

Chapter 1

Linear algebra: concepts and examples

1.1 Vector spaces

Definition. A *vector space* V over a *field* \mathbb{F} is a set V with two operations:

addition $V \times V \rightarrow V : (v, w) \mapsto v + w$ with respect to which V is an abelian group:

- $v + w = w + v$, for all $v, w \in V$;
- $u + (v + w) = (u + v) + w$, for all $u, v, w \in V$;
- there is a *zero element* $0 \in V$ for which $v + 0 = v = 0 + v$, for all $v \in V$;
- each element $v \in V$ has an *additive inverse* $-v \in V$ for which $v + (-v) = 0 = (-v) + v$.

scalar multiplication $\mathbb{F} \times V \rightarrow V : (\lambda, v) \mapsto \lambda v$ such that

- $(\lambda + \mu)v = \lambda v + \mu v$, for all $v \in V, \lambda, \mu \in \mathbb{F}$.
- $\lambda(v + w) = \lambda v + \lambda w$, for all $v, w \in V, \lambda \in \mathbb{F}$.
- $(\lambda\mu)v = \lambda(\mu v)$, for all $v \in V, \lambda, \mu \in \mathbb{F}$.
- $1v = v$, for all $v \in V$.

We call the elements of \mathbb{F} *scalars* and those of V *vectors*.

1.2 Subspaces

Definition. A *vector* (or *linear*) *subspace* of a vector space V over \mathbb{F} is a non-empty subset $U \subseteq V$ which is closed under addition and scalar multiplication: whenever $u, u_1, u_2 \in U$ and $\lambda \in \mathbb{F}$, then $u_1 + u_2 \in U$ and $\lambda u \in U$.

In this case, we write $U \leq V$.

Say that U is *trivial* if $U = \{0\}$ and *proper* if $U \neq V$.

1.3 Bases

Definitions. Let v_1, \dots, v_n be a list of vectors in a vector space V .

(1) The *span* of v_1, \dots, v_n is

$$\text{span}\{v_1, \dots, v_n\} := \{\lambda_1 v_1 + \dots + \lambda_n v_n \mid \lambda_i \in \mathbb{F}, 1 \leq i \leq n\} \leq V.$$

(2) v_1, \dots, v_n *span* V (or *are a spanning list for* V) if $\text{span}\{v_1, \dots, v_n\} = V$.

(3) v_1, \dots, v_n are *linearly independent* if, whenever $\lambda_1 v_1 + \dots + \lambda_n v_n = 0$, then each $\lambda_i = 0$, $1 \leq i \leq n$, and *linearly dependent* otherwise.

(4) v_1, \dots, v_n is a *basis* for V if they are linearly independent and $\text{span } V$.

Definition. A vector space is *finite-dimensional* if it admits a finite list of vectors as basis and *infinite-dimensional* otherwise.

If V is finite-dimensional, the *dimension* of V , $\dim V$, is the number of vectors in a (any) basis of V .

Proposition 1.1 (Algebra 1B, Proposition 1.3.4). v_1, \dots, v_n is a basis for V if and only if any $v \in V$ can be written in the form

$$v = \lambda_1 v_1 + \dots + \lambda_n v_n \tag{1.1}$$

for unique $\lambda_1, \dots, \lambda_n \in \mathbb{F}$. In this case, $(\lambda_1, \dots, \lambda_n)$ is called the coordinate vector of v with respect to v_1, \dots, v_n .

1.3.1 Standard bases

Proposition 1.2. For \mathcal{I} a set and $i \in \mathcal{I}$, define $e_i \in \mathbb{F}^{\mathcal{I}}$ by

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

for all $j \in \mathcal{I}$.

If \mathcal{I} is finite then $(e_i)_{i \in \mathcal{I}}$ is a basis, called the standard basis, of $\mathbb{F}^{\mathcal{I}}$.

In particular, $\dim \mathbb{F}^{\mathcal{I}} = |\mathcal{I}|$.

1.3.2 Useful facts

Proposition 1.3 (Algebra 1B, Corollary 1.4.7). Any linearly independent list of vectors in a finite-dimensional vector space can be extended to a basis.

Lemma 1.4 (Algebra 1B, Corollary 1.4.6). Let V be a finite-dimensional vector space and $U \leq V$. Then

$$\dim U \leq \dim V$$

with equality if and only if $U = V$.

1.4 Linear maps

Definitions. A map $\phi : V \rightarrow W$ of vector spaces over \mathbb{F} is a *linear map* (or, in older books, *linear transformation*) if

$$\begin{aligned} \phi(v + w) &= \phi(v) + \phi(w) \\ \phi(\lambda v) &= \lambda \phi(v), \end{aligned}$$

for all $v, w \in V$, $\lambda \in \mathbb{F}$.

