$

If in the field, $2 = 0$ then the map is the zero map, if not then it's a bijective map.

EXAMPLE 5.4 (Identity map)

$$I : V \rightarrow V, v \rightarrow v$$

EXAMPLE 5.5 (Trivial map)

$$T_0 : V \rightarrow W, v \rightarrow 0_w$$

EXAMPLE 5.6 (Matrices)

$$A \in M_{n \times n}(\mathbb{R})$$

$$L_A : \mathbb{R}^n \rightarrow \mathbb{R}^n$$

$$\begin{aligned} \begin{pmatrix} x_1 \\ \vdots \\ x_n \end{pmatrix} &\rightarrow A \begin{pmatrix} x_1 \\ \vdots \\ x_n \end{pmatrix} \\ L_A \left(\begin{pmatrix} x_1 \\ \vdots \\ x_n \end{pmatrix} + \begin{pmatrix} y_1 \\ \vdots \\ y_n \end{pmatrix} \right) &= L_A \begin{pmatrix} x_1 \\ \vdots \\ x_n \end{pmatrix} + L_A \begin{pmatrix} y_1 \\ \vdots \\ y_n \end{pmatrix} \\ L_A \left(\gamma \begin{pmatrix} x_1 \\ \vdots \\ x_n \end{pmatrix} \right) &\rightarrow \gamma L_A \begin{pmatrix} x_1 \\ \vdots \\ x_n \end{pmatrix} \end{aligned}$$

EXAMPLE 5.7 (Reflection)

$$T : \mathbb{R}^2 \rightarrow \mathbb{R}^2, (x, y) \rightarrow (x, -y)$$

This is for reflection across x-axis, for any other reflection the line as to pass through the origin because 0 has to be mapped to 0 and in general $T.T$ gives us the identity map.

EXAMPLE 5.8 (Rotation)

$$T : \mathbb{R}^2 \rightarrow \mathbb{R}^2, (x, y) \rightarrow (-y, x)$$

This is rotaion of $\pi/2$ clockwise, for a more general rotaion,

$$\begin{aligned} T_\theta : \mathbb{R}^2 &\rightarrow \mathbb{R}^2 \\ \begin{pmatrix} x \\ y \end{pmatrix} &\rightarrow \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} \\ ||T(x, y)|| &= ||(x, y)|| \end{aligned}$$

This is a property of every rotation linear map.

EXAMPLE 5.9 (Projection)

$$\begin{aligned} P : \mathbb{R}^2 &\rightarrow \mathbb{R}^2, (x, y) \rightarrow (x, 0) \\ Q : \mathbb{R}^2 &\rightarrow \mathbb{R}^2, (x, y) \rightarrow (x - y, 0) \\ P^2 &= P.P = P \\ Q^2 &= Q.Q = Q \end{aligned}$$

This is the defining property of a projection map.

EXAMPLE 5.10 (Inclusion)

$$\begin{aligned} T : \mathbb{R}^2 &\rightarrow \mathbb{R}^3, (x, y) \rightarrow (x, y, 0) \\ T' : \mathbb{R}^2 &\rightarrow \mathbb{R}^3, (x, y) \rightarrow (x, y, ax + by) \end{aligned}$$

5.2 Null Space

DEFINITION 5.11 (Null Space) Given $T : V \rightarrow W$, null space $N(T)$ is given by,

$$N(T) = \{v \in V : T(v) = 0_w\}$$

EXAMPLE 5.12 (Scaling Linear Map)

$$T : \mathbb{R} \rightarrow \mathbb{R}, x \rightarrow \gamma \circ x$$

$$N(T) = \{0\}$$

EXAMPLE 5.13 (Dilation)

$$T : V \rightarrow V, v \rightarrow 2v (= v + v)$$

$$N(T) = \begin{cases} V & 2 = 0 \text{ in } F \\ \{0\} & 2 \neq 0 \text{ in } F \end{cases}$$

