

115B – Linear Algebra

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This is math 115B – Linear Algebra which is the second course of the undergrad linear algebra at UCLA – continuation of 115A(H). Similar to 115AH, this class is instructed by Professor Elman, and we meet weekly on MWF from 2:00 pm to 2:50 pm. There is no official textbook used for the class. You can find the previous linear algebra notes (115AH) with other course notes through my [github](#). Any error in this note is my responsibility and please [email](#) me if you happen to notice it.

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§1 | Lec 1: Mar 29, 2021

§1.1 Vector Spaces

Notation: if $\star : A \times B \rightarrow B$ is a map (= function) write $a \star b$ for $\star(a, b)$, e.g., $+$: $\mathbb{Z} \times \mathbb{Z} \rightarrow \mathbb{Z}$ where \mathbb{Z} = the integer.

Definition 1.1 (Field) — A set F is called a FIELD under

- Addition: $+$: $F \times F \rightarrow F$
- Multiplication: \cdot : $F \times F \rightarrow F$

if $\forall a, b, c \in F$, we have

$$\text{A1) } (a + b) + c = a + (b + c)$$

$$\text{A2) } \exists 0 \in F \ni a + 0 = a = 0 + a$$

$$\text{A3) } \text{A2) holds and } \exists x \in F \ni a + x = 0 = x + a$$

$$\text{A4) } a + b = b + a$$

$$\text{M1) } (a \cdot b) \cdot c = a \cdot (b \cdot c)$$

$$\text{M2) } \text{A2) holds and } \exists 1 \neq 0 \in F \text{ s.t. } a \cdot 1 = a = 1 \cdot a \text{ (} 1 \text{ is unique and written } 1 \text{ or } 1_F)$$

$$\text{M3) } \text{M2) holds and } \forall 0 \neq x \in F \exists y \in F \ni xy = 1 = yx \text{ (} y \text{ is seen to be unique and written } x^{-1})$$

$$\text{M4) } x \cdot y = y \cdot x$$

$$\text{D1) } a \cdot (b + c) = a \cdot b + a \cdot c$$

$$\text{D2) } (a + b) \cdot c = a \cdot c + b \cdot c$$

Example 1.2

$\mathbb{Q}, \mathbb{R}, \mathbb{C}$ are fields as is

$\mathbb{F}_2 := \{0, 1\}$ with $+$: given by

+	0	1
0	0	1
1	1	0

\cdot	0	1
0	0	0
1	0	1

Fact 1.1. Let $p > 0$ be a prime number in \mathbb{Z} . Then \exists a field \mathbb{F}_{p^n} having p^n elements write $|\mathbb{F}_{p^n}| = p^n \quad \forall n \in \mathbb{Z}^+$.

Definition 1.3 (Ring) — Let R be a set with

- $+: R \times R \rightarrow R$
- $\cdot: R \times R \rightarrow R$

satisfying A1) – A4), M1), M2), D1), D2), then R is called a RING.
A ring is called

- i) a commutative ring if it also satisfies M4).
- ii) an (integral) domain if it is a commutative ring and satisfies

$$\text{M 3')} \quad a \cdot b = 0 \implies a = 0 \text{ or } b = 0$$

($0 = \{0\}$ is also called a ring – the only ring with $1 = 0$)

Example 1.4 (Proof left as exercises) 1. \mathbb{Z} is a domain and not a field.

2. Any field is a domain.

3. Let F be a field

$$F[t] := \{\text{polys coeffs in } F\}$$

with usual $+, \cdot$ of polys, is a domain but not a field. So if $f \in F[t]$

$$f = a_0 + a_1 t + \dots + a_n t^n$$

where $a_0, \dots, a_n \in F$.

4. $\mathbb{Q} := \left\{ \frac{a}{b} \mid a, b \in \mathbb{Z}, b \neq 0 \right\} < \mathbb{C}$ ($<$ means \subset and \neq) with usual $+, \cdot$ of fractions.
(when does $\frac{a}{b} = \frac{c}{d}$?)

5. If F is a field

$$F(t) := \left\{ \frac{f}{g} \mid f, g \in F[t], g \neq 0 \right\} \text{ (rational function)}$$

with usual $+, \cdot$ of fractions is a field.

Example 1.5 (Cont'd from above) 6. $\mathbb{Q}[\sqrt{-1}] := \{\alpha + \beta\sqrt{-1} \in \mathbb{C} \mid \alpha, \beta \in \mathbb{Q}\} < \mathbb{C}$.
Then $\mathbb{Q}[\sqrt{-1}]$ is a field and

$$\begin{aligned}\mathbb{Q}(\sqrt{-1}) &:= \left\{ \frac{a}{b} \mid a, b \in \mathbb{Q}[\sqrt{-1}], b \neq 0 \right\} \\ &= \mathbb{Q}[\sqrt{-1}] \\ &= \left\{ \frac{a}{b} \mid a, b \in \mathbb{Z}[\sqrt{-1}], b \neq 0 \right\}\end{aligned}$$

where $\mathbb{Z}[\sqrt{-1}] := \{\alpha + \beta\sqrt{-1} \in \mathbb{C}, \alpha, \beta \in \mathbb{Z}\} < \mathbb{C}$. How to show this? – rationalize ($\mathbb{Z}[\sqrt{-1}]$ is a domain not a field, $F[t] < F(t)$ if F is a field so we have to be careful).

7. F a field

$$\mathbb{M}_n F := \{n \times n \text{ matrices entries in } F\}$$

is a ring under $+$, \cdot of matrices.

$$\begin{aligned}1_{\mathbb{M}_n F} &= I_n = n \times n \text{ identity matrix} \begin{pmatrix} 1 & & 0 \\ & \ddots & \\ 0 & & 1 \end{pmatrix} \\ 0_{\mathbb{M}_n F} &= 0 = 0_n = n \times n \text{ zero matrix} \begin{pmatrix} 0 & \dots & 0 \\ \vdots & & \vdots \\ 0 & \dots & 0 \end{pmatrix}\end{aligned}$$

is not commutative if $n > 1$.

In the same way, if R is a ring we have

$$\mathbb{M}_n R = \{n \times n \text{ matrices entries in } R\}$$

e.g., if R is a field $\mathbb{M}_n F[t]$.

8. Let $\emptyset \neq I \subset \mathbb{R}$ be a subset, e.g., $[\alpha, \beta], \alpha < \beta \in \mathbb{R}$. Then

$$C(I) = \{f : I \rightarrow \mathbb{R} \mid f \text{ continuous}\}$$

is a commutative ring and not a domain where

$$\begin{aligned}(f \dot{+} g)(x) &:= f(x) \dot{+} g(x) \\ 0(x) &= 0 \\ 1(x) &= x\end{aligned}$$

for all $x \in I$.

Notation: Unless stated otherwise F is always a field.

Definition 1.6 (Vector Space) — Let F be a field, V a set. Then V is called a VECTOR SPACE OVER F write V is a vector space over F under

- $+: V \times V \rightarrow V$ – Addition
- $\cdot: F \times V \rightarrow V$ – Scalar multiplication

if $\forall x, y, z \in V \quad \forall \alpha, \beta \in F$.

1. $(x + y) + z = x + (y + z)$
2. $\exists 0 \in V \ni x + 0 = x = 0 + x$ (0 is seen to be unique and written 0 or 0_V)
3. 2) holds and $\exists v \in V \ni x + v = 0 = v + x$ (v is seen to be unique and written $-x$)
4. $x + y = y + x$
5. $1_F \cdot x = x$.
6. $(\alpha \cdot \beta) \cdot x = \alpha \cdot (\beta \cdot x)$
7. $(\alpha + \beta) \cdot x = \alpha \cdot x + \beta \cdot x$
8. $\alpha \cdot (x + y) = \alpha \cdot x + \alpha \cdot y$

Remark 1.7. The usual properties we learned in 115A hold for V a vector space over F , e.g., $0_F V = 0_V$, general association law,...

§ 2 | Lec 2: Mar 31, 2021

§ 2.1 Vector Spaces (Cont'd)

Example 2.1

The following are vector space over F

1. $F^{m \times n} := \{m \times n \text{ matrices entries in } F\}$, usual $+$, scalar multiplication, i.e., if $A \in F^{m \times n}$, let $A_{ij} = i j^{\text{th}}$ entry of A . If $A, B \in F^{m \times n}$, then

$$\begin{aligned}(A + B)_{ij} &:= A_{ij} + B_{ij} \\ (\alpha A)_{ij} &:= \alpha A_{ij} \quad \forall \alpha \in F\end{aligned}$$

i.e., component-wise operations.

2. $F^n = F^{1 \times n} := \{(\alpha_1, \dots, \alpha_n) \mid \alpha_i \in F\}$
3. Let V be a vector space over F , $\emptyset \neq S$ a set. Define

$$\mathcal{F}cn(S, V) := \{f : S \rightarrow V \mid f \text{ a fcn}\}$$

Then $\mathcal{F}cn(S, V)$ is a vector space over $F \forall f, g \in \mathcal{F}cn(S, V), \forall \alpha \in F$. For all $x \in S$,

$$\begin{aligned}f + g &: x \mapsto f(x) + g(x) \\ \alpha f &: x \mapsto \alpha f(x)\end{aligned}$$

i.e.

$$\begin{aligned}(f + g)(x) &= f(x) + g(x) \\ (\alpha f)(x) &= \alpha f(x)\end{aligned}$$

with 0 by $0(x) = 0_V \forall x \in S$.

4. Let R be a ring under $+, \cdot$, F a field $\ni F \subseteq R$ with $+, \cdot$ on F induced by $+, \cdot$ on R and $0_F = 0_R, 1_F = 1_R$, i.e.

$$\underbrace{+}_{\text{on } R} \Big| \underbrace{F \times F}_{\text{restrict dom}} : F \times F \rightarrow F \text{ and } \underbrace{\cdot}_{\text{on } R} \Big| \underbrace{F \times F}_{\text{restrict dom}} : F \times F \rightarrow F$$

i.e. closed under the restriction of $+, \cdot$ on R to F and also with $0_F = 0_R$ and $1_F = 1_R$ (we call F a subring of R). Then R is a vector space over F by restriction of scalar multiplication, i.e., same $+$ on R but scalar multiplication

$$\cdot \Big|_{F \times R} : F \times R \rightarrow R$$

e.g., $\mathbb{R} \subseteq \mathbb{C}$ and $F \subseteq F[t]$.

Note: \mathbb{C} is a vector space over \mathbb{R} by the above but as a vector space over \mathbb{C} is different.

5. In 4) if R is also a field (so $F \subseteq R$ is a subfield). Let V be a vector space over R . Then V is also a vector space over F by restriction of scalars, e.g., $M_n \mathbb{C}$ is a vector space over \mathbb{C} so is a vector space over \mathbb{R} so is a vector space over \mathbb{Q} .

§2.2 Subspaces

Definition 2.2 (Subspace) — Let V be a vector space under $+, \cdot, \emptyset \neq W \subseteq V$ a subset. We call W a subspace of V if $\forall w_1, w_2 \in W, \forall \alpha \in F$,

$$\alpha w_1, w_1 + w_2 \in W$$

with $0_W = 0_V$ is a vector space over F under $+\big|_{W \times W}$ and $\cdot\big|_{F \times W}$ i.e., closed under the operation on V .

Theorem 2.3

Let V be a vector space over F , $\emptyset \neq W \subseteq V$ a subset. Then W is a subspace of V iff $\forall \alpha \in F, \forall w_1, w_2 \in W, \alpha w_1 + w_2 \in W$.

Example 2.4 1. Let $\emptyset \neq I \subseteq \mathbb{R}$, $C(I)$ the commutative ring of continuous function $f : I \rightarrow \mathbb{R}$. Then $C(I)$ is a vector space over \mathbb{R} and a subspace of $\mathcal{F}cn(I, \mathbb{R})$.

2. $F[t]$ is a vector space over F and $n \geq 0$ in \mathbb{Z} .

$$F[t]_n := \{f \mid f \in F[t], f = 0 \text{ or } \deg f \leq n\}$$

is a subspace of $F[t]$ (it is not a ring).

[Attached](#) is a review of theorems about vector spaces from math 115A.

§2.3 Motivation

Problem 2.1. Can you break down an object into simpler pieces? If yes can you do it uniquely?

Example 2.5

Let $n > 1$ in \mathbb{Z} . Then n is a product of primes unique up to order.