The *kernel* of ϕ is $\ker \phi := \{v \in V \mid \phi(v) = 0\} \leq V$.

The *image* of ϕ is $\text{im } \phi := \{\phi(v) \mid v \in V\} \leq W$.

Definition. A linear map $\phi : V \rightarrow W$ is a (*linear*) *isomorphism* if there is a linear map $\psi : W \rightarrow V$ such that

$$\psi \circ \phi = \text{id}_V, \quad \phi \circ \psi = \text{id}_W.$$

If there is an isomorphism $V \rightarrow W$, say that V and W are isomorphic and write $V \cong W$.

Lemma 1.5 (Algebra 1B, lemma 1.2.3). $\phi : V \rightarrow W$ is an isomorphism if and only if ϕ is a linear bijection (and then $\psi = \phi^{-1}$).

1.4.1 Vector spaces of linear maps

Notation. For vector spaces V, W over \mathbb{F} , denote by $L_{\mathbb{F}}(V, W)$ (or simply $L(V, W)$) the set $\{\phi : V \rightarrow W \mid \phi \text{ is linear}\}$ of linear maps from V to W .

Theorem 1.6 (Linearity is a linear condition). $L(V, W)$ is a vector space under pointwise addition and scalar multiplication. Otherwise said, $L(V, W) \leq W^V$.

1.4.2 Linear maps and matrices

Definition. Let V, W be finite-dimensional vector spaces over \mathbb{F} with bases $\mathcal{B} : v_1, \dots, v_n$ and $\mathcal{B}' : w_1, \dots, w_m$ respectively. Let $\phi \in L(V, W)$. The *matrix of ϕ with respect to $\mathcal{B}, \mathcal{B}'$* is the matrix $A = (A_{ij}) \in M_{m \times n}(\mathbb{F})$ defined by:

$$\phi(v_j) = \sum_{i=1}^m A_{ij} w_i, \tag{1.2}$$

for all $1 \leq j \leq n$.

In the special case where $V = W$ and $\mathcal{B} = \mathcal{B}'$, we call A the *matrix of ϕ with respect to \mathcal{B}* .

1.4.3 Extension by linearity

Proposition 1.7 (Extension by linearity). Let V, W be vector spaces over \mathbb{F} . Let v_1, \dots, v_n be a basis of V and w_1, \dots, w_n any vectors in W .

Then there is a unique $\phi \in L(V, W)$ such that

$$\phi(v_i) = w_i, \quad 1 \leq i \leq n. \tag{1.3}$$

1.4.4 The rank-nullity theorem

Theorem 1.8 (Rank-nullity). Let $\phi : V \rightarrow W$ be linear with V finite-dimensional. Then

$$\dim \text{im } \phi + \dim \ker \phi = \dim V.$$

Proposition 1.9. Let $\phi : V \rightarrow W$ be linear with V, W finite-dimensional vector spaces of the same dimension: $\dim V = \dim W$.

Then the following are equivalent:

- (1) ϕ is injective.
- (2) ϕ is surjective.
- (3) ϕ is an isomorphism.

Chapter 2

Sums and quotients

Convention. In this chapter, all vector spaces are over the same field \mathbb{F} unless we say otherwise.

2.1 Sums of subspaces

Definition. Let $V_1, \dots, V_k \leq V$. The *sum* $V_1 + \dots + V_k$ is the set

$$V_1 + \dots + V_k := \{v_1 + \dots + v_k \mid v_i \in V_i, 1 \leq i \leq k\}.$$

Proposition 2.1. Let $V_1, \dots, V_k \leq V$. Then

- (1) $V_1 + \dots + V_k \leq V$.
- (2) If $W \leq V$ and $V_1, \dots, V_k \leq W$ then $V_1, \dots, V_k \leq V_1 + \dots + V_k \leq W$.

2.2 Direct sums

Definition. Let $V_1, \dots, V_k \leq V$. The sum $V_1 + \dots + V_k$ is *direct* if each $v \in V_1 + \dots + V_k$ can be written

$$v = v_1 + \dots + v_k$$

in only one way, that is, for unique $v_i \in V_i$, $1 \leq i \leq k$.

In this case, we write $V_1 \oplus \dots \oplus V_k$ instead of $V_1 + \dots + V_k$.

Proposition 2.2. Let $V_1, V_2 \leq V$. Then $V_1 + V_2$ is direct if and only if $V_1 \cap V_2 = \{0\}$.