EXAMPLE 5.14 (Identity map)

$$I : V \rightarrow V, v \rightarrow v$$

$$N(T) = \{0\}$$

EXAMPLE 5.15 (Trivial map)

$$T_0 : V \rightarrow W, v \rightarrow 0_w$$

$$N(T) = V$$

EXAMPLE 5.16 (Reflection)

$$T : \mathbb{R}^2 \rightarrow \mathbb{R}^2, (x, y) \rightarrow (x, -y)$$

$$N(T) = \{0\}$$

EXAMPLE 5.17 (Rotation)

$$T_\theta : \mathbb{R}^2 \rightarrow \mathbb{R}^2$$

$$\begin{pmatrix} x \\ y \end{pmatrix} \rightarrow \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}$$

$$N(T) = \{0\}$$

EXAMPLE 5.18 (Projection)

$$P : \mathbb{R}^2 \rightarrow \mathbb{R}^2, (x, y) \rightarrow (x, 0)$$

$$N(P) = \{(0, y)\}$$

$$Q : \mathbb{R}^2 \rightarrow \mathbb{R}^2, (x, y) \rightarrow (x - y, 0)$$

$$N(Q) = \{(x, y) : x = y\}$$

EXAMPLE 5.19 (Inclusion)

$$\begin{aligned} T : \mathbb{R}^2 &\rightarrow \mathbb{R}^3, (x, y) \rightarrow (x, y, 0) \\ N(T) &= \{0\} \\ T' : \mathbb{R}^2 &\rightarrow \mathbb{R}^3, (x, y) \rightarrow (x, y, ax + by) \\ N(T) &= \{0\} \end{aligned}$$

5.3 Range

DEFINITION 5.20 (Range) Given $T : V \rightarrow W$, null space $R(T)$ is given by,

$$R(T) = \text{Image of } V \text{ under } T$$

EXAMPLE 5.21 (Scaling Linear Map)

$$\begin{aligned} T : \mathbb{R} &\rightarrow \mathbb{R}, x \rightarrow \gamma \circ x \\ R(T) &= \mathbb{R} \end{aligned}$$

EXAMPLE 5.22 (Dilation)

$$\begin{aligned} T : V &\rightarrow V, v \rightarrow 2v (= v + v) \\ R(T) &= \begin{cases} \{0\} & 2 = 0 \text{ in } F \\ V & 2 \neq 0 \text{ in } F \end{cases} \end{aligned}$$

EXAMPLE 5.23 (Identity map)

$$\begin{aligned} I : V &\rightarrow V, v \rightarrow v \\ R(T) &= V \end{aligned}$$

EXAMPLE 5.24 (Trivial map)

$$\begin{aligned} T_0 : V &\rightarrow W, v \rightarrow 0_w \\ R(T) &= \{0\} \end{aligned}$$

EXAMPLE 5.25 (Reflection)

$$\begin{aligned} T : \mathbb{R}^2 &\rightarrow \mathbb{R}^2, (x, y) \rightarrow (x, -y) \\ R(T) &= \mathbb{R}^2 \end{aligned}$$

EXAMPLE 5.26 (Rotation)

$$\begin{aligned} T_\theta : \mathbb{R}^2 &\rightarrow \mathbb{R}^2 \\ \begin{pmatrix} x \\ y \end{pmatrix} &\rightarrow \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} \\ R(T) &= \mathbb{R}^2 \end{aligned}$$

EXAMPLE 5.27 (Projection)

$$\begin{aligned}P &: \mathbb{R}^2 \rightarrow \mathbb{R}^2, (x, y) \rightarrow (x, 0) \\R(P) &= \{(x, 0)\} \\Q &: \mathbb{R}^2 \rightarrow \mathbb{R}^2, (x, y) \rightarrow (x - y, 0) \\R(Q) &= \{(x, 0)\}\end{aligned}$$

EXAMPLE 5.28 (Inclusion)

$$\begin{aligned}T &: \mathbb{R}^2 \rightarrow \mathbb{R}^3, (x, y) \rightarrow (x, y, 0) \\R(T) &= \{(x, y, 0)\} \\T' &: \mathbb{R}^2 \rightarrow \mathbb{R}^3, (x, y) \rightarrow (x, y, ax + by) \\R(T) &= \{(x, y, ax + by)\}\end{aligned}$$

5.4 Null space and Range as vector subspaces

$$v_1, v_2 \in N(T), \gamma \in F$$

$$T(v_1 + v_2) = Tv_1 + Tv_2$$

$$T(v_1 + v_2) = 0 + 0 = 0$$

$$\therefore v_1 + v_2 \in N(T)$$

$$T(\gamma v_1) = \gamma Tv_1 = \gamma 0 = 0$$

$$\therefore \gamma v_1 \in N(T)$$

Therefore $N(T)$ is a subspace.

$$w_1, w_2 \in R(T), \gamma \in F$$

$$w_1 = Tv_1$$

$$w_2 = Tv_2$$

$$w_1 + w_2 = Tv_1 + Tv_2 = T(v_1 + v_2)$$

$$\therefore w_1 + w_2 \in R(T)$$

$$w_1 = Tv_1$$

$$\gamma Tv_1 = \gamma w_1 = T(\gamma v_1)$$

$$\therefore \gamma w_1 \in R(T)$$

Therefore $R(T)$ is a subspace.