Example 2.6

Let V be a finite dimensional inner product space over \mathbb{R} (or \mathbb{C}) and $T : V \rightarrow V$ a hermitian (=self adjoint) operator. Then \exists an ON basis for V consisting of eigenvectors for T . In particular, T is diagonalizable. This means

$$V = E_T(\lambda_1) \perp \dots \perp E_T(\lambda_r) \quad (*)$$

$E_T(\lambda_i) := \{v \in V \mid Tv = \lambda_i v\} \neq 0$ eigenspace of λ_i ; $\lambda_1, \dots, \lambda_r$ the distinct eigenvalues of T . So

$$T|_{E_T(\lambda_i)} : E_T(\lambda_i) \rightarrow E_T(\lambda_i)$$

i.e., $E_T(\lambda_i)$ is T -invariant and

$$T|_{E_T(\lambda_i)} = \lambda_i 1_{E_T(\lambda_i)}$$

and $(*)$ is unique up to order.

Goal: Generalize this to V any finite dimensional vector space over F , any F , and $T : V \rightarrow V$ linear. We have many problems to overcome in order to get a meaningful result, e.g.,

Problem 2.2. 1. V may not be an inner product space.

2. $F \neq \mathbb{R}$ or \mathbb{C} is possible.

3. $F \not\subseteq \mathbb{R}$ is possible, so cannot even define an inner product.

4. V may not have any eigenvalues for $T : V \rightarrow V$.

5. If we prove an existence theorem, we may not have a uniqueness one.

We shall show: given V a finite dimensional vector space over F and $T : V \rightarrow V$ a linear operator. Then V breaks up uniquely up to order into small T -invariant subspace that we shall show are completely determined by polys in $F[t]$ arising from T .

§2.4 Direct Sums

Motivation: Generalize the concept of linear independence, Spectral Theorem Decomposition, to see how pieces are put together (if possible).

Definition 2.7 (Span) — Let V be a vector space over F , $W_i \subseteq V$, $i \in I$ — may not be finite, subspaces. Let

$$\sum_{i \in I} W_i = \text{Span} \left(\bigcup_{i \in I} W_i \right) := \left\{ v \in V \mid \exists w_i \in W_i, i \in I, \text{ almost all } w_i = 0 \ni v = \sum_{i \in I} w_i \right\}$$

when almost all zero means only finitely many $w_i \neq 0$. Warning: In a vector space/ F we can only take finite linear combination of vectors. So

$$\sum_{i \in I} W_i = \text{Span} \left(\bigcup_{i \in I} W_i \right) = \left\{ \text{finite linear combos of vectors in } \bigcup_{i \in I} W_i \right\}$$

e.g., if I is finite, i.e., $|I| < \infty$, say $I = \{1, \dots, n\}$ then

$$\sum_{i \in I} W_i = W_1 + \dots + W_n := \{w_1 + \dots + w_n \mid w_i \in W_i \forall i \in I\}$$

cf. Linear Combinations.

Definition 2.8 (Direct Sum) — Let V be a vector space over F , $W_i \subseteq V$, $i \in I$, subspace. Let $W \subseteq V$ be a subspace. We say that W is the (internal) direct sum of the W_i , $i \in I$ write $W = \bigoplus_{i \in I} W_i$ if

$$\forall w \in W \exists! w_i \in W_i \text{ almost all } 0 \ni w = \sum_{i \in I} w_i$$

e.g., if $I = \{1, \dots, n\}$, then

$$w \in W_1 \oplus \dots \oplus W_n \text{ means } \exists! w_i \in W_i \ni w = w_1 + \dots + w_n$$

Warning: It may not exist.

§3 | Lec 3: Apr 2, 2021

§3.1 Direct Sums (Cont'd)

Definition 3.1 (Independent Subspace) — Let V be a vector space over F , $W_i \subseteq V$, $i \in I$ subspaces. We say the W_i , $i \in I$, are independent if whenever $w_i \in W_i$, $i \in I$, almost all $w_i = 0$, satisfy $\sum w_i = 0$, then $w_i = 0 \forall i \in I$.

Theorem 3.2

Let V be a vector space over F , $W_i \subseteq V$, $i \in I$ subspaces, $W \subseteq V$ a subspace. Then the following are equivalent:

1. $W = \bigoplus_{i \in I} W_i$

2. $W = \sum_{i \in I} W_i$ and $\forall i$

$$W_i \cap \sum_{j \in I \setminus \{i\}} W_j = 0 := \{0\}$$

3. $W = \sum_{i \in I} W_i$ and the W_i , $i \in I$, are independent.

Proof. 1) \implies 2) Suppose $W = \bigoplus_{i \in I} W_i$. Certainly, $W = \sum_{i \in I} W_i$. Fix i and suppose that

$$\exists x \in W_i \cap \sum_{j \in I \setminus \{i\}} W_j$$

By definition, $\exists w_i \in W_i$, $w_j \in W_j$, $j \in I \setminus \{i\}$ almost all 0 satisfying

$$w_i = x = \sum_{j \neq i} w_j$$

So

$$0_V = 0_W = w_i - \sum_{j \neq i} w_j$$

But

$$0_W = \sum_I 0_{W_k} \quad 0_{W_k} = 0_V \quad \forall k \in I$$

By uniqueness of 1), $w_i = 0$ so $x = 0$.

2) \implies 3) Let $w_i \in W_i$, $i \in I$, almost all zero satisfy

$$\sum_{i \in I} w_i = 0$$

Suppose that $w_k \neq 0$. Then

$$w_k = - \sum_{i \in I \setminus \{k\}} w_i \in W_k \cap \sum_{i \neq k} W_i = 0,$$

a contradiction. So $w_i = 0 \forall i$

3) \implies 1) Suppose $v \in \sum_{i \in I} W_i$ and $\exists w_i, w'_i \in W_i$, $i \in I$, almost all 0 \ni

$$\sum_{i \in I} w_i = v = \sum_{i \in I} w'_i$$

Then $\sum_{i \in I} (w_i - w'_i) = 0$, $w_i - w'_i \in W_i \forall i$. So

$$w_i - w'_i = 0, \text{ i.e., } w_i = w'_i \quad \forall i$$

and the w'_i s are unique. □

Warning: 2) DOES NOT SAY $W_i \cap W_j = 0$ if $i \neq j$. This is too weak. It says $W_i \cap \sum_{j \neq i} W_j = 0$.

Corollary 3.3

Let V be a vector space over F , $W_i \subseteq V$, $i \in I$ subspaces. Suppose $I = I_1 \cup I_2$ with $I_1 \cap I_2 = \emptyset$ and $V = \bigoplus_{i \in I} W_i$. Set

$$W_{I_1} = \bigoplus_{i \in I_1} W_i \quad \text{and} \quad W_{I_2} = \bigoplus_{j \in I_2} W_j$$

Then

$$V = W_{I_1} \oplus W_{I_2}$$

Proof. Left as exercise – Homework. □

Notation: Let V be a vector space over F , $v \in V$. Set

$$Fv := \{\alpha v \mid \alpha \in F\} = \text{Span}(v)$$

if $v \neq 0$, then Fv is the line containing v , i.e., Fv is the one dimensional vector space over F with basis $\{v\}$.

Example 3.4

Let V be a vector space over F

1. If $\emptyset \neq S \subseteq V$ is a subset, then

$$\sum_{v \in S} Fv = \text{Span}(S)$$

the span of S . So

$$\text{Span } S = \{\text{all finite linear combos of vectors in } S\}$$

2. If $\emptyset \neq S$ is linearly indep. (i.e. meaning every finite nonempty subset of S is linearly indep.), then

$$\text{Span}(S) = \bigoplus_{s \in S} Fs$$

3. If S is a basis for V , then $V = \bigoplus_{s \in S} Fs$

4. If \exists a finite set $S \subseteq V \ni V = \text{Span}(S)$, then $V = \sum_{s \in S} Fs$ and \exists a subset $\mathcal{B} \subseteq S$ that is a basis for V , i.e., V is a finite dimensional vector space over F and $\dim V = \dim_F V = |\mathcal{B}|$ is indep. of basis \mathcal{B} for V .

5. Let V be a vector space over F , $W_1, W_2 \subseteq V$ finite dimensional subspaces. Then $W_1 + W_2$, $W_1 \cap W_2$ are finite dimensional vector space over F and

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

So

$$W_1 + W_2 = W_1 \oplus W_2 \iff W_1 \cap W_2 = \emptyset$$

(warning: be very careful if you wish to generalize this)

Definition 3.5 (Complementary Subspace) — Let V be a finite dimensional vector space over F , $W \subseteq V$ a subspace if

$$V = W \oplus W', \quad W' \subseteq V \text{ a subspace}$$

We call W' a complementary subspace of W in V .

Example 3.6

Let \mathcal{B}_0 be a basis of W . Extend \mathcal{B}_0 to a basis \mathcal{B} for V (even works if V is not finite dimensional). Then

$$W' = \bigoplus_{\mathcal{B} \setminus \mathcal{B}_0} Fv \text{ is a complement of } W \text{ in } V$$

Note: W' is not the unique complement of W in V – counter-example?

Consequences: Let V be a finite dimensional vector space over F , $W_1, \dots, W_n \subseteq V$ subspaces, $W_i \neq 0 \forall i$. Then the following are equivalent

1. $V = W_1 \oplus \dots \oplus W_n$.
2. If \mathcal{B}_i is a basis (resp., ordered basis) for $W_i \forall i$, then $\mathcal{B} = \mathcal{B}_1 \cup \dots \cup \mathcal{B}_n$ is a basis (resp. ordered) – with obvious order – for V .

Proof. Left as exercise (good one)! □

Notation: Let V be a vector space over F , \mathcal{B} a basis for V , $x \in V$. Then, $\exists! \alpha_v \in F$, $v \in \mathcal{B}$, almost all $\alpha_v = 0$ (i.e., all but finitely many) s.t. $x = \sum_{\mathcal{B}} \alpha_v v$. Given $x \in V$,

$$x = \sum_{v \in \mathcal{B}} \alpha_v v$$

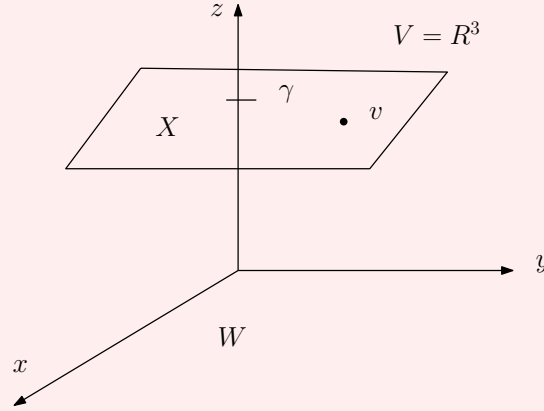
to mean α_v is the unique complement of x on v and hence $\alpha_v = 0$ for almost all $v \in \mathcal{B}$.

§3.2 Quotient Spaces

Idea: Given a surjective map $f : X \rightarrow Y$ and “nice”, can we use properties of Y to obtain properties of X ?

Example 3.7

Let $V = \mathbb{R}^3$, $W = X - Y$ plane. Let $X =$ plane parallel to W intersecting the z -axis at γ .



So

$$\begin{aligned} X &= \{(\alpha, \beta, \gamma) | \alpha, \beta \in \mathbb{R}\} \\ &= \{(\alpha, \beta, 0) + (0, 0, \gamma) | \alpha, \beta \in \mathbb{R}\} \\ &= W + \underbrace{\gamma e_3}_{(0,0,1)} \end{aligned}$$

Note: X is a vector space over $\mathbb{R} \iff \gamma = 0 \iff W = X$ (need 0_V). Let $v \in X$. So $v = (x, y, \gamma)$ some $x, y \in \mathbb{R}$. So

$$\begin{aligned} W + v &:= \left\{ \underbrace{(\alpha, \beta, 0)}_{\text{arbitrary}} + \underbrace{(x, y, \gamma)}_{\text{fixed}} \mid \alpha, \beta \in \mathbb{R} \right\} \\ &= \{(\alpha + x, \beta + y, \gamma) \mid \alpha, \beta \in \mathbb{R}\} \\ &= W + \gamma e_3 \end{aligned}$$

It follows if $v, v' \in V$, then

$$W + v = W + v' \implies v - v' \in W$$

Conversely, if $v, v' \in V$ with $X = W + v$, then

$$v' \in X \implies v' = w + v \text{ some } w \in W$$

hence

$$v' - v \in W$$

So for arbitrary $v, v' \in V$, we have the conclusion $W + v = W + v' \iff v - v' \in W$. We can also write $W + v$ as $v + W$.