Definition. Let $V_1, V_2 \leq V$. V is the (*internal*) *direct sum* of V_1 and V_2 if $V = V_1 \oplus V_2$.

In this case, say that V_2 is a *complement* of V_1 (and V_1 is a complement of V_2).

Proposition 2.3. Let $V_1, \dots, V_k \leq V$, $k \geq 2$. Then the sum $V_1 + \dots + V_k$ is direct if and only if for each $1 \leq i \leq k$, $V_i \cap (\sum_{j \neq i} V_j) = \{0\}$.

2.2.1 Direct sums and projections

Definition. Let V be a vector space. A linear map $\pi : V \rightarrow V$ is a *projection* if $\pi \circ \pi = \pi$.

Proposition 2.4. Let $V_1, V_2 \leq V$ with $V = V_1 \oplus V_2$. Then there are projections $\pi_1, \pi_2 : V \rightarrow V$ such that:

- (a) $\text{im } \pi_i = V_i$, $i = 1, 2$;

(b) $\ker \pi_1 = V_2$, $\ker \pi_2 = V_1$;

(c) $v = \pi_1(v) + \pi_2(v)$, for all $v \in V$. Otherwise said, $\text{id}_V = \pi_1 + \pi_2$.

Proposition 2.5. Let $V = V_1 \oplus V_2$ with V finite-dimensional. Then

$$\dim V = \dim V_1 + \dim V_2.$$

2.2.2 Induction from two summands

Lemma 2.6. Let $V_1, \dots, V_k \leq V$. Then $V_1 + \dots + V_k$ is direct if and only if $V_1 + \dots + V_{k-1}$ is direct and $(V_1 + \dots + V_{k-1}) \cap V_k = \{0\}$ (two summands) is direct.

Corollary 2.7. Let $V_1, \dots, V_k \leq V$ be subspaces of a finite-dimensional vector space V with $V_1 + \dots + V_k$ direct. Then

$$\dim V_1 \oplus \dots \oplus V_k = \dim V_1 + \dots + \dim V_k.$$

2.2.3 Direct sums and bases

Proposition 2.8. Let $V_1, V_2 \leq V$ be finite-dimensional subspaces with bases $\mathcal{B}_1 : v_1, \dots, v_k$ and $\mathcal{B}_2 : w_1, \dots, w_l$. Then $V_1 + V_2$ is direct if and only if the concatenation¹ $\mathcal{B}_1 \mathcal{B}_2 : v_1, \dots, v_k, w_1, \dots, w_l$ is a basis of $V_1 + V_2$.

Corollary 2.9. Let $V_1, \dots, V_k \leq V$ be finite-dimensional subspaces with \mathcal{B}_i a basis of V_i , $1 \leq i \leq k$. Then $V_1 + \dots + V_k$ is direct if and only if the concatenation $\mathcal{B}_1 \dots \mathcal{B}_k$ is a basis for $V_1 + \dots + V_k$.

2.2.4 Complements

Proposition 2.10 (Complements exist). Let $U \leq V$, a finite-dimensional vector space. Then there is a complement to U .

Proposition 2.11 (Extension of linear maps). Let V, W be vector spaces with V finite-dimensional. Let $U \leq V$ be a subspace and $\phi : U \rightarrow W$ a linear map. Then there is a linear map $\Phi : V \rightarrow W$ such that the restriction² of Φ to U is ϕ : $\Phi|_U = \phi$. Otherwise said: for all $u \in U$

$$\Phi(u) = \phi(u).$$

2.3 Quotients

Definition. Let $U \leq V$. Say that $v, w \in V$ are congruent modulo U if $v - w \in U$. In this case, we write $v \equiv w \pmod{U}$.

Lemma 2.12. Congruence modulo U is an equivalence relation.

Definition. For $v \in V$, $U \leq V$, the set $v + U := \{v + u \mid u \in U\} \subseteq V$ is called a coset of U and v is called a coset representative of $v + U$.

Definition. Let $U \leq V$. The quotient space V/U of V by U is the set V/U , pronounced “ $V \pmod{U}$ ”, of cosets of U :

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

This is a subset of the power set³ $\mathcal{P}(V)$ of V .

¹The concatenation of two lists is simply the list obtained by adjoining all entries in the second list to the first.

²Recall that if $f : X \rightarrow Y$ is a map of sets and $A \subseteq X$ then the restriction of f to A is the map $f|_A : A \rightarrow Y$ given by $f|_A(a) = f(a)$, for all $a \in A$.

³Recall from Algebra 1A that the power set of a set A is the set of all subsets of A .