EXAMPLE 5.29 (Differentiation)

$$D : P(\mathbb{R}) \rightarrow P(\mathbb{R}), P \rightarrow P'$$

$$a_0 + a_1x + \cdots + a_kx^k \rightarrow a_1 + 2a_2x + \cdots + ka_kx^{k-1}$$

$$D.(P_1 + P_2) = D.P_1 + D.P_2$$

$$D.(\gamma P_1) = \gamma D.P_1$$

$$D : P_n(\mathbb{R}) \rightarrow P_n(\mathbb{R})$$

$$N(D) = \{a_0 \in \mathbb{R}\}$$

$$R(D) = P_{n-1}(\mathbb{R})$$

EXAMPLE 5.30 (Integration)

$$I : P(\mathbb{R}) \rightarrow P(\mathbb{R}), P \rightarrow \int P dx$$

$$a_0 + \cdots + a_kx^k \rightarrow a_0x + \cdots + \frac{a_kx^{k+1}}{k+1}$$

$$N(I) = \{0\}$$

$$R(I) = \{J(x) \in P_{n+1}(\mathbb{R}) : J(0) = 0\}$$

DEFINITION 5.31 (Nullity) Given a linear map, nullity of the linear map is the dimension of the null space.

DEFINITION 5.32 (Rank) Given a linear map, rank of the linear map is the dimension of the range.

5.5 Rank Nullity Theorem

THEOREM 5.33 (Rank Nullity) Let V be a finite dimensional vector space and W be any vector space, if $T : V \rightarrow W$ is a linear map then,

$$\dim_F(R(T)) + \dim_F(N(T)) = \dim_F V$$

Proof | Let $\beta_0 = \{v_1, \dots, v_k\}$ be a basis of $N(T)$, now extend this to a basis of V , β

$$\beta = \{v_1, \dots, v_k, v_{k+1}, \dots, v_l\}$$

We know,

$$T(\beta) = \{0_w, T(v_{k+1}), \dots, T(v_l)\}$$

$$L = \{T(v_{k+1}), \dots, T(v_l)\}$$

Let's take,

$$\gamma_1 T(v_{k+1}) + \cdots + \gamma_l T(v_l) = 0$$

$$\begin{aligned}
T(\gamma_1 v_1' + \cdots + \gamma_l v_l') &= 0 \\
\gamma_1 v_1' + \cdots + \gamma_l v_l' &\in N(T) \\
\gamma_1 v_1' + \cdots + \gamma_l v_l' &= \gamma_1' v_1 + \cdots + \gamma_l' v_k \\
\gamma_1 v_1' + \cdots + \gamma_l v_l' - \gamma_1' v_1 - \cdots - \gamma_l' v_k &= 0
\end{aligned}$$

By the linear independence of β we can conclude that,

$$\gamma_1 = \cdots = v_l' = \gamma_1' = \gamma_l' = 0$$

Which gives us that L is linearly independent and this is a set which spans $R(T)$ which makes it a basis of $R(T)$

$$\begin{aligned}
\dim_F(R(T)) + \dim_F(N(T)) &= |L| + |\beta| = l + k \\
\dim_F V &= |\beta| = l + k \\
\therefore \dim_F(R(T)) + \dim_F(N(T)) &= \dim_F V
\end{aligned}$$

■



Given a linear map $T : V \rightarrow W$, if $S \subseteq V$ spans V , then $T(S)$ spans $R(T)$.

Proof | Given $w = T(v) \in R(T)$, express $v = \sum \gamma_i v_i$, where $v_i \in S$ and $\gamma_i \in F$. $T(v) = \sum \gamma_i T(v_i) \implies T(v) \in \text{span}(T(S))$ ■

COROLLARY 5.35 Given a linear map, $T : V \rightarrow V$, where V is a finite dimensional vector space, then the following are equivalent.