§4 | Lec 4: Apr 5, 2021

§4.1 Quotient Spaces (Cont'd)

Recall from the last example of the last lecture, we have

$$V = \bigcup_{v \in V} W + v$$

If $v, v' \in V$, then

$$0 \neq v'' \in (W + v) \cap (W + v')$$

means

$$W + v - W + v'' = W + v'$$

This means either $W + v = W + v'$ or $W + v \cap W + v' = \emptyset$, i.e., planes parallel to the xy-plane partition V into a disjoint unions of planes.

Let

$$S := \{W + v \mid v \in V\}$$

the set of these planes. We make S into a vector space over \mathbb{R} as follows: $\forall v, v' \in V, \forall \alpha \in \mathbb{R}$ define

$$\begin{aligned} (W + v) + (W + v') &:= W + (v + v') \\ \alpha \cdot (W + v) &:= W + \alpha v \end{aligned}$$

We must check these two operations are well-defined and we set

$$0_S := W$$

Then $(W + v) + W = W + v = W + (W + v)$ make S into a vector space over \mathbb{R} .

If $v \in V$ let $\gamma_v^1 =$ the k^{th} component of v . Define

$$S \rightarrow \{(0, 0, \gamma) \mid \gamma \in \mathbb{R}\} \rightarrow \mathbb{R}$$

by

$$W + v \mapsto (0, 0, \gamma_v) \mapsto \gamma$$

both maps are bijection and, in fact, linear isomorphism. So

$$S \cong \{(0, 0, \gamma) \mid \gamma \in \mathbb{R}\} \cong \mathbb{R}$$

Note: $\dim V = 3$, $\dim W = 2$, $\dim S = 1$ and we also have a linear transformation

$$V \rightarrow S \text{ by } (\alpha, \beta, \gamma) \mapsto W + \gamma e_3$$

a surjection.

We can now generalize this.

Construction: Let V be a vector space over F , $W \subseteq V$ a subspace. Define $\equiv \pmod{W}$ called congruent mod W on V as follows: if $x, y \in V$, then

$$x \equiv y \pmod{W} \iff x - y \in W \iff \exists w \in W \ni x = w + y$$

Then, for all $x, y, z \in V$, $\equiv \pmod{W}$ satisfies

1. $x \equiv x \pmod{W}$
2. $x \equiv y \pmod{W} \implies y \equiv x \pmod{W}$
3. $x \equiv y \pmod{W}$ and $y \equiv z \pmod{W} \implies x \equiv z \pmod{W}$

We can conclude that $\equiv \pmod{W}$ is an equivalence relation on V .

Notation: For $x \in V$, $W \subseteq V$, let

$$\bar{x} := \{y \in V \mid y \equiv x \pmod{W}\}$$

We can also write \bar{x} as $[x]_W$ if W is not understood. Also, $\bar{x} \subseteq V$ is a subset and not an element of V called a coset of V by W . We have

$$\begin{aligned} \bar{x} &= \{y \in V \mid y \equiv x \pmod{W}\} \\ &= \{y \in V \mid y = w + x \text{ for some } w \in W\} \\ &= \{w + x \mid w \in W\} = W + x = x + W \end{aligned}$$

Example 4.1

$$\bar{0}_V = W + 0_V = W.$$

Note: $W + x$ translates every element of W by x . By 2), 3) of $\equiv \pmod{W}$, we have check

$$y \in \bar{x} = W + x \iff x \in \bar{y} = W + y$$

and

$$x \equiv y \pmod{W} \iff \bar{x} = \bar{y} \iff W + x = W + y$$

and check

$$\bar{x} \cap \bar{y} = \emptyset \iff (W + x) \cap (W + y) = \emptyset \iff x \not\equiv y \pmod{W}$$

This means the $W + x$ partition V , i.e.,

$$V = \bigcup_V (W + x) \text{ with } (W + x) \cap (W + y) = \emptyset \text{ if } \bar{x} = (W + x) \neq (W + y) = \bar{y}$$

Let

$$\bar{V} := V/W := \{\bar{x} \mid x \in V\} = \{W + x \mid x \in V\}$$

a collection of subsets of V .

§5 | Lec 5: Apr 7, 2021

§5.1 Quotient Spaces (Cont'd)

Suppose we have $W \subseteq V$ a subspace. For $x, y, z, v \in V$

$$\begin{aligned} x &\equiv y \pmod{W} \\ z &\equiv v \pmod{W} \end{aligned} \quad (+)$$

Then

$$(x + z) - (y + v) = \underbrace{(x - y)}_{\in W} + \underbrace{(z - v)}_{\in W} \in W$$

So

$$x + z \pmod{y + v} \pmod{W}$$

and if $\alpha \in F$

$$\alpha x - \alpha y = \alpha(x - y) \in W \quad \forall x, y \in V$$

So

$$\alpha x \equiv \alpha y \pmod{W}$$

Therefore, $\bar{V} = V/W$. If (+) holds, then for all $x, y, z, v \in V$ and $\alpha \in F$, we have

$$\begin{aligned} \overline{x + z} &= \overline{y + v} \in \bar{V} \\ \overline{\alpha x} &= \overline{\alpha y} \in \bar{V} \end{aligned}$$

Notice $\bar{V} = V/W$ satisfies all the axioms of a vector space with $0_{\bar{V}} = \overline{0_V} = \{y \in V \mid y \equiv 0 \pmod{W}\} = W + 0_V = W$.

We call $\bar{V} = V/W$ the **QUOTIENT SPACE** of V by W .

We also have a map

$$- : V \rightarrow \bar{V} = V/W \text{ by } x \mapsto \bar{x} = W + x$$

which satisfies

$$\alpha v + v' \mapsto \overline{\alpha v + v'} = \alpha \bar{v} + \bar{v}'$$

for all $v, v' \in V$ and $\alpha \in F$. Then

$$\begin{aligned} \dim V &= \dim \ker^- \\ \dim V &= \dim W + \dim V/W \\ \dim V/W &= \dim V - \dim W \end{aligned}$$

which is called the codimension of W in V .

Proposition 5.1

Let V be a vector space over F , $W \subseteq V$ a subspace, $\bar{V} = V/W$. Let \mathcal{B}_0 be a basis for W and

$$\mathcal{B}_1 = \{v_i \mid i \in I, v_i - v_j \notin W \text{ if } i \neq j\}$$

where $\bar{v}_i \neq \bar{v}_j$ if $i \neq j$ or $w + v_i \neq w + v_j$ if $i \neq j$.

Let

$$\mathcal{C} = \{\bar{v}_i = W + v_i \mid i \in I, v_i \in \mathcal{B}_1\}$$

If \mathcal{C} is a basis for $\bar{V} = V/W$, then $\mathcal{B}_0 \cup \mathcal{B}_1$ is a basis for V (compare with the proof of the Dimension Theorem).

Proof. Hw 2 # 3. □

§5.2 Linear Transformation

A review of linear of linear transformation can be found [here](#).

Now, we consider

$$GL_n F := \{A \in \mathbb{M}_n F \mid \det A \neq 0\}$$

The elements in $GL_n F$ in the ring $\mathbb{M}_n F$ are those having a multiplicative inverse. If R is a commutative ring, determinants are still as before but

$$\begin{aligned} GL_n R &:= \{A \in \mathbb{M}_n R \mid \det A \text{ is a unit in } R\} \\ &= \{A \in \mathbb{M}_n R \mid A^{-1} \text{ exists}\} \end{aligned}$$

Example 5.2

Let V be a vector space over F , $W \subseteq V$ a subspace. Recall

$$\bar{V} = V/W = \{\bar{v} = W + v \mid v \in V\}$$

a vector space over F s.t. for all $v_1, v_2 \in F$ and $\alpha \in F$

$$\begin{aligned} 0_{\bar{V}} &= \bar{0}_V = W \\ \bar{v}_1 + \bar{v}_2 &= \overline{v_1 + v_2} \\ \alpha \bar{v}_1 &= \overline{\alpha v_1} \end{aligned}$$

Then

$$- : V \rightarrow V/W = \bar{V} \text{ by } v \mapsto \bar{v} = W + v$$

is an epimorphism with $\ker^- = W$.

Recall from 115A(H) that the most important theorem about linear transformation is [Universal Property of Vector Spaces](#). As a result, we can deduce the following corollary

Corollary 5.3

Let V, W be vector space over F with bases \mathcal{B}, \mathcal{C} respectively. Suppose there exists a bijection $f : \mathcal{B} \rightarrow \mathcal{C}$, i.e., $|\mathcal{B}| = |\mathcal{C}|$. Then $V \cong W$.

Proof. There exists a unique $T : V \rightarrow W \ni T|_{\mathcal{B}} = f$. T is monic by the Monomorphism Theorem (T takes linearly indep. sets to linearly indep. sets iff it's monic) and is onto as $W = \text{Span}(\mathcal{C}) = \text{Span}(f(\mathcal{B}))$. \square

§6 | Lec 6: Apr 9, 2021

§6.1 Linear Transformation (Cont'd)

Theorem 6.1

Let $T : V \rightarrow W$ be linear. Then $\exists X \subseteq V$ a subspace s.t.

$$V = \ker T \oplus X \text{ with } X \cong \operatorname{im} T$$

Proof. Let \mathcal{B}_0 be a basis for $\ker T$. Extend \mathcal{B}_0 to a basis \mathcal{B} for V by the [Extension Theorem](#). Let $\mathcal{B}_1 = \mathcal{B} \setminus \mathcal{B}_0$, so $\mathcal{B} = \mathcal{B}_0 \cup \mathcal{B}_1$ ($\mathcal{B} = \mathcal{B}_0 \cup \mathcal{B}_1$ and $\mathcal{B}_0 \cap \mathcal{B}_1 = \emptyset$) and let

$$X = \bigoplus_{\mathcal{B}_1} Fv$$

As $\ker T = \bigoplus_{\mathcal{B}_0} Fv$, we have

$$V = \ker T \oplus X$$

and we have to show

$$X \cong \operatorname{im} T$$

Claim 6.1. $Tv, v \in \mathcal{B}_1$ are linearly indep.

In particular, $Tv \neq Tv'$ if $v, v' \in \mathcal{B}_1$ and $v \neq v'$. Suppose

$$\sum_{v \in \mathcal{B}} \alpha_v Tv = 0_W, \quad \alpha_v \in F \text{ almost all } \alpha_v = 0$$

Then

$$0_W = T \left(\sum_{v \in \mathcal{B}_1} \alpha_v v \right), \quad \text{i.e.} \quad \sum_{\mathcal{B}_1} \alpha_v v \in \ker T$$

Hence

$$\sum_{\mathcal{B}_1} \alpha_v v = \sum_{\mathcal{B}_0} \beta_v v \in \ker T \text{ almost all } \beta_v \in F = 0$$

As $\sum_{\mathcal{B}_1} \alpha_v v - \sum_{\mathcal{B}_0} \beta_v v = 0$ and $\mathcal{B} = \mathcal{B}_0 \cup \mathcal{B}_1$ is linearly indep., $\alpha_v = 0 \forall v$. This proves the above claim.

Let $\mathcal{C} = \{Tv | v \in \mathcal{B}_1\}$. By the claim

$$\mathcal{B}_1 \rightarrow \mathcal{C} \text{ by } v \mapsto Tv \text{ is } 1-1$$

and onto as \mathcal{C} is linearly indep. Lastly, we must show \mathcal{C} spans $\operatorname{im} T$. Let $w \in \operatorname{im} T$. Then $\exists x \in V \ni Tx = w$. Then

$$\begin{aligned} w = Tx &= T \left(\sum_{\mathcal{B}_0} \alpha_v v \right) + T \left(\sum_{\mathcal{B}_1} \alpha_v v \right) \\ &= \sum_{\mathcal{B}_0} \alpha_v Tv + \sum_{\mathcal{B}_1} \alpha_v Tv = \sum_{\mathcal{B}_1} \alpha_v Tv \end{aligned}$$

lies in $\operatorname{span} \mathcal{C}$ as needed. □

Remark 6.2. Note that the proof is essentially the same as the proof of the [Dimension Theorem](#).