The quotient map $q : V \rightarrow V/U$ is defined by

$$q(v) = v + U.$$

Theorem 2.13. Let $U \leq V$. Then, for $v, w \in V$, $\lambda \in \mathbb{F}$,

$$\begin{aligned}(v + U) + (w + U) &:= (v + w) + U \\ \lambda(v + U) &:= (\lambda v) + U\end{aligned}$$

give well-defined operations of addition and scalar multiplication on V/U with respect to which V/U is a vector space and $q : V \rightarrow V/U$ is a linear map.

Moreover, $\ker q = U$ and $\operatorname{im} q = V/U$.

Corollary 2.14. Let $U \leq V$. If V is finite-dimensional then so is V/U and

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

Theorem 2.15 (First Isomorphism Theorem). Let $\phi : V \rightarrow W$ be a linear map of vector spaces.

Then $V/\ker \phi \cong \operatorname{im} \phi$.

In fact, define $\bar{\phi} : V/\ker \phi \rightarrow \operatorname{im} \phi$ by

$$\bar{\phi}(q(v)) = \phi(v),$$

where $q : V \rightarrow V/\ker \phi$ is the quotient map.

Then $\bar{\phi}$ is a well-defined linear isomorphism.

Chapter 3

Polynomials, operators and matrices

3.1 Polynomials

Definitions. A polynomial in a variable x with coefficients in a field \mathbb{F} is a formal expression

$$p = \sum_{k=0}^{\infty} a_k x^k$$

with coefficients $a_k \in \mathbb{F}$ such that only finitely many a_k are non-zero.

Two polynomials are equal if all their coefficients are equal.

The zero polynomial has all coefficients zero.

The degree of a polynomial p is $\deg p = \max\{k \in \mathbb{N} \mid a_k \neq 0\}$. By convention, $\deg 0 = -\infty$.

The set of all polynomials in x with coefficients in \mathbb{F} is denoted $\mathbb{F}[x]$.

Definition. A polynomial is *monic* if its leading coefficient is 1:

$$p = a_0 + \cdots + x^n.$$

Theorem 3.1 (Algebra 1A, Proposition 3.10). *Let $p, q \in \mathbb{F}[x]$. Then there are unique $r, s \in \mathbb{F}[x]$ such that*

$$p = sq + r$$

with $\deg r < \deg q$.

Theorem 3.2 (Fundamental Theorem of Algebra). *Let $p \in \mathbb{C}[x]$ be a polynomial with $\deg p \geq 1$. Then p has a root. Thus there is $t \in \mathbb{C}$ with $p(t) = 0$.*

Theorem 3.3. *Let $p \in \mathbb{C}[x]$ and $\lambda_1, \dots, \lambda_k$ the distinct roots of p . Then*

$$p = a \prod_{i=1}^k (x - \lambda_i)^{n_i},$$

for some $a \in \mathbb{C}$ and $n_i \in \mathbb{Z}_+$, $1 \leq i \leq k$.

n_i is called the multiplicity of the root λ_i .

3.2 Linear operators and matrices

Definition. Let V be a vector space over \mathbb{F} . A linear operator on V is a linear map $\phi : V \rightarrow V$.

The vector space of linear operators on V is denoted $L(V)$ (instead of $L(V, V)$).

Notation. Write $M_n(\mathbb{F})$ for $M_{n \times n}(\mathbb{F})$.

Notation. For $\phi, \psi \in L(V)$ write $\phi\psi$ for $\phi \circ \psi \in L(V)$.

Similarly, write ϕ^n for the n -fold composition of ϕ with itself:

$$\phi^n = \underbrace{\phi \circ \cdots \circ \phi}_{n \text{ times}}$$

and define $\phi^0 := \text{id}_V$, $\phi^1 := \phi$.

Finally, for $A \in M_n(\mathbb{F})$, set $A^0 = I_n$, $A^1 = A$.

Definition. Let $p \in \mathbb{F}[x]$, $p = a_0 + \cdots + a_n x^n$, $\phi \in L(V)$ and $A \in M_n(\mathbb{F})$. Then $p(\phi) \in L(V)$ and $p(A) \in M_n(\mathbb{F})$ are given by:

$$p(\phi) := a_0 \text{id}_V + a_1 \phi + \cdots + a_n \phi^n = \sum_{k \in \mathbb{N}} a_k \phi^k,$$

$$p(A) := a_0 I_n + a_1 A + \cdots + a_n A^n = \sum_{k \in \mathbb{N}} a_k A^k.$$

Proposition 3.4. For $p, q \in \mathbb{F}[x]$, $\phi \in L(V)$ and $A \in M_n(\mathbb{F})$,

$$(p + q)(\phi) = p(\phi) + q(\phi) \qquad (p + q)(A) = p(A) + q(A) \qquad (3.1)$$

$$(pq)(\phi) = p(\phi)q(\phi) = q(\phi)p(\phi) \qquad (pq)(A) = p(A)q(A) = q(A)p(A). \qquad (3.2)$$

3.3 The minimum polynomial

Proposition 3.5. Let $A \in M_n(\mathbb{F})$. Then there is a monic polynomial $p \in \mathbb{F}[x]$ such that $p(A) = 0$.