- 1) T is injective
- 2) T is surjective

Proof | T is injective implies, $N(T) = \{0\} \implies \text{Nullity} = 0 \implies \text{Rank} = \dim_F V - 0 = \dim_F V \implies R(T) = V \implies T$ is surjective.

T is surjective implies, $R(T) = V \implies \text{rank} = \dim_F V \implies \text{Nullity} = 0 \implies N(0) = \{0\}$.

If $Tv_1 = Tv_2$ and $N(0) = \{0\}$, then, $T(v_1 - v_2) = 0 \implies v_1 - v_2 \in N(T) \implies v_1 - v_2 \in \{0\} \implies v_1 = v_2$.

Therefore, T is surjective implies injectivity as well. ■

6 ISOMORPHISM, MATRICES AND LINEAR MAPS AS VECTOR SPACES

6.1 Linear Isomorphism

DEFINITION 6.1 (Linear Isomorphism) A linear map $T : V \rightarrow W$ between vector spaces V and W both over a common field F is called an isomorphism if T is bijective.

EXAMPLE 6.2

$$T : P_2(\mathbb{R}) \rightarrow \mathbb{R}^3, a + bx + cx^2 \rightarrow (a, b, c)$$

Zero in \mathbb{R}^3 is $(0, 0, 0)$, clearly only polynomial which is mapped to it is 0. Therefore $N(T) = \{0\}$ and $\text{Nullity} = 0$. If $TP_1 = TP_2$, then, $T(p_1 - p_2) = (0, 0, 0) \implies T(a_1 - a_2 + (b_1 - b_2)x + (c_1 - c_2)x^2) = (0, 0, 0) \implies (a_1 - a_2, b_1 - b_2, c_1 - c_2) = (0, 0, 0) \implies a_1 = a_2, b_1 = b_2, c_1 = c_2 \implies p_1 = p_2$, therefore T is injective. $\text{Rank} = \dim_F P_2(\mathbb{R}) - 0 = 3 \implies R(T) = \mathbb{R}^3$, therefore T is surjective. Therefore T is bijective.



When we say a vector space looks like another vector space, we mean that there exists a linear isomorphism from one vector space to another, ie V is isomorphic to W as a vector space.

EXAMPLE 6.4

$$T : M_2(\mathbb{R}) \rightarrow \mathbb{R}^4$$

$$\begin{pmatrix} a & b \\ c & d \end{pmatrix} \rightarrow \begin{pmatrix} a \\ b \\ c \\ d \end{pmatrix}$$

Properties of isomorphic linear maps (we will take $T : V \rightarrow W$ as our isomorphic linear map to discuss the properties):

1) $T^{-1} : W \rightarrow V$ is a linear map

Proof | For $w_1, w_2 \in W$ there exists unique $v_1, v_2 \in V$ such that, $Tv_1 = w_1$ and $Tv_2 = w_2$ because of bijectivity of T , there also exists unique $v \in V$ such that, $Tv = w_1 + w_2$.

$$\begin{aligned} T^{-1}w_1 &= v_1, T^{-1}w_2 = v_2 \\ \implies v_1 + v_2 &= T^{-1}w_1 + T^{-1}w_2 \\ \implies T(v_1 + v_2) &= T(T^{-1}w_1 + T^{-1}w_2) \\ \implies T(v_1 + v_2) &= T(T^{-1}w_1) + T(T^{-1}w_2) = w_1 + w_2 \\ \implies T(v_1 + v_2) &= w_1 + w_2 \end{aligned}$$

Therefore unique $v = v_1 + v_2$. Therefore $T^{-1}(w_1 + w_2) = T^{-1}w_1 + T^{-1}w_2$.

For $w \in W$ there exists unique $v \in V$ such that, $Tv = w$ because of bijectivity of T , there also exists unique $v' \in V$ such that, $Tv = \gamma w$.

$$\begin{aligned} T^{-1}w &= v \\ \gamma T^{-1}w &= \gamma v \\ \implies T(\gamma v) &= T(\gamma T^{-1}w) \\ \implies T(\gamma v) &= \gamma T(T^{-1}w) = \gamma w \\ \implies T(\gamma v) &= \gamma w \end{aligned}$$

Therefore unique $v' = \gamma v$. Therefore $T^{-1}(\gamma w) = \gamma T^{-1}w$

Showing that addition and scaling is closed is suffice to show that T^{-1} is a linear map. ■

2) $\gamma T : V \rightarrow W, V \rightarrow \gamma Tv$ is an isomorphic linear map.