Corollary 6.3 (Dimension Theorem)

If V is a finite dimensional vector space over F , $T : V \rightarrow W$ linear then

$$\dim V = \dim \ker T + \dim \operatorname{im} T$$

Corollary 6.4

If V is a finite dimensional vector space over F , $W \subseteq V$ a subspace, then

$$\dim V = \dim W + \dim V/W$$

Proof. $- : V \rightarrow V/W$ by $v \mapsto \bar{v} = W + v$ is an epi. □

Important Construction: Set

$T : V \rightarrow Z$ be linear

$$W = \ker T$$

$$\bar{V} = V/W$$

$- : V \rightarrow V/W$ by $v \mapsto \bar{v} = W + v$ linear

$\forall x, y \in V$ we have

$$\bar{x} = \bar{y} \in \bar{V} \iff x \equiv y \pmod{W} \iff x - y \in W \iff T(x - y) = 0_Z$$

i.e., when $W = \ker T$

$$\bar{x} = \bar{y} \iff Tx = Ty \tag{*}$$

This means

$$\bar{T} : \bar{V} \rightarrow Z \text{ defined by } W + v = \bar{v} \mapsto Tv$$

is well-defined, i.e., via function, since if $\bar{x} = \bar{y}$, then $\bar{T}(\bar{x}) := Tx = Ty =: \bar{T}(\bar{y})$. From (*),

$$\bar{x} = \bar{y} \iff \bar{T}(\bar{x}) = T(x) = T(y) =: \bar{T}(\bar{y})$$

so

$$\bar{T} : \bar{V} \rightarrow Z \text{ is also injective}$$

As \bar{T} is linear, let $\alpha \in F$, $x, y \in V$, then

$$\begin{aligned} \bar{T}(\alpha\bar{x} + \bar{y}) &= \bar{T}(\overline{\alpha x + y}) = T(\alpha x + y) \\ &= \alpha Tx + Ty = \alpha \bar{T}(\bar{x}) + \bar{T}(\bar{y}) \end{aligned}$$

as needed. Therefore,

$$\bar{T} : \bar{V} \rightarrow Z \text{ by } \bar{x} \mapsto T(x)$$

is a monomorphism, so induces an isomorphism onto $\text{im } \bar{T}$ and we recall $\text{im } \bar{T} = \text{im } T$, so

$$\bar{V} \cong \text{im } \bar{T} = \text{im } T$$

and we have a commutative diagram

$$\begin{array}{ccc} V & \xrightarrow{T} & Z \\ \downarrow - & & \nearrow \bar{T} \\ V/\ker T = \bar{V} & & \end{array}$$

This can also be written as

$$\begin{array}{ccc} V & \xrightarrow{T} & Z \\ \downarrow - & & \uparrow \text{inclusion map} \\ V/\ker T = \bar{V} & \xrightarrow{\bar{T}} & \text{im } T \end{array}$$

Consequence: Any linear transformation $T : V \rightarrow Z$ induces an isomorphism

$$\bar{T} : V/\ker T \rightarrow \text{im } T \text{ by } \bar{v} = \ker T + v \mapsto Tv$$

This is called the **First Isomorphism Theorem**. We also have

$$V = \ker T \oplus X \text{ with } X \subseteq V \text{ and } X \cong \text{im } T \cong V/\ker T$$

This means that all images of linear transformations from V are determined, up to isomorphism, by V and its subspaces. It also means, if V is a finite dimensional vector space over F , we can try prove things by induction.

§6.2 Projections

Motivation: Let $m < n$ in \mathbb{Z}^+ and

$$\pi : \mathbb{R}^n \rightarrow \mathbb{R}^n \text{ by } (\alpha_1, \dots, \alpha_n) \mapsto (\alpha_1, \dots, \alpha_n, 0, \dots, 0)$$

a linear operator onto $\bigoplus_{i=1}^m \Gamma e_i$ where $e_i = \left(0, \dots, \underbrace{1}_{i^{\text{th}}}, \dots, 0\right)$.

Definition 6.5 (T-invariant) — Let $T : V \rightarrow V$ be linear, $W \subseteq V$ a subspace. We say W is T -invariant if $T(W) \subseteq W$ if this is the case, then the restriction $T|_W$ of T can be viewed as a linear operator

$$T|_W : W \rightarrow W$$

Example 6.6

Let $T : V \rightarrow V$ be linear.

1. $\ker T$ and $\operatorname{im} T$ are T -invariant.
2. Let $\lambda \in F$ be an eigenvalue of T , i.e., $\exists 0 \neq v \in V \ni Tv = \lambda v$, then any subspace of the eigenspace

$$E_T(\lambda) := \{v \in V \mid Tv = \lambda v\}$$

is T -invariant as $T|_{E_T(\lambda)} = \lambda 1_{E_T(\lambda)}$

Remark 6.7. Let V be a finite dimensional vector space over F , $T : V \rightarrow V$ linear. Suppose that

$$V = W_1 \oplus \dots \oplus W_n$$

with each W_i T -invariant, $i = 1, \dots, n$ and \mathcal{B}_i an ordered basis for W_i , $i = 1, \dots, n$. Let $\mathcal{B} = \mathcal{B}_1 \cup \dots \cup \mathcal{B}_n$ be a basis of V ordered in the obvious way.

Then the matrix representation of T in the \mathcal{B} basis is

$$[T]_{\mathcal{B}} = \begin{pmatrix} [T|_{W_1}]_{\mathcal{B}_1} & & 0 \\ & \ddots & \\ 0 & & [T|_{W_n}]_{\mathcal{B}_n} \end{pmatrix}$$

Example 6.8

Suppose that $T : V \rightarrow V$ is diagonalizable, i.e., there exists a basis \mathcal{B} of eigenvectors of T for V . Then, $T : V \rightarrow V$,

$$V = \bigoplus E_T(\lambda_i)$$

each $E_T(\lambda_i)$ is T -invariant.

$$T|_{E_T(\lambda_i)} = \lambda_i 1_{E_T(\lambda_i)}$$

Goal: Let V be a finite dimensional vector space over F , $n = \dim V$, $T : V \rightarrow V$ linear. Then $\exists W_1, \dots, W_m \subseteq V$ all T -invariant subspaces with $m = m(T)$ with each W_i being as small as possible with $V = W_1 \oplus \dots \oplus W_m$. This is the theory of canonical forms.

Recall: If V is a finite dimensional vector space over F , $T : V \rightarrow V$ linear, \mathcal{B} an ordered basis for V , then the matrix representation $[T]_{\mathcal{B}}$ is only unique up to similarity, i.e., if \mathcal{C} is an another ordered basis

$$[T]_{\mathcal{C}} = P [T]_{\mathcal{B}} P^{-1}$$

where $P = [1_V]_{\mathcal{B}, \mathcal{C}} \in GL_n F$, the change of basis matrix $\mathcal{B} \rightarrow \mathcal{C}$.

Definition 6.9 (Projection) — Let V be a vector space over F , $P : V \rightarrow V$ linear. We call P a projection if $P^2 = P \circ P = P$.

- Example 6.10**
1. $P = 0_V$ or $1_V : V \rightarrow V$, V is a vector space over F .
 2. An orthogonal projection in 115A.
 3. If P is a projection, so is $1_V - P$.

If $T : V \rightarrow V$ is linear, then

$$V = \ker T \oplus X \text{ with } X \cong \operatorname{im} T$$

Lemma 6.11

Let $P : V \rightarrow V$ be a projection. Then

$$V = \ker P \oplus \operatorname{im} P$$

Moreover, if $v \in \operatorname{im} P$, then

$$Pv = v$$

i.e.

$$P|_{\operatorname{im} P} : \operatorname{im} P \rightarrow \operatorname{im} P \text{ is } 1_{\operatorname{im} P}$$

In particular, if V is a finite dimensional vector space over F , \mathcal{B}_1 an ordered basis for $\ker P$, \mathcal{B}_2 an ordered basis for $\operatorname{im} P$, then $\mathcal{B} = \mathcal{B}_1 \cup \mathcal{B}_2$ is an ordered basis for V and

$$[P]_{\mathcal{B}} = \begin{pmatrix} [0]_{\mathcal{B}_1} & 0 \\ 0 & [1_{\operatorname{im} P}]_{\mathcal{B}_2} \end{pmatrix} = \begin{pmatrix} 0 & & & & \\ & \ddots & & & \\ & & 0 & & \\ & & & 1 & \\ & & & & \ddots \\ & & & & & 1 \end{pmatrix}$$

Proof. Let $v \in V$, then $v - Pv \in \ker P$, since

$$P(v - Pv) = Pv - P^2v = Pv - Pv = 0$$

Hence

$$v = (v - Pv) + Pv \in \ker P + \operatorname{im} P$$

$\ker P \cap \operatorname{im} P = 0$ and $P|_{\operatorname{im} P} = 1_{\operatorname{im} P}$. Let $v \in \operatorname{im} P$. By definition, $Pw = v$ for some $w \in V$. Therefore,

$$Pv = PPw = Pw = v$$

Hence

$$P|_{\operatorname{im} P} = 1_{\operatorname{im} P}$$

If $v \in \ker P \cap \operatorname{im} P$, then

$$v = Pv = 0$$

□

§7 | Lec 7: Apr 12, 2021

§7.1 Projection (Cont'd)

Lemma 7.1

Let V be a vector space over F , $W, X \subseteq V$ subspaces. Suppose

$$V = W \oplus X$$

Then $\exists! P : V \rightarrow V$ a projection satisfying

$$W = \ker P \quad (*)$$

$$X = \operatorname{im} P$$

We say such a P is the projection along W onto X .

Proof. Existence: Let $v \in V$. Then

$$\exists! w \in W, x \in X \ni v = w + x$$

Define

$$P : V \rightarrow V \text{ by } v \mapsto x$$

To show $P^2 = P$, we suppose $v \in V$ satisfies $v = w + x$, for unique $w \in W, x \in X$. Then

$$Pv = Pw + Px = Px = 1_X x = x$$

so

$$P^2 v = Px = x = Pv \quad \forall v \in V$$

hence $P^2 = P$.

Uniqueness: Any P satisfying $(*)$ takes a basis for W to 0 and fix a basis of X . Therefore, P is unique by the UPVS. \square

check P
is linear
and well
defined

Remark 7.2. Compare the above to the case that V is an inner product space over F , $W \subseteq V$ is a finite dimensional subspace and $P : V \rightarrow V$ by $v \mapsto v_W$, the orthogonal projection of P onto W .

Proposition 7.3

Let V be a vector space over F , $W, X \subseteq V$ subspaces s.t. $V = W \oplus X$, $P : V \rightarrow V$ the projection along W onto X , and $T : V \rightarrow V$ linear. Then the following are equivalent:

1. W and X are both T -invariant.
2. $PT = TP$.

Proof. 2) \implies 1) : W is T -invariant: We have $W = \ker P$, so if $w \in W$, $Pw = 0$. Hence

$$PTw = TPw = T0 = 0$$

$Tw \in \ker P = W$ so W is T -invariant.

X is T -invariant, $X = \text{im } P$, $P|_X = 1_X$. So if $x \in X$

$$Tx = TPx = PTx \in \text{im } P = X$$

So X is T -invariant.

1) \implies 2) Let $v \in V$. Then $\exists! w \in W, x \in X$ s.t.

$$v = w + x$$

As $P|_X = 1_X$ and $P|_W = 0$, so $Pv = Px$. By 1), W and X are T -invariant, so

$$\begin{aligned} PTv &= PT(w + x) = PTw + PTx \\ &= 0 + Tx = TPx = TPw + TPx = TPv \end{aligned}$$

for all $v \in V$ and $PT = TP$. □

Remark 7.4. One can easily generalize from the case

$$V = W_1 \oplus W_2$$

that we did to the case

$$V = W_1 \oplus \dots \oplus W_n$$

by induction on n as

$$V = W_i \oplus \left(W_1 \oplus \dots \oplus \underbrace{\hat{W}_i}_{\text{omit}} \oplus \dots \oplus W_n \right)$$

Construction: Let

$$V = W_1 \oplus \dots \oplus W_n$$

as above. Define

$$P_{W_i} : V \rightarrow V$$

to be the projection along $W_1 \oplus \dots \oplus \hat{W}_i \oplus \dots \oplus W_n$, i.e.

$$\ker P_{W_i} = W_1 \oplus \dots \oplus \hat{W}_i \oplus \dots \oplus W_n$$

and onto $W_i = \text{im } P_{W_i}$ as in the above Proposition. Then we have

- a) Each P_{W_i} is linear (and a projection).
- b) $\ker P_{W_i} = W_1 \oplus \dots \oplus \hat{W}_i \oplus \dots \oplus W_n$.
- c) W_i is P_{W_i} -invariant and $P_{W_i}|_{W_i} = 1_{W_i}$. In particular, $\text{im } P_{W_i} = W_i$.
- d) $P_{W_i}P_{W_j} = \delta_{ij}P_{W_i}$ where

$$\delta_{ij} = \begin{cases} 1, & \text{if } i = j \\ 0, & \text{if } i \neq j \end{cases}$$

$$\text{e) } 1_V = P_{W_1} + \dots + P_{W_n}.$$

Moreover, if $T : V \rightarrow V$ is linear and each W_i is T -invariant, then

$$TP_{W_i} = P_{W_i}T, \quad i = 1, \dots, n$$

Hence

$$\begin{aligned} T &= T1_V = T(P_{W_1} + \dots + P_{W_n}) = TP_{W_1} + \dots + TP_{W_n} \\ &= P_{W_1}T + \dots + P_{W_n}T \end{aligned}$$

i.e., $1_V T = T 1_V$. This implies

$$T|_{W_i} : W_i \rightarrow W_i$$

is given by

$$T|_{W_i} = TP_{W_i}|_{W_i}$$

or T is determined by what it does to each W_i .