Similarly, if $\phi \in L(V)$ is a linear operator on a finite-dimensional vector space over \mathbb{F} then there is a monic polynomial $p \in \mathbb{F}[x]$ with $p(\phi) = 0$.

Definition. A *minimum polynomial* for $\phi \in L(V)$, V a vector space over \mathbb{F} is a monic polynomial $p \in \mathbb{F}[x]$ of minimum degree with $p(\phi) = 0$: thus, if $r \in \mathbb{F}[x]$ has $r(\phi) = 0$ and $\deg r < \deg p$, then $r = 0$.

Similarly, a minimum polynomial for $A \in M_n(\mathbb{F})$ is a monic polynomial p of least degree with $p(A) = 0$.

Theorem 3.6. Let $\phi \in L(V)$ be a linear operator on a finite-dimensional vector space over a field \mathbb{F} . Then ϕ has a unique minimum polynomial.

Similarly, any $A \in M_n(\mathbb{F})$ has a unique minimum polynomial.

We denote these by m_ϕ and m_A respectively.

Proposition 3.7. Let $\phi \in L(V)$ be a linear operator on a finite-dimensional vector space over \mathbb{F} and $p \in \mathbb{F}[x]$.

Then $p(\phi) = 0$ if and only if m_ϕ divides p , that is, there is $s \in \mathbb{F}[x]$ such that $p = sm_\phi$.

3.4 Eigenvalues and the characteristic polynomial

Definitions. Let V be a vector space over \mathbb{F} and $\phi \in L(V)$.

An *eigenvalue* of ϕ is a scalar $\lambda \in \mathbb{F}$ such that there is a *non-zero* $v \in V$ with

$$\phi(v) = \lambda v.$$

Such a vector v is called an *eigenvector* of ϕ with *eigenvalue* λ .

The λ -*eigenspace* $E_\phi(\lambda)$ of ϕ is given by

$$E_\phi(\lambda) := \ker(\phi - \lambda \text{id}_V) \leq V.$$

Definition. Let V be a finite-dimensional vector space over \mathbb{F} and $\phi \in L(V)$.

The *characteristic polynomial* Δ_ϕ of ϕ is given by

$$\Delta_\phi(\lambda) := \det(\phi - \lambda \text{id}_V) = \det(A - \lambda I),$$

where A is the matrix of ϕ with respect to some (any!) basis of V .

Thus $\deg \Delta_\phi = \dim V$.

Lemma 3.8. A scalar $\lambda \in \mathbb{F}$ is an eigenvalue of ϕ if and only if λ is a root of Δ_ϕ .

Definitions. Let $\phi \in L(V)$ be a linear operator on a finite-dimensional vector space V over \mathbb{F} and λ an eigenvalue of ϕ . Then

- (1) The *algebraic multiplicity* of λ , $\text{am}(\lambda) \in \mathbb{Z}_+$, is the multiplicity of λ as a root of Δ_ϕ .
- (2) The *geometric multiplicity* of λ , $\text{gm}(\lambda) \in \mathbb{Z}_+$, is $\dim E_\phi(\lambda)$.

Theorem 3.9. Let ϕ be a linear operator on a finite-dimensional vector space V over \mathbb{C} . Then ϕ has an eigenvalue.

Proposition 3.10. Let $\phi \in L(V)$ be a linear operator on a vector space over a field \mathbb{F} and let $v \in V$ be an eigenvector of ϕ with eigenvalue λ :

$$\phi(v) = \lambda v. \tag{3.3}$$

Let $p \in \mathbb{F}[x]$. Then

$$p(\phi)(v) = p(\lambda)v,$$

so that v is an eigenvector of $p(\phi)$ also with eigenvalue $p(\lambda)$.

Corollary 3.11. Let ϕ be a linear operator on a finite-dimensional vector space V over \mathbb{F} . Then any eigenvalue of ϕ is a root of m_ϕ .