Proof | Take $v_1, v_2 \in V$, such that,

$$\begin{aligned} \gamma Tv_1 &= \gamma Tv_2 \\ \implies \gamma T(v_1 - v_2) &= 0 \\ \implies T(v_1 - v_2) &= 0 \\ \implies v_1 &= v_2 \end{aligned}$$

This implies injectivity of γT .

Suppose γT is not surjective, then $\exists w \in W$ such that, $\forall v \in V$,

$$\gamma T v \neq w$$

$$T v \neq w / \gamma$$

But this is a contradiction given we know T to be a bijection, therefore γT has to be surjective, therefore is bijective and an isomorphism. ■

- 3) • a) If $T : V \rightarrow W$ is an injective linear map and $\{v_1, \dots, v_n\}$ is a linearly independent set, then $\{T v_1, \dots, T v_n\}$ is also a linearly independent set.

Proof |

$$\begin{aligned} \gamma_1 T v_1 + \dots + \gamma_n T v_n &= 0 \\ \implies T (\gamma_1 v_1 + \dots + \gamma_n v_n) &= 0 \end{aligned}$$

Injectivity of the linear map implies,

$$\gamma_1 v_1 + \dots + \gamma_n v_n = 0$$

Linear independence of $\{v_1, \dots, v_n\}$

$$\gamma_1 = \dots = \gamma_n = 0$$

- b) If $T : V \rightarrow W$ is an surjective linear map and let $\{w_1, \dots, w_n\}$ be a subset of W and choose $v_i \in V$ such that $T v_i = w_i$ and if $\{v_1, \dots, v_n\}$ spans V , then $\{w_1, \dots, w_n\}$ spans W . ■

Proof | We know for a given $w \in W$ there exists at one $v \in V$ such that, $T v = w$.

$$\begin{aligned} v &= \gamma_1 v_1 + \dots + \gamma_n v_n \\ T v &= T (\gamma_1 v_1 + \dots + \gamma_n v_n) \\ w &= T (\gamma_1 v_1) + \dots + T (\gamma_n v_n) \\ w &= \gamma_1 T v_1 + \dots + \gamma_n T v_n \\ w &= \gamma_1 w_1 + \dots + \gamma_n w_n \end{aligned}$$

Since we choose an arbitart w , $\{w_1, \dots, w_n\}$ spans the set W . ■

6.2 Linear maps as vectors

CONVENTION 6.5 $\mathcal{L}(V, W)$ represents set of all linear maps from $V \rightarrow W$ and $\mathcal{L}(V)$ represents set of all linear maps from $V \rightarrow V$.

$$+ : \mathcal{L}(V, W) \times \mathcal{L}(V, W) \rightarrow \mathcal{L}(V, W)$$

$$(T_1 + T_2) : V \rightarrow W, v \rightarrow T_1 v + T_2 v$$

$$(T_1 + T_2) \in \mathcal{L}(V, W)$$

$$\times : F \times \mathcal{L}(V, W) \rightarrow \mathcal{L}(V, W)$$

$$(\gamma T) : V \rightarrow W, v \rightarrow \gamma T v$$

$$(\gamma T) \in \mathcal{L}(V, W)$$

EXAMPLE 6.6 (Dual of V) $W = \mathbb{R}$, where V is a vector space over R . Represented by $V^* = \mathcal{L}(V, \mathbb{R})$ and $\dim_F(V^*) = \dim_F(V)$.

EXAMPLE 6.7 $V = \mathbb{R}$, where W is a vector space over R . $\mathcal{L}(\mathbb{R}, W)$ is a vector space, any element in $\mathcal{L}(\mathbb{R}, W)$ has unique property where the map is determined by just where 1 is mapped to.

$$T : \mathbb{R} \rightarrow W$$

$$T(\gamma) = \gamma T(1)$$

$$\Phi : \mathcal{L}(\mathbb{R}, W) \rightarrow W$$

Φ is an isomorphism.