Remark 7.5. Compare this to the case that T is diagonalizable and the W_i are the eigenspaces.

Question 7.1. Let V be a real or complex finite dimensional inner product space, $T : V \rightarrow V$ hermitian. What can you replace \oplus by? What if V is a complex finite dimensional inner product space and $T : V \rightarrow V$ is normal.

Exercise 7.1. Suppose V is a vector space over F , $P_1, \dots, P_n : V \rightarrow V$ linear and satisfy

- i) $P_i - P_j = \delta_{ij}P_i, i = 1, \dots, n$
- ii) $1_V = P_1 + \dots + P_n$
- iii) $W_i = \text{im } P_i, i = 1, \dots, n$

Then

$$\begin{aligned} V &= W_1 \oplus \dots \oplus W_n \\ P_i &= P_{W_i} \quad i = 1, \dots, n \end{aligned}$$

§7.2 Dual Spaces

Question 7.2. Let $V = \mathbb{R}^3$, $v \in V$. What is the first question that we should ask about v ?

Motivation/Construction: Let V be a vector space over F , \mathcal{B} a basis for V . Fix $v_0 \in \mathcal{B}$. By the UPVS, $\exists! f_{v_0} : V \rightarrow F$ linear satisfying

$$f_{v_0}(v) = \begin{cases} 1 & \text{if } v_0 = v \\ 0 & \text{if } v_0 \neq v \end{cases} = \delta_{v, v_0} \quad \forall v \in \mathcal{B}$$

Example 7.6

Let $\mathcal{E}_n = \{e_1, \dots, e_n\}$ be the standard basis for \mathbb{R}^n and in the above $e_1 = v_0 \dots$. Then

$f_{e_1} : \mathbb{R}^n \rightarrow \mathbb{R}$ satisfies

If $v = (\alpha_1, \dots, \alpha_n)$ in \mathbb{R}^n

$$v = \sum_{i=1}^n \alpha_i e_i$$

so

$$\begin{aligned} f_{e_1}(v) &= f_{e_1} \left(\sum_{i=1}^n \alpha_i e_i \right) \\ &= \sum_{i=1}^n \alpha_i f_{e_1}(e_i) = \sum_{i=1}^n \alpha_i \delta_{ii} = \alpha_1 \end{aligned}$$

this first coordinate of v .

Notation: If $A \subseteq B$ are sets, we write $A < B$ if $A \neq B$.

As $v_0 \neq 0$,

$0 < \text{im } f_{v_0} \subseteq F$ is a subspace

Notice $\dim_F F = 1$, so $\dim \text{im } f_{v_0} \leq \dim F = 1$ and

$$\dim \text{im } f_{v_0} = 1, \quad \text{i.e. } \text{im } f_0 = F$$

So $f_{v_0} : V \rightarrow F$ is a surjective linear transformation. Since this is true for all $v_0 \in \mathcal{B}$, for each $v \in \mathcal{B}$, $\exists! f_v : V \rightarrow F$ s.t.

$$f_v(v') = \delta_{v,v'} = \begin{cases} 1 & \text{if } v = v' \\ 0 & \text{if } v \neq v' \end{cases} \quad \forall v' \in \mathcal{B}$$

Now suppose that $x \in V$, then

$$\exists! \alpha_v \in F, v \in \mathcal{B}, \text{ almost all } 0 \text{ s.t. } x = \sum_{\mathcal{B}} \alpha_v v$$

Hence

$$\begin{aligned} f_{v_0}(x) &= f_{v_0} \left(\sum_{v \in \mathcal{B}} \alpha_v v \right) = \sum_{\mathcal{B}} \alpha_v f_{v_0}(v) \\ &= \sum_{\mathcal{B}} \alpha_v \delta_{v,v_0} = \alpha_{v_0} \end{aligned}$$

Example 7.7

$\mathcal{B} = \mathcal{E}_n$ standard basis for \mathbb{R}^n

$$f_{e_i}(e_j) = \delta_{e_i, e_j} = \delta_{i,j} = \begin{cases} 1 & \text{if } e_i = e_j \\ 0 & \text{if } e_i \neq e_j \end{cases}$$

Then if $v = (\alpha_1, \dots, \alpha_n) \in \mathbb{R}^n = V$. Then

$$f_{e_i}(v) = f_{e_i}(\alpha_1, \dots, \alpha_n) = \alpha_i$$

So we observe in the above that if $x \in V$, then

$$x = \sum_{\mathcal{B}} f_v(x)v$$

We call f_v the coordinate function on v relative to \mathcal{B} .

Example 7.8

Let V be a finite dimensional inner product space over \mathbb{R} , $\mathcal{B} = \{v_1, \dots, v_n\}$ an orthonormal basis. Then if $x = \sum_{\mathcal{B}} \alpha_i v_i$, then

$$\alpha_i = \langle x, v_i \rangle$$

Take

$$\begin{aligned} \langle x, v_i \rangle &= \langle \sum \alpha_j v_j, v_i \rangle = \sum \alpha_j \langle v_j, v_i \rangle \\ &= \sum \alpha_j \delta_{ij} \|v_i\|^2 = \sum \alpha_j \delta_{ij} = \alpha_i \end{aligned}$$

i.e. the linear map

$$f_{v_i} := \langle \cdot, v_i \rangle : V \rightarrow \mathbb{R} \text{ by } x \mapsto \langle x, v_i \rangle$$

is the coordinate function on vectors relative to \mathcal{B} .

Definition 7.9 (Dual Space) — Let V be a vector space over F . A linear transformation $f : V \rightarrow F$ is called a linear functional. Set

$$V^* := L(V, F) := \{f : V \rightarrow F \mid f \text{ is linear}\}$$

is called the dual space of V .

Proposition 7.10

Let V, W be a vector space over F . Then

$$L(V, W) := \{T : V \rightarrow W \mid T \text{ linear}\}$$

is a vector space over F . Moreover, if V, W are finite dimensional vector spaces over F

$$\dim L(V, W) = \dim V \dim W$$

In particular, if V is a finite dimensional vector space over F , then so is V^* and

$$\dim V = \dim V^*$$

so

$$V \cong V^*$$

Proof. 115A. □

Example 7.11

Let V be a vector space over F . Then the following are linear functionals

1. $0 : V \rightarrow F$
2. Let $0 \neq v_0 \in V$ then $\{v_0\}$ is a basis for Fv_0 . Therefore, $\{v_0\}$ extends to a basis \mathcal{B} for V . Let $f_{v_0} \in V^*$ be the coordinate function for V on v_0 relative to \mathcal{B} . Then $f_{v_0} \in \mathcal{B}^* := \{fv \mid v \in \mathcal{B}\}$.

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§8.1 Dual Spaces (Cont'd)

Example 8.1 (Cont'd from Lec 7) 3. trace: $\mathbb{M}_n F \rightarrow F$ by

$$A \mapsto \sum_{i=1}^n A_{ii}$$

4. $\alpha < \beta \in \mathbb{R}$, then

$$I : C[\alpha, \beta] \rightarrow \mathbb{R} \text{ by } f \mapsto \int_{\alpha}^{\beta} f$$

5. Fix $\gamma \in [\alpha, \beta]$, $\alpha < \beta \in \mathbb{R}$. Then the evaluation map at γ

$$e_{\gamma} : C[\alpha, \beta] \rightarrow \mathbb{R} \text{ by } f \mapsto f(\gamma)$$

Lemma 8.2

Let V be a vector space over F , \mathcal{B} a basis for V ,

$$\mathcal{B}^* := \{f_{v_0} : V \rightarrow F \mid \text{coordinate function on } v_0 \text{ relative to } \mathcal{B}\}$$

so

$$f_{v_0}(v) = \delta_{v_0, v} \quad \forall v \in \mathcal{B}$$

the set of coordinate functions relative to \mathcal{B} . Then $\mathcal{B}^* \subseteq V^*$ is linearly indep.

Proof. Suppose

$$0 = 0_{V^*} = \sum_{v \in \mathcal{B}} \beta_v f_v, \quad \beta_v \in F \text{ almost all } 0$$

We need to show $\beta_v = 0 \forall v \in \mathcal{B}$. Evaluation at $v_0 \in \mathcal{B}$ yields

$$\begin{aligned} 0 &= 0_{V^*}(v_0) = \left(\sum_{\mathcal{B}} \beta_v f_v \right)(v_0) = \sum \beta_v f_v(v_0) \\ &= \sum_{\mathcal{B}} \beta_v f_{v, v_0} = \beta_{v_0} \end{aligned}$$

So $\beta_v = 0 \forall v \in \mathcal{B}$ and the lemma follows. \square

Corollary 8.3

Let V be a vector space over F with basis \mathcal{B} . Then the linear transformation

$$D_{\mathcal{B}} : V \rightarrow V^* \text{ induced by } \mathcal{B} \rightarrow \mathcal{B}^* \text{ by } v \mapsto fv$$

is a monomorphism.

In particular, if V is a finite dimensional vector space over F , then \mathcal{B}^* is a basis for V^* and

$$D_{\mathcal{B}} : V \rightarrow V^* \text{ is an isomorphism}$$

Proof. By the Monomorphism Theorem, $D_{\mathcal{B}}$ is monic in view of the lemma if V is a finite dimensional vector space over F , then

$$\dim V = \dim V^*$$

so $V \cong V^*$ by the Isomorphism Theorem. \square

Remark 8.4. 1. If $V = \mathbb{R}_f^\infty := \{(\alpha_1, \alpha_2, \dots) \mid \alpha_i \in \mathbb{R} \text{ almost all } 0\}$, then by HW1 # 4,

$$D_{\mathcal{E}_\infty} : V \rightarrow V^* \text{ is not an isomorphism}$$

2. $D_{\mathcal{B}} : V \rightarrow V^*$ in the corollary depends on \mathcal{B} . There exists no monomorphism $V \rightarrow V^*$ that does not depend on a choice of basis. However, there exists a “nice” monomorphism, i.e., defined independent of basis.

$$L : V \rightarrow (V^*)^* =: V^{**}$$

V^{**} is called the double dual of V . We now construct it.

Lemma 8.5

Let V be a vector space over F , $v \in V$. Then

$$L_v : V^* \rightarrow F \text{ by } f \mapsto L_v(f) := f(v)$$

the evaluation map at v is linear, i.e.

$$L_v \in V^{**}$$

Proof. For all $f, g \in V^*$, $\alpha \in F$

$$L_v(\alpha f + g) = (\alpha f + g)(v) = \alpha f(v) + g(v) = \alpha L_v f + L_v g$$

\square

Theorem 8.6

The “natural” map

$$L : V \rightarrow V^{**} \text{ by } v \mapsto L(v) := L_v$$

is a monomorphism.

Proof. L is linear: Let $v, w \in V$, $\alpha \in F$. Then for all $f \in V^*$, as $V^{**} = (V^*)^*$

$$\begin{aligned} L(\alpha v + w)(f) &= L_{\alpha v + w}(f) = f(\alpha v + w) \\ &= \alpha f(v) + f(w) = \alpha L_v f + L_w f = (\alpha L_v + L_w)(f) \\ &= (\alpha L(v) + L(w))(f) \end{aligned}$$

So

$$L(\alpha v + w) = \alpha L(v) + L(w)$$

L is monic. Suppose $v \neq 0$. To show $L_v = L(v) \neq 0$. By example 2,

$$\exists 0 \neq f \in V^* \ni f(v) \neq 0$$

So

$$L_v f = f(v) \neq 0$$

so $L_v = L(v) \neq 0$ and L is monic. □

Corollary 8.7

If V is a finite dimensional vector space over F , then $L : V \rightarrow V^{**}$ is a natural isomorphism.