3.5 The Cayley–Hamilton theorem

Theorem 3.12 (Cayley–Hamilton¹ Theorem). Let $\phi \in L(V)$ be a linear operator on a finite-dimensional vector space over a field \mathbb{F} .

Then $\Delta_\phi(\phi) = 0$.

Equivalently, for any $A \in M_n(\mathbb{F})$, $\Delta_A(A) = 0$.

Corollary 3.13. Let $\phi \in L(V)$ be a linear operator on a finite-dimensional vector space over a field \mathbb{F} .

- (1) m_ϕ divides Δ_ϕ . Equivalently, m_A divides Δ_A , for any $A \in M_n(\mathbb{F})$.
- (2) The roots of m_ϕ are exactly the eigenvalues of ϕ .

¹Arthur Cayley, 1821–1895; William Rowan Hamilton, 1805–1865.

Chapter 4

The structure of linear operators

4.1 On normal forms

Definition. Matrices $A, B \in M_n(\mathbb{F})$ are *similar* if there is an invertible matrix $P \in M_n(\mathbb{F})$ such that

$$B = P^{-1}AP.$$

4.2 Invariant subspaces

Definition. Let ϕ be a linear operator on a vector space V . A subspace $U \subseteq V$ is ϕ -invariant if and only if $\phi(u) \in U$, for all $u \in U$.

Lemma 4.1. Let $\phi, \psi \in L(V)$ be linear operators and suppose that $\phi\psi = \psi\phi$ (say that ϕ and ψ commute). Then $\ker \psi$ and $\text{im } \psi$ are ϕ -invariant.

Definition. Let $V_1, \dots, V_k \leq V$ with $V = V_1 \oplus \dots \oplus V_k$ and let $\phi_i \in L(V_i)$, for $1 \leq i \leq k$.

Define $\phi : V \rightarrow V$ by

$$\phi(v) = \phi_1(v_1) + \dots + \phi_k(v_k),$$

where $v = v_1 + \dots + v_k$ with $v_i \in V_i$, for $1 \leq i \leq k$.

Call ϕ the *direct sum of the ϕ_i* and write $\phi = \phi_1 \oplus \dots \oplus \phi_k$.

Definition. Let A_1, \dots, A_k be square matrices with $A_i \in M_{n_i}(\mathbb{F})$. The *direct sum of the A_i* is

$$A_1 \oplus \dots \oplus A_k := \begin{pmatrix} A_1 & & & 0 \\ & \ddots & & \\ & & \ddots & \\ 0 & & & A_k \end{pmatrix} \in M_n(\mathbb{F}),$$

where $n = n_1 + \dots + n_k$.

A matrix of this type is said to be *block diagonal*.

Proposition 4.2. Let $V_1, \dots, V_k \leq V$ with $V = V_1 \oplus \dots \oplus V_k$ and let $\phi_i \in L(V_i)$, for $1 \leq i \leq k$. Let $\phi = \phi_1 \oplus \dots \oplus \phi_k$. Then

- (1) ϕ is linear so that $\phi \in L(V)$.
- (2) Each V_i is ϕ -invariant and $\phi|_{V_i} = \phi_i$, $1 \leq i \leq k$.
- (3) Let \mathcal{B}_i be a basis of V_i and ϕ_i have matrix A_i with respect to \mathcal{B}_i , $1 \leq i \leq k$. Then ϕ has matrix $A_1 \oplus \dots \oplus A_k$ with respect to the concatenated basis $\mathcal{B} = \mathcal{B}_1 \dots \mathcal{B}_k$.

Proposition 4.3. Let $V_1, \dots, V_k \leq V$ with $V = V_1 \oplus \dots \oplus V_k$ and let $\phi \in L(V)$. Suppose that each V_i is ϕ -invariant.

Then $\phi = \phi_1 \oplus \dots \oplus \phi_k$ where $\phi_i := \phi|_{V_i} \in L(V_i)$.

Proposition 4.4. Let $V_1, \dots, V_k \leq V$ with $V = V_1 \oplus \dots \oplus V_k$, $\phi_i \in L(V_i)$, $1 \leq i \leq k$ and $\phi = \phi_1 \oplus \dots \oplus \phi_k$.

Then:

- (1) $\ker \phi = \ker \phi_1 \oplus \dots \oplus \ker \phi_k$.
- (2) $\text{im } \phi = \text{im } \phi_1 \oplus \dots \oplus \text{im } \phi_k$.
- (3) $p(\phi) = p(\phi_1) \oplus \dots \oplus p(\phi_k)$, for any $p \in \mathbb{F}[x]$.
- (4) $\Delta_\phi = \prod_{i=1}^k \Delta_{\phi_i}$.