Proof | For every $w \in W$ there is a unique $T_w \in \mathcal{L}(\mathbb{R}, W)$ such that, $T_w : \mathbb{R} \rightarrow W, \gamma \rightarrow \gamma w$ or $T_w(\gamma) = \gamma w$. set of all T_w is the same as $\mathcal{L}(\mathbb{R}, W)$ since if there exists an element T' which is not in the set of all T_w then the property that the map is determined by where 1 is mapped to will yield a contradiction. Therefore, we have a bijective between W and $\mathcal{L}(\mathbb{R}, W)$. Therefore, Φ is an isomorphism. ■



CONJECTURE 6.8 $\dim_F \mathcal{L}(V, W) = \dim_F V \times \dim_F W$

6.3 Ordered Basis

DEFINITION 6.9 (Ordered Basis) An ordered basis of a vector space V is $\beta = \{v_1, \dots, v_n\}$ where β is an ordered set.

EXAMPLE 6.10 $V = \mathbb{R}^2, \beta = \{(1, 0), (0, 1)\}$

EXAMPLE 6.11 $V = P_2(\mathbb{R}), \beta = \{1, x, x^2\}$

6.4 Matrix Representation

Goal is to create a matrix to represent $T : V \rightarrow W$, let $\beta = \{v_1, \dots, v_m\}$ be an ordered basis of V , let $\alpha = \{w_1, \dots, w_n\}$ be an ordered basis of W .

$$T v_j = \sum_{i=1}^n \gamma_{ij} w_i$$

$$\begin{pmatrix} T v_1 \\ T v_2 \\ \vdots \\ T v_m \end{pmatrix} = \begin{pmatrix} w_1 & w_2 & \cdots & w_n \end{pmatrix} \begin{pmatrix} \gamma_{11} & \gamma_{12} & \cdots & \gamma_{1m} \\ \gamma_{21} & \gamma_{22} & \cdots & \gamma_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ \gamma_{n1} & \gamma_{n2} & \cdots & \gamma_{nm} \end{pmatrix}$$

$$\begin{pmatrix} \gamma_{11} & \gamma_{12} & \cdots & \gamma_{1m} \\ \gamma_{21} & \gamma_{22} & \cdots & \gamma_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ \gamma_{n1} & \gamma_{n2} & \cdots & \gamma_{nm} \end{pmatrix} \in M_{m \times n}(F)$$

Aim is to associate a matrix $[T]_{\beta}^{\alpha}$ for a linear map $T : V \rightarrow W$, where $\beta = \{v_1, \dots, v_m\}$ is an ordered basis of V and $\alpha = \{w_1, \dots, w_n\}$ is an ordered basis of W .

$$S_{\beta} : V \rightarrow F^m$$

Where S_{β} is given by, for any $v \in V$,

$$v = \sum_{i=1}^m \gamma_i v_i \rightarrow \begin{pmatrix} \gamma_1 \\ \vdots \\ \gamma_m \end{pmatrix} \in F^m$$

$$S_{\alpha} : W \rightarrow F^n$$

Where S_{α} is given by, for any $w \in W$,

$$w = \sum_{i=1}^n \gamma_i w_i \rightarrow \begin{pmatrix} \gamma_1 \\ \vdots \\ \gamma_n \end{pmatrix} \in F^n$$

$$T : V \rightarrow W$$

$$S_{\beta} : V \rightarrow F^m$$

$$S_{\alpha} : W \rightarrow F^n$$

$$S_{\alpha} \cdot T \cdot S_{\beta}^{-1} : F^m \rightarrow F^n$$

We now define $[T]_{\beta}^{\alpha}$ to be the matrix associated with the map $S_{\alpha} \cdot T \cdot S_{\beta}^{-1} : F^m \rightarrow F^n$



CONJECTURE 6.12 $[Tv]_{\beta}^{\alpha} = [T]_{\beta}^{\alpha} [v]_{\beta}$

EXAMPLE 6.13

$$I : V \rightarrow V$$

For $\beta = \alpha$,

$$[I]_{\beta}^{\alpha} = I_n$$

For $\beta = \{e_1, e_2\}$ and $\alpha = \{e_2, e_1\}$,

$$[I]_{\beta}^{\alpha} = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

EXAMPLE 6.14 (Differentiation)

$$D : P_2(\mathbb{R}) \rightarrow P_2(\mathbb{R}), P(x) \rightarrow P'(x)$$

$$\beta = \{1, x, x^2\}$$

$$[D]_{\beta}^{\beta} = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 2 \\ 0 & 0 & 0 \end{pmatrix}$$

$$\alpha = \{2x, 1, x^2\}$$

$$[D]_{\beta}^{\alpha} = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$