Proof. $\dim V = \dim V^* = \dim V^{**}$ and the Isomorphism Theorem. □

Identification: Let V be a finite dimensional vector space over F . Then $\forall v, w \in V$

1. $v = w \iff L_v = L_w$
2. $\forall f \in V^* f(v) = f(w) \iff L_v f = L_w f$

Moreover, if W is also a finite dimensional vector space over F , then if $T : V \rightarrow W$ is linear, $\exists! \tilde{T} : V^{**} \rightarrow W^{**}$ linear and if $\tilde{T} : V^{**} \rightarrow W^{**}$ $\exists! T : V \rightarrow W$ linear. In other words, V and V^{**} can be identified by

$$v \leftrightarrow L_v$$

because

$$L_v(f) = f(v) \quad \forall v \in V \quad \forall f \in V^*$$

Construction: Let V be a finite dimensional vector space over F with basis $\mathcal{B} = \{v_1, \dots, v_n\}$. Then

$$\mathcal{B}^* := \{f_1, \dots, f_n\}$$

defined by

$$f_i(v_j) = \delta_{ij} \quad \forall i, j$$

i.e., f_i is the coordinate function on v_i relative to \mathcal{B} . Since

$$L_{v_i}(f_j) = f_j(v_i) = \delta_{ij} \quad \forall i, j$$

$L_{v_i} \in V^{**}$

$$\mathcal{B}^{**} := \{L_{v_1}, \dots, L_{v_n}\}$$

is the dual basis of \mathcal{B}^* for V^{**} . So we have if $x = \sum_{i=1}^n \alpha_i v_i \in V$, $g = \sum_{i=1}^n \beta_i f_i \in V^*$.

$$\begin{aligned} x &= \sum_{i=1}^n \alpha_i v_i = \sum_{i=1}^n f_i(x) v_i \\ g &= \sum_{i=1}^n \beta_i f_i = \sum_{i=1}^n L_{v_i}(g) f_i = \sum_{i=1}^n g(v_i) f_i \end{aligned}$$

i.e.

$$\begin{aligned} x &= \sum_{i=1}^n f_i(x) v_i & \forall x \in V \\ g &= \sum_{i=1}^n g(v_i) f_i & \forall g \in V^* \end{aligned}$$

Motivation: Let V be an inner product space over \mathbb{R} , $\emptyset \neq S \subseteq V$ a subset. What is S^\perp ?

Note: $\forall v \in V$, $\langle \cdot, v \rangle : V \rightarrow \mathbb{R}$ by $x \mapsto \langle x, v \rangle$ is a linear functional. To generalize this to an arbitrary vector space over F , we define the following.

Definition 8.8 (Annihilator) — Let V be a vector space over F , $\emptyset \neq S \subseteq V$ a subset. Define the annihilator of S to be

$$\begin{aligned} S^\circ &:= \{f \in V^* \mid f(x) = 0 \forall x \in S\} \\ &= \{f \in V^* \mid f|_S = 0\} \subseteq V^* \end{aligned}$$

Remark 8.9. Many people write $\langle v, f \rangle$ for $f(v)$ in the above even though $f \notin v$.

§9 | Lec 9: Apr 16, 2021

§9.1 Dual Spaces (Cont'd)

Lemma 9.1

Let V be a vector space over F , $\emptyset \neq S \subseteq V$ a subset. Then

1. $S^\circ \subseteq V^*$ is a subspace.
2. If V is a finite dimensional vector space over F and we identify V as V^{**} (by $v \leftrightarrow L_v$), then $S \subseteq S^{\circ\circ} := (S^\circ)^\circ$.

Proof. 1. For all $f, g \in S^\circ$, $\alpha \in F$, we have

$$(\alpha f + g)(x) = \alpha f(x) + g(x) = 0 \quad \forall x \in S$$

Hence $\alpha f + g \in S^\circ$ and $S^\circ \subseteq V^*$ is a subspace.

2. Let $x \in S$. Then $\forall f \in S^\circ$, we have

$$0 = f(x) = L_x f, \quad \text{so } L_x \in (S^\circ)^\circ = S^{\circ\circ}$$

□

Theorem 9.2

Let V be a finite dimensional vector space over F , $S \subseteq V$ a subspace. Then

$$\dim V = \dim S + \dim S^\circ$$

Proof. Let $\mathcal{B}_0 = \{v_1, \dots, v_k\}$ be a basis for S . Extend this to

$$\begin{aligned} \mathcal{B} &= \{v_1, \dots, v_n\} \text{ a basis for } V \\ \mathcal{B}_0 &= \{f_1, \dots, f_n\} \text{ the dual basis of } \mathcal{B} \end{aligned}$$

Claim 9.1. $\mathcal{C} := \{f_{k+1}, \dots, f_n\}$ is a basis for S° .

If we show this, the theorem follows. Let $f \in S^\circ$. Then

$$\begin{aligned} f &= \sum_{i=1}^n L_{v_i}(f) f_i = \sum_{i=1}^n f(v_i) f_i \\ &= \sum_{i=1}^k f(v_i) f_i + \sum_{i=k+1}^n f(v_i) f_i = \sum_{i=k+1}^n f(v_i) f_i \end{aligned}$$

lies in span \mathcal{C} so \mathcal{C} spans. As $\mathcal{C} \subseteq \mathcal{B}^*$ which is linearly indep., so is \mathcal{C} . This proves the claim. □

Corollary 9.3

Let V be a finite dimensional vector space over F , $S \subseteq V$ a subspace. Then $S = S^{\circ\circ}$.

Proof. As $S \subseteq S^{\circ\circ}$, it suffices to show $\dim S = \dim S^{\circ\circ}$. By the theorem, we have

$$\begin{aligned}\dim V &= \dim S + \dim S^\circ \\ \dim V^* &= \dim S^\circ + \dim S^{\circ\circ}\end{aligned}$$

where $\dim V = \dim V^*$. So $\dim S = \dim S^{\circ\circ}$. \square

Remark 9.4. If V is an inner product space over \mathbb{R} , compare all this to $\emptyset \neq S \subseteq V$ a subset and $S^\perp, S^{\perp\perp}$.

§9.2 The Transpose

Construction: Fix $T : V \rightarrow W$ linear. For every $S : W \rightarrow X$, we have a composition

$$S \circ T : V \rightarrow X \text{ is linear}$$

So $T : V \rightarrow W$ linear induces a map

$$T^* : L(W, X) \rightarrow L(V, X)$$

by

$$S \mapsto S \circ T$$

Proposition 9.5

Let V, W, X be vector spaces over F , $T : V \rightarrow W$ linear. Then

$$T^* : L(W, X) \rightarrow L(V, X)$$

is linear.

Proof. Let $S_1, S_2 \in L(W, X)$, $\alpha \in F$. Then

$$\begin{aligned}T^*(\alpha S_1 + S_2) &= (\alpha S_1 + S_2) \circ T \\ &= \alpha S_1 \circ T + S_2 \circ T = \alpha T^* S_1 + T^* S_2\end{aligned}$$

\square

Corollary 9.6

Let $T : V \rightarrow W$ be linear. Then

$$T^* : W^* \rightarrow V^* \text{ by } f \mapsto f \circ T$$

is linear.

Proof. Let $X = F$ in the proposition. \square

Definition 9.7 (Transpose) — Let $T : V \rightarrow W$ be linear. The linear map $T^* : W^* \rightarrow V^*$ in the corollary is called the transpose of T and denoted by T^\top .

Note: The transpose “turns thing around”

$$\begin{array}{ccc} V & \xrightarrow{T} & W \\ V^* & \xleftarrow{T^\top} & W^* \end{array}$$

Lemma 9.8

Let $T : V \rightarrow W$ be linear. Then

$$\ker T^\top = (\operatorname{im} T)^\circ \in W^*$$

Proof. $g \in \ker T^\top \iff T^\top g = 0 \iff (T^\top g)(v) = 0 \forall v \in V \iff (g \circ T)(v) = 0 \forall v \in V \iff g(Tv) = 0 \forall v \in V \iff g \in (\operatorname{im} T)^\circ$. \square

Theorem 9.9

Let V, W be finite dimensional vector space over F , $T : V \rightarrow W$ linear. Then

$$\dim \operatorname{im} T = \dim \operatorname{im} T^\top$$

Proof. Consider:

$$\begin{aligned} \dim W^* &= \dim \ker T^\top + \dim \operatorname{im} T^\top \\ \dim W &= \dim \operatorname{im} T + \dim (\operatorname{im} T)^\circ \end{aligned}$$

Notice that $\dim W^* = \dim W$. By the lemma, $\dim \operatorname{im} T = \dim \operatorname{im} T^\top$. \square

Computation: Let V, W be finite dimensional vector space over F .

$\mathcal{B}, \mathcal{B}^*$ ordered dual bases for V, V^*
 $\mathcal{C}, \mathcal{C}^*$ ordered dual bases for W, W^*

Suppose

$$\begin{aligned} \mathcal{B} &= \{v_1, \dots, v_n\}, \quad \mathcal{B}^* = \{f_1, \dots, f_n\} \\ f_i(v_j) &= \delta_{ij} \quad \forall i, j \end{aligned}$$

So

$$\begin{aligned} \mathcal{C} &= \{w_1, \dots, w_n\}, \quad \mathcal{C}^* = \{g_1, \dots, g_n\} \\ g_i(w_j) &= \delta_{ij} \quad \forall i, j \end{aligned}$$

Let

$$A = [T]_{\mathcal{B}, \mathcal{C}}, \quad B = [T^\top]_{\mathcal{C}^*, \mathcal{B}^*}$$

be the matrix representation of T, T^\top in the ordered bases \mathcal{B}, \mathcal{C} and $\mathcal{C}^*, \mathcal{B}^*$ respectively. By definition of A and B , we have

$$Tv_k = \sum_{i=1}^m A_{ik} w_i \quad k = 1, \dots, n$$

$$T^\top g_j = \sum_{i=1}^n B_{ij} f_i \quad j = 1, \dots, m$$

So

$$B_{kj} = A_{jk} \quad \forall j, k$$

So we just proved...

Theorem 9.10

Let V, W be finite dimensional vector space over F , $T : V \rightarrow W$ linear, $\mathcal{B}, \mathcal{B}^*$ ordered dual bases for V, V^* and $\mathcal{C}, \mathcal{C}^*$ ordered dual bases for W, W^* . Then

$$[T^\top]_{\mathcal{C}^*, \mathcal{B}^*} = ([T]_{\mathcal{B}, \mathcal{C}})^\top$$

Definition 9.11 (Row/Column Rank) — Let $A \in F^{m \times n}$. The row (column) rank of A is the dimension of the span of the rows (columns) of A .

We know if $A \in F^{m \times n}$, we can view

$$A : F^{n \times 1} \rightarrow F^{m \times 1} \text{ by } v \mapsto A \cdot v$$

a linear transformation and the matrix representation of A is

$$A = [A]_{\mathcal{E}_{n,1}, \mathcal{E}_{m,1}}$$

where $\mathcal{E}_{n,1}, \mathcal{E}_{m,1}$ are the standard bases for $F^{n \times 1}$ and $F^{m \times 1}$ respectively.

Corollary 9.12

Let $A \in F^{m \times n}$. Then

$$\text{row rank } A = \text{column rank } A$$

and we call this common number the rank of A .

§9.3 Polynomials

Definition 9.13 (Polynomial Division) — Let $f, g \in F[t]$, $f \neq 0$. We say that f divides $g \in F[t]$ write $f|g$ if $\exists h \in F[t]$ s.t. $g = fh$, i.e. g is multiple of f , e.g. $t+1|t^2-1$.

Lemma 9.14

If $f|g$ and $f|h$ in $F[t]$, then $f|gk + hl$ in $F[t]$ for all $k, l \in F[t]$.

Proof. By definition,

$$g = fg_1, \quad h = fh_1, \quad g_1, h_1 \in F[t]$$

So

$$gk + hl = fg_1k + fh_1l = f(g_1k + h_1l)$$

in $F[t]$. □

Remark 9.15. If $f|g \in F[t]$ and $0 \neq a \in F$, then $af|g$ and $f|ag$.

Definition 9.16 (Polynomial Degree and Leading Coefficient) — Let

$$0 \neq f = at^n + a_{n-1}t^{n-1} + \dots + a_1t + a_0 \in F[t]$$

with $a, a_0, \dots, a_{n-1} \in F$ and $a \neq 0$. We call n the degree of f write $\deg f = n$ and a the leading coefficient of F write $\text{lead } f = a$. If $a = 1$, we say f is monic.