Proposition 4.5. Let $\phi \in L(V)$ be a linear operator on a finite-dimensional vector space over a field \mathbb{F} and let $\lambda_1, \dots, \lambda_k$ be the distinct eigenvalues of ϕ .

Then ϕ is diagonalisable if and only if

$$V = \bigoplus_{i=1}^k E_\phi(\lambda_i). \quad (4.1)$$

4.3 Jordan decomposition

4.3.1 Powers of operators and Fitting's Lemma

Proposition 4.6 (Increasing kernels, decreasing images). Let V be a vector space over a field \mathbb{F} and $\phi \in L(V)$. Then

- (1) $\ker \phi^k \leq \ker \phi^{k+1}$, for all $k \in \mathbb{N}$. That is,

$$\{0\} = \ker \phi^0 \leq \ker \phi \leq \ker \phi^2 \leq \dots$$

If $\ker \phi^k = \ker \phi^{k+1}$ then $\ker \phi^k = \ker \phi^{k+n}$, for all $n \in \mathbb{N}$.

- (2) $\text{im } \phi^k \geq \text{im } \phi^{k+1}$, for all $k \in \mathbb{N}$. That is,

$$V = \text{im } \phi^0 \geq \text{im } \phi \geq \text{im } \phi^2 \geq \dots$$

If $\text{im } \phi^k = \text{im } \phi^{k+1}$ then $\text{im } \phi^k = \text{im } \phi^{k+n}$, for all $n \in \mathbb{N}$.

Corollary 4.7. Let V be finite-dimensional with $\dim V = n$ and $\phi \in L(V)$. Then, for all $k \in \mathbb{N}$,

$$\begin{aligned} \ker \phi^n &= \ker \phi^{n+k} \\ \text{im } \phi^n &= \text{im } \phi^{n+k}. \end{aligned}$$

Theorem 4.8 (Fitting¹'s Lemma). Let $\phi \in L(V)$ be a linear operator on a finite-dimensional vector space over a field \mathbb{F} . Then, with $n = \dim V$, we have

$$V = \ker \phi^n \oplus \text{im } \phi^n.$$

4.3.2 Generalised eigenspaces

Definition. Let $\phi \in L(V)$ be a linear operator on a vector space over a field \mathbb{F} . A *generalised eigenvector* of ϕ with eigenvalue λ is $v \in V$ such that, for some $k \in \mathbb{N}$,

$$(\phi - \lambda \text{id})^k(v) = 0. \quad (4.2)$$

¹Hans Fitting, 1906–1938.

The set of all such is called the *generalised eigenspace of ϕ with eigenvalue λ* and denoted $G_\phi(\lambda)$. Thus

$$G_\phi(\lambda) = \{v \in V \mid (\phi - \lambda \text{id})^k(v) = 0, \text{ for some } k \in \mathbb{N}\} = \bigcup_{k \in \mathbb{N}} \ker(\phi - \lambda \text{id}_V)^k.$$

Lemma 4.9. $E_\phi(\lambda) \leq G_\phi(\lambda) \leq V$ and $G_\phi(\lambda)$ is ϕ -invariant.

Lemma 4.10. Let $\phi \in L(V)$ be a linear operator on a vector space over \mathbb{F} and $\lambda_1, \lambda_2 \in \mathbb{F}$ distinct eigenvalues of ϕ .

Then $G_\phi(\lambda_1) \cap G_\phi(\lambda_2) = \{0\}$.

Theorem 4.11 (Jordan² decomposition). Let $\phi \in L(V)$ be a linear operator on a finite-dimensional vector space over \mathbb{C} with distinct eigenvalues $\lambda_1, \dots, \lambda_k$. Then

$$V = \bigoplus_{i=1}^k G_\phi(\lambda_i).$$

Definition. A linear operator ϕ on a vector space V is *nilpotent* if $\phi^k = 0$, for some $k \in \mathbb{N}$. or, equivalently, if $\ker \phi^k = V$.

Proposition 4.12. Let $\phi \in L(V)$ be a linear operator on a finite-dimensional vector space V over \mathbb{F} .