We can define the degree of $0 \in F[t]$ to be the symbol $-\infty$ or just do not define it at all.

Remark 9.17. Let $f, g \in F[t] \setminus \{0\}$. Then

$$\text{lead}(fg) = \text{lead}(f) \cdot \text{lead}(g) \neq 0 \in F$$

So

$$\deg(fg) = \deg f + \deg g$$

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§10.1 Polynomials (Cont'd)

Division Algorithm: Let $0 \neq f \in F[t]$, $g \in F[t]$. Then

$$\exists! q, r \in F[t]$$

satisfying

$$g = fq + r \quad \text{with} \quad r = 0 \quad \text{or} \quad \deg r < \deg f$$

Definition 10.1 (Greatest Common Divisor) — Let $f, g \in F[t] \setminus \{0\}$. We say d in $F[t]$ is a gcd (greatest common divisor) of f, g if

- i) d is monic.
- ii) $d|f$ and $d|g$ in $F[t]$.
- iii) if $e|f$ and $e|g$ in $F[t]$, then $e|d$ in $F[t]$.

Remark 10.2. If a gcd of f, g exists, then it is unique.

Remark 10.3. If $d = 1$ is a gcd of $f, g \in F[t]$, we say that f, g are relatively bear.

Remark 10.4. Compare the above with analogous in \mathbb{Z} .

Theorem 10.5

Let $f, g \in F[t] \setminus \{0\}$. Then a gcd of f, g exists and is unique write $\gcd(f, g)$ for the gcd of f, g . Moreover, we have an equation

$$d = fk + gl \in F[t] \quad \text{for some } k, l \in F[t] \quad (\star)$$

Proof. The existence and (\star) follow from the Euclidean Algorithm. Let $f, g \in F[t] \setminus \{0\}$. Then iteration of the Division Algorithm produces equations in $F[t]$, if $f + g \in F[t]$,

$$\begin{aligned} g &= q_1 f + r_1 & \deg r_1 < \deg f \\ f &= q_2 r_1 + r_2 & \deg r_2 < \deg r_1 \\ &\vdots \\ r_{n-3} &= q_{n-1} r_{n-2} + r_{n-1} & \deg r_{n-1} < \deg r_{n-2} \\ r_{n-2} &= q_n r_{n-1} + r_n & \deg r_{n-1} < \deg r_n \\ r_{n-1} &= q_{n+1} + r_n \end{aligned}$$

where r_n is the remainder of least degree ($r_n \neq 0$).

This must stop in $\leq \deg f$ steps. Plugging from the bottom up and using the lemma shows

$$r_n = fk + gl \in F[t]$$

and if $e|r_1 \rightarrow e|r_2 \rightarrow \dots \rightarrow e|r_n$ then $(\text{lead } r_n)^{-1}r_n$ is the gcd of f and g in $F[t]$ if $a = \text{lead } f$

$$a^{-1}r_n = a^{-1}fk + a^{-1}gl \quad \square$$

Definition 10.6 (Irreducible Polynomial) — $f \in F[t] \setminus F$ is called irreducible if there does not exist $g, h \in F[t] \ni f = gh$ with $\deg g, \deg h < \deg f$. Equivalently, if

$$f = gh \in F[t], \quad \text{then } 0 \neq g \in F \text{ or } 0 \neq h \in F$$

Example 10.7

If $f \in F[t]$, $\deg f = 1$, then f is irreducible.

Remark 10.8. If $f, g \in F[t] \setminus F$ with f irreducible, then either f and g are relatively prime or $f|g$ since only $a, af, 0 \neq a \in F$ can divide f .

Lemma 10.9 (Euclid)

Let $f \in F[t]$ be irreducible and $f|gh$ in $F[t]$. Then $f|g$ or $f|h$.

Proof. Suppose $f \nmid g$ where \nmid means does not divide. Then f and g are relatively prime. By the Euclidean Algorithm, there exists an equation

$$1 = fk + gl \in F[t]$$

Hence

$$h = fhk + gh \in F[t]$$

As $f|fhk$ and $f|gh$ in $F[t]$, $f|h$ by the lemma. \square

Remark 10.10. In \mathbb{Z} the analog of an irreducible element is called a prime element.

Remark 10.11. Euclid's lemma is the key idea. The “correct” generalization of “prime” is the conclusion of Euclid's lemma. This generalization is profound as, in general, there is difference between the two conditions “irreducible” and “prime”, although not for \mathbb{Z} or $F[t]$.

We know that any positive integer is a product of positive primes unique up to order n . If we allow $n < 0$ such is unique up to ± 1 .

Theorem 10.12 (Fundamental Theorem of Arithmetic (Polynomial Case))

Let $g \in F[t] \setminus F$. Then there exists uniquely $a \in F$, $r \in \mathbb{Z}^+$, $p_1, \dots, p_r \in F[t]$ distinct monic irreducible polynomial, $e_1, \dots, e_r \in \mathbb{Z}^+$ s.t. we have a factorization

$$g = ap_1^{e_1} \dots p_r^{e_r}$$

unique up to order.

Proof. (Sketch) Existence: We induct on $n = \deg g \geq 1$. If g is irreducible, $a, (\text{lead } g)^{-1}g$, $a = \text{lead } g$ work. If g is reducible,

$$g = fh \in F[t], \quad 1 < \deg f, \quad \deg h < \deg g$$

By induction, f, h have factorization hence we're done as $g = fh$.

Uniqueness: We induct on $n = \deg g \geq 1$. If

$$ap_1^{e_1} \dots p_r^{e_r} = g = bq_1^{f_1} \dots q_s^{f_s}$$

with p_i, q_i monic irreducible, $a, b \in F$, $e_i, f_j \in \mathbb{Z}^+$ for all i, j , $\deg q_1 \geq 1$, so $\deg q_1 \times a$. By Euclid's lemma

$$q_i | p_j \text{ for some } j$$

Changing notation, we may assume that $j = 1$. As p_1 is irreducible $p_1 = q_1$ and by (M3')

$$g_0 := ap_1^{e_1-1} p_2^{e_2} \dots p_r^{e_r} = bq_1^{f_1-1} q_2^{f_2} \dots q_s^{f_s}$$

As $\deg g_0 < \deg g$, induction yields

$$r = s, e_1 - 1 = f_1 - 1, e_i = f_i, i > 1, a = b = \text{lead } g_0, p_i = q_i \forall i, e_i = f_i \forall i \quad \square$$

Remark 10.13. Applying the Euclidean Algorithm is relatively fast to compute, (for $f|g$ takes $\leq \deg f$ steps to get a gcd). Factoring into the irreducible is not.

§11 | Lec 11: Apr 21, 2021

§11.1 Minimal Polynomials

We use the following theorem from 115A, [Matrix Theory Theorem](#).

Remark 11.1. Let $T : V \rightarrow V$ be linear. If $f = a_n t^n + \dots + a_1 t + a_0 \in F[t]$, we can plug T in for t to get

$$f(T) = a_n T^n + \dots + a_1 T + a_0 1_V \in L(V, V)$$

More precisely

$$e_T : F[t] \rightarrow L(V, V) \text{ by } t \mapsto T$$

i.e. $f = \sum a_i t^i \mapsto f(T) = \sum a_i T^i$ is a ring homomorphism. Since we have

$$T^n = \underbrace{T \circ \dots \circ T}_n, \quad n \geq 0$$

Can we use the remark if V is a finite dimensional vector space over F ?

Lemma 11.2

Let V be a finite dimensional vector space over F , $f, g, h \in F[t]$, \mathcal{B} an ordered basis for V , $T : V \rightarrow V$ linear. Then

1. $[g(T)]_{\mathcal{B}} = g([T]_{\mathcal{B}})$
2. If $f = gh \in F[t]$, then

$$f(T) = g(T)h(T)$$

Proof. • By [MTT](#), if $g = \sum_{i=0}^n a_i t^i \in F[t]$, then

$$\begin{aligned} [g(T)]_{\mathcal{B}} &= \left[\sum_{i=0}^n a_i T^i \right]_{\mathcal{B}} = \sum_{i=0}^n a_i [T^i]_{\mathcal{B}} \\ &= \sum_{i=0}^n a_i [T]_{\mathcal{B}}^i = g([T]_{\mathcal{B}}) \end{aligned}$$

- Left as exercise. □

Lemma 11.3

Let V be a finite dimensional vector space over F , $T : V \rightarrow V$ linear. Then $\exists q \in F[t] \setminus \{0\}$ $q(T) = 0$ and if $a = \text{lead } q$, then $q_0 := a^{-1}q$ is monic and satisfies $q_0(T) = 0$

$$q \in \ker e_T := \{f \in F[t] \mid f(T) = 0\}$$

Proof. Let $n = \dim V$. By [MTT](#)

$$\dim L(V, V) = \dim \mathbb{M}_n F = n^2 < \infty$$

So

$$1_V, T, T^2, \dots, T^{n^2} \in L(V, V)$$

are linearly dependent. So $\exists a_0, \dots, a_{n^2} \in F$ not all 0 s.t.

$$\sum_{i=0}^{n^2} a_i T^i = 0$$

Then $q = \sum_{i=0}^{n^2} a_i t^i$ works. □

Theorem 11.4

Let V be a finite dimensional vector space over F , $T : V \rightarrow V$ linear. Then $\exists! 0 \neq q_T \in F[t]$ monic called the minimal polynomial of T having the following properties:

1. $q_T(T) = 0$
2. If $g \in F[t]$ satisfies $g(T) = 0$, then $q_T | g \in F[t]$. In particular, if $0 \neq g \in F[t]$ satisfies $g(T) = 0$, then $\deg g \geq \deg q_T$ and if $\deg g = \deg q_T$, then $g = (\text{lead } g)q_T$

Proof. By the lemma, $\exists 0 \neq q \in F[t]$ monic s.t. $q(T) = 0$. Among all such q , choose one with $\deg q$ minimal.

Claim 11.1. q works.

Let $g \neq 0$ in $F[t]$ satisfy $g(T) = 0$. To show $q | g \in F[t]$. Write $g = qh + r$ in $F[t]$ with $r = 0$ or $\deg r < \deg q$. Then

$$0 = g(T) = q(T)h(T) + r(T) = r(T)$$

If $r \neq 0$, then $r_0 = (\text{lead } r)^{-1}r$ is a monic poly satisfying $r_0(T) = 0$, $\deg r_0 < \deg q$, contradicting the minimality of $\deg q$. So $r = 0$ and $q | g \in F[t]$. If q' also satisfies 1) and 2), then

$$q | q' \text{ and } q' | q \in F[t] \text{ both monic so } q = q'$$

The last statement follows as if

$$h, g \in F[t], \quad g | h, h \neq 0, \text{ then } \deg h \geq \deg g$$
□

Corollary 11.5

Let V be a finite dimensional vector space over F , \mathcal{B} an ordered basis for V_1 and $T : V \rightarrow V$ linear. Then

$$q_T = q_{[T]_{\mathcal{B}}}$$

In particular, if $A, B \in \mathbb{M}_n F$ are similar write $A \sim B$. Then

$$q_A = q_B$$

Proof. $q_T = q_{[T]_{\mathcal{B}}}$ by MTT and the first lemma. □

Note: By the theorem, if V is a finite dimensional vector space over F , $g \in F[t]$, $g \neq 0$, and $\deg g < \deg q_T$, then $q(T) \neq 0$.

Goal: Let V be a finite dimensional vector space over F , \mathcal{B} an ordered basis of V , $T : V \rightarrow V$ linear. Call

$$tI - [T]_{\mathcal{B}} \text{ the characteristics matrix of } T \text{ relative to } \mathcal{B}$$

Recall the characteristics polynomial f_T of T is defined to be

$$f_T := f_{[T]_{\mathcal{B}}} = \det(tI - [T]_{\mathcal{B}}) \in F[t]$$

We want to show f_T satisfies the

Theorem 11.6 (Cayley-Hamilton)

If V is a finite dimensional vector space over F , $T : V \rightarrow V$ linear, then

$$q_T | f_T, \quad \text{hence } f_T(T) = 0$$

In particular, $\deg q_T \leq \deg f_T$.

Remark 11.7. 1. There exists a determinant proof of this – essentially Cramer's rule.

2. A priori we only know $\deg q_T \leq n^2$, where $n = \dim V$.

3. f_T is independent of \mathcal{B} depends on properties of $\det : \mathbb{M}_n F[t] \rightarrow F[t]$

$$\begin{aligned} \det(tI - A) &= \det(P(tI - A)P^{-1}) \\ &= \det(tI - PAP^{-1}) \end{aligned}$$

for each $P \in GL_n F$

Proposition 11.8

Let V be a finite dimensional vector space over F , $T : V \rightarrow V$ linear. Then q_T and f_T have the same roots in F , the eigenvalues of T .

Proof. Let λ be a root of q_T . To show λ is an eigenvalue of T , i.e., a root of f_T . As λ is a root of q_T , using the Division Algorithm that

$$q_T = (t - \lambda)h \in F[t]$$

So

$$0 = q_T(T) = (T - \lambda 1_V)h(T)$$

As

$$0 \leq \deg h < \deg q_T, \quad \text{we have } h(T) \neq 0$$

Since $h(T) \neq 0 \exists 0 \neq v \in V$ s.t.

$$w = h(T)v \neq 0$$

Then

$$0 = q_T(T)v = (T - \lambda 1_V)h(T)v = (T - \lambda 1_V)w$$

So $0 \neq w \in E_T(\lambda)$ and λ is an eigenvalue of T .

Conversely, suppose λ is a root of f_T so an eigenvalue of T . Let $0 \neq v \in E_T(\lambda)$. Then $t - \lambda \in F[t]$ satisfies $(T - \lambda)w = 0$ for all $w \in Fv$, i.e. it is the minimal poly of $T|_{Fv} : Fv \rightarrow Fv$. But $q_T(T) = 0$ on V so $t - \lambda | q_T$ by the definition that $t - \lambda$ is the minimal poly of $T|_{Fv}$. \square

§11.2 Algebraic Aside

Let V be a finite dimensional vector space over F , $T : V \rightarrow V$ linear. The minimality poly q_T of T is algebraically more interesting than f_T . Recall we have a ring homomorphism

$$e_T : F[t] \rightarrow L(V, V)$$

given by

$$\sum a_i t^i \mapsto \sum a_i T^i$$

so e_T is not only a linear transformation but a ring homomorphism, i.e., it also follows that

$$(fg)(T) = f(T)g(T) \quad \forall f, g \in F[t]$$

We know that

$$\dim_F F[t] = \infty$$

which has $\{1, t, \dots, t^n, \dots\}$ is a basis for $F[t]$ and

$$\dim_F L(V, V) = (\dim V)^2 < \infty$$

by MTT. So

$$0 < \ker e_T := \{f \in F[t] \mid e_T f = f(T) = 0\}$$

is a vector space over F and a subspace of $F[t]$. This induces a linear transformation

$$\bar{e}_T : V / \ker e_T \rightarrow \text{im } e_T = F[T]$$

which is an isomorphism. If $\bar{V} = V / \ker T$, we have

$$\begin{aligned} \bar{e}_T \left(\overline{\sum a_i t^i} \right) &= \overline{e_T \left(\sum a_i t^i \right)} = \sum \bar{a}_i \bar{T}^i \\ &= \sum a_i \bar{T}^i = \sum a_i T^i \end{aligned}$$

Check that \bar{e}_T is also a ring isomorphism onto $\text{im } e_T$. By definition, if $f(T) = 0$, $f \in F[t]$, then

$$q_T | f \in F[t]$$

It follows that

$$\ker e_T = \{q_T g \mid g \in F[t]\} \subseteq F[t]$$

called an ideal in the ring $F[t]$.

The first isomorphism of rings gives rise to $\ker e_T$ which quotient isomorphic to $F[t] \subseteq L(V, V)$. So we are at a higher level of algebra. Then this allows us to view $F[t]$ as acting on V , i.e. there exists a map

$$F[t] \times V \rightarrow V \quad (*)$$

by

$$\begin{aligned} f \cdot v &:= f(T)v \\ q_T(T) &= 0 \end{aligned}$$

This turns V into what is called an $F[t]$ -module, i.e., V via (*) satisfies the axioms of a vector space over F but the scalars $F[t]$ are now a ring rather than only a field.

§12 | Lec 12: Apr 23, 2021

§12.1 Triangularizability

Proposition 12.1

Let V be a finite dimensional vector space over F , $T : V \rightarrow V$ linear, $W \subseteq V$ a T -invariant subspace. Then T induces a linear transformation

$$\bar{T} : V/W \rightarrow V/W \text{ by } \bar{T}(\bar{v}) := \overline{T(v)}$$

where $\bar{v} = W + v$, $\bar{V} = V/W$ and

$$q_{\bar{T}} | q_T \in F[t]$$

Proof. By the hw, we need only to prove that

$$q_{\bar{T}} | q_T \in F[t]$$

But also by the hw,

$$q_T(\bar{T}) = \overline{q_T(T)}$$

As $q_T(T) = 0$,

$$0 = \overline{q_T(T)} = q_T(\bar{T})$$

so

$$q_{\bar{T}} | q_T$$

by the defining property of $q_{\bar{T}}$. □

Definition 12.2 (Triangularizability) — Let V be a finite dimensional vector space over F , $T : V \rightarrow V$ linear. We say T is triangularizable if \exists an ordered basis \mathcal{B} for V s.t. $A = [T]_{\mathcal{B}}$ satisfies $A_{ij} = 0 \ \forall i < j$, i.e.

$$A = \begin{pmatrix} * & & 0 \\ & \ddots & \\ * & & * \end{pmatrix} \text{ is lower triangular} \quad (*)$$

Note: If $\mathcal{B} = \{v_1, \dots, v_n\}$ in $(*)$ and $\mathcal{C} = \{v_n, v_{n-1}, \dots, v_1\}$, then

$$[T]_{\mathcal{C}} = \begin{pmatrix} * & & * \\ & \ddots & \\ 0 & & * \end{pmatrix} \text{ is upper triangular}$$

Hence, by [Change of Basis Theorem](#),

$$[T]_{\mathcal{B}} \sim [T]_{\mathcal{C}}$$

Remark 12.3. Suppose V is a finite dimensional vector space over F , $\dim V = n$, $T : V \rightarrow V$ linear, \mathcal{B} an ordered basis for V , $A = [T]_{\mathcal{B}}$ is triangular (upper or lower). Then

$$f_T = (t - A_{11}) \dots (t - A_{nn}) \in F[t]$$

and A_{11}, \dots, A_{nn} are all the eigenvalues of T (not necessarily distinct) and hence roots of q_T .

Definition 12.4 (Splits) — We say $g \in F[t] \setminus F$ splits in $F[t]$ if g is a product of linear polys in $F[t]$, i.e.,

$$g = (\text{lead } g)(t - \alpha_1) \dots (t - \alpha_n) \in F[t]$$

Example 12.5

If V is a finite dimensional vector space over F , $T : V \rightarrow V$ linear and T is triangularizable, then f_T splits in $F[t]$.

Note: $\begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \in \mathbb{M}_2\mathbb{R}$ is not triangularizable as it has no eigenvalues.

Theorem 12.6

Let V be a finite dimensional vector space over F , $T : V \rightarrow V$ linear. Then T is triangularizable if and only if q_T splits in $F[t]$.

Proof. “ \implies ” We induct on $n = \dim V$.

$n = 1$: It's obvious.

$n > 1$: We proceed by induction: let λ be a root of q_T in F (q_T splits in $F[t]$). Then λ is a root of q_T hence an eigenvalue of T . Let $0 \neq v_n \in E_T(\lambda)$, so $W = Fv_n$ is T -invariant. By the Proposition, T induces a linear map

$$\overline{T} : V/W \rightarrow V/W \text{ by } \overline{v} \mapsto \overline{T(v)}$$

and

$$q_{\overline{T}} | q_T \in F[t]$$

We also know that

$$W = \ker(- : V \rightarrow V/W) \text{ by } v \mapsto \overline{v}$$

and

$$\dim V/W = \dim V - \dim W = n - 1$$

as $- : v \rightarrow \overline{v}$ is epic. Since q_T splits in $F[t]$ and $q_{\overline{T}} | q_T$ in $F[t]$, $q_{\overline{T}}$ also splits in $F[t]$ by **Fundamental Theorem of Algebra**. Thus, by induction,

$$\exists v_1, \dots, v_{n-1} \in V \ni \mathcal{C} = \{\overline{v_1}, \dots, \overline{v_{n-1}}\}$$

is an ordered basis for $\overline{V} = V/W$ with $A = [\overline{T}]_{\mathcal{C}}$ is lower triangular, i.e., $A_{ij} = 0$ if $i < j \leq n - 1$. Thus

$$\overline{T}\overline{v_j} = \sum_{i=j}^{n-1} A_{ij}\overline{v_i}, \quad 1 \leq j \leq n - 1$$

hence

$$0 = \overline{T}\overline{v}_j - \sum_{i=j}^{n-1} A_{ij}\overline{v}_i = \overline{Tv_j - \sum_{i=j}^{n-1} A_{ij}v_i}$$

$1 \leq j \leq n-1$ in $\overline{V} = V/W$. Therefore,

$$Tv_j - \sum_{i=j}^{n-1} A_{ij}v_i \in \ker^- = W = Fv_n$$

by definition as $W = \ker^- : V \rightarrow V/W$.

In particular, $\exists A_{nj} \in F$, $1 \leq j \leq n-1$ satisfying

$$Tv_j - \sum_{i=j}^{n-1} A_{ij}v_i = A_{nj}v_n$$

So

$$Tv_j = \sum_{i=j}^n A_{ij}v_n \quad 1 \leq j \leq n-1$$

By choice, $A_{ij} = 0$, $i < j \leq n-1$ and

$$Tv_n = \lambda v_n$$

By hw 2 # 3, $\mathcal{B} = \{v_1, \dots, v_n\}$ is an ordered basis for V and

$$[T]_{\mathcal{B}} = \begin{pmatrix} [T]_{\mathcal{C}} & 0 \\ & \vdots \\ & 0 \\ A_{n1} \dots A_{n,n-1} & \lambda \end{pmatrix}$$

which is lower triangular, as needed. “ \implies ” Let $\mathcal{B} = \{v_1, \dots, v_n\}$ be an ordered basis for V . $A = [T]_{\mathcal{B}}$ is lower triangular. Then

$$f_T = \prod_{i=1}^n (t - A_{ii}) \text{ splits in } F[t]$$

A_{11}, \dots, A_{nn} are the (not necessarily distinct) eigenvalues of T and hence roots of q_T .

Let $\lambda_i = A_{ii}$, $i = 1, \dots, n$. We have

$$Tv_j = \sum_{i=1}^n A_{ij}v_i = \lambda_j v_j + \sum_{i=j+1}^n A_{ij}v_i, \quad 1 \leq j \leq n-1$$

$$Tv_n = \lambda_n v_n$$

So

$$(T - \lambda_j 1_V)v_j = \sum_{i=j+1}^n A_{ij}v_i \in \text{Span}(v_{j+1}, \dots, v_n) \quad \forall 1 \leq j \leq n-1 \quad (*)$$

Now

$$(T - \lambda_n 1_V)v_n = 0$$

So

$$(T - \lambda_n 1_V)v_{n-1} \in \text{Span}(v_n) \text{ by } (*)$$

This implies

$$(T - \lambda_n 1_V)(T - \lambda_{n-1} 1_V)v_{n-1} = 0$$

By induction, we may assume that

$$(T - \lambda_n 1_V) \dots (T - \lambda_j 1_V)v_j = 0$$

So by (*),

$$(T - \lambda_n 1_V) \dots (T - \lambda_j 1_V)(T - \lambda_{j-1} 1_V)v_{j-1} = 0$$

Therefore,

$$f_T(T)v_i = (T - \lambda_n 1_V) \dots (T - \lambda_i 1_V)v_i = 0$$

for $i = 1, \dots, n$. As \mathcal{B} is a basis for V , $f_T(T) = 0$. Thus $q_T | f_T \in F[t]$. In particular, q_T splits in $F[t]$. \square

Corollary 12.7

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

$$q_T | f_T \in F[t]$$

In particular,

$$f_T(T) = 0$$

Definition 12.8 (Algebraically Closed) — A field F is called algebraically closed if every $f \in F[t] \setminus F$ splits in $F[t]$. Equivalently, $f \in F[t] \setminus F$ has a root in F .

Corollary 12.9 (Cayley-Hamilton – Special Case)

Let F be algebraically closed, V a finite dimensional vector space over F , $T : V \rightarrow V$ linear. Then

1. T is triangularizable.
2. $q_T | f_T$
3. $f_T(T) = 0$

Theorem 12.10 (Fundamental Theorem of Algebra)

(FTA) \mathbb{C} is algebraically closed.

Proof. It's assumed (proven in 132 – Complex Analysis or 110C – Algebra). \square