Then ϕ is nilpotent if and only if there is a basis with respect to which ϕ has a strictly upper triangular matrix A (thus $A_{ij} = 0$ whenever $i \geq j$):

$$A = \begin{pmatrix} 0 & & & * \\ & \ddots & & \\ & & \ddots & \\ 0 & & & 0 \end{pmatrix}.$$

Proposition 4.13. Let $\lambda \in \mathbb{C}$ be an eigenvalue of a linear operator ϕ on a complex finite-dimensional vector space. Then

$$\text{am}(\lambda) = \dim G_\phi(\lambda).$$

Proposition 4.14. Let $\phi \in L(V)$ be a linear operator on a finite-dimensional vector space over \mathbb{C} with distinct eigenvalues $\lambda_1, \dots, \lambda_k$. Set $\phi_i = \phi|_{G_\phi(\lambda_i)}$. Then

- (1) Each $m_{\phi_i} = (x - \lambda_i)^{s_i}$, for some $s_i \leq \dim G_\phi(\lambda_i)$.
- (2) $m_\phi = \prod_{i=1}^k m_{\phi_i} = \prod_{i=1}^k (x - \lambda_i)^{s_i}$.

Corollary 4.15. Let $\phi \in L(V)$ be a linear operator with minimum polynomial $\prod_{i=1}^k (x - \lambda_i)^{s_i}$. Then

$$G_\phi(\lambda_i) = \ker(\phi - \lambda_i \text{id}_V)^{s_i}.$$

4.4 Jordan normal form

4.4.1 Jordan blocks

Definition. The *Jordan block of size $n \in \mathbb{Z}_+$ and eigenvalue $\lambda \in \mathbb{F}$* is $J(\lambda, n) \in M_n(\mathbb{F})$ with λ 's on the diagonal, 1's on the super-diagonal and zeros elsewhere. Thus

$$J(\lambda, n) = \begin{pmatrix} \lambda & 1 & 0 & \dots & 0 \\ & \lambda & 1 & \dots & 0 \\ & & \lambda & \dots & 0 \\ & & & \ddots & 1 \\ 0 & & & & \lambda \end{pmatrix}$$

²Camille Jordan, 1838–1922.

Notation. Set $J_n := J(0, n)$ so that $J(\lambda, n) = \lambda I_n + J_n$.

Lemma 4.16. Let v_1, \dots, v_n be a basis for a vector space V and $\phi \in L(V)$.

Then the following are equivalent:

- (1) ϕ has matrix J_n with respect to v_1, \dots, v_n .
- (2) $\phi(v_1) = 0$ and $\phi(v_i) = v_{i-1}$, for $2 \leq i \leq n$.
- (3) $v_i = \phi^{n-i}(v_n)$, $0 \leq i \leq n-1$ and $\phi^n(v_n) = 0$.

Theorem 4.17. Let $\phi \in L(V)$ be a nilpotent operator on a finite-dimensional vector space over \mathbb{F} . Then there are $v_1, \dots, v_k \in V$ and $n_1, \dots, n_k \in \mathbb{Z}_+$ such that

$$\phi^{n_1-1}(v_1), \dots, \phi(v_1), v_1, \dots, \phi^{n_k-1}(v_k), \dots, \phi(v_k), v_k$$

is a basis of V and $\phi^{n_i}(v_i) = 0$, for $1 \leq i \leq k$.

Corollary 4.18. Let $\phi \in L(V)$ be a nilpotent operator on a finite-dimensional vector space over \mathbb{F} . Then there is a basis for which ϕ has matrix $J_{n_1} \oplus \dots \oplus J_{n_k}$.

Proposition 4.19. Let $\phi \in L(V)$ be nilpotent with matrix $J_{n_1} \oplus \dots \oplus J_{n_k}$ for some basis of V . Then n_1, \dots, n_k are unique up to order. Indeed,

$$\#\{i \mid n_i \geq s\} = \dim \ker \phi^s - \dim \ker \phi^{s-1},$$

for each $s \geq 1$.

Proposition 4.20. In the situation of Proposition 4.19, we have

$$m_\phi = x^s,$$

where $s = \max\{n_1, \dots, n_k\}$.

4.4.2 Jordan normal form

Theorem 4.21. Let $\phi \in L(V)$ be a linear operator on a finite-dimensional vector space V over \mathbb{C} . Then there is a basis of V for which ϕ has as matrix a direct sum of Jordan blocks which are unique up to order.

Such a basis is called a Jordan basis and the direct sum of Jordan blocks is called the Jordan normal form (JNF) of ϕ .

Corollary 4.22. Let $\phi \in L(V)$ be a linear operator on a finite-dimensional vector space V over \mathbb{C} with distinct eigenvalues $\lambda_1, \dots, \lambda_k$. Then

$$m_\phi = \prod_{i=1}^k (x - \lambda_i)^{s_i}$$

where s_i is the size of the largest Jordan block of ϕ with eigenvalue λ_i .

Corollary 4.23. Any $A \in M_n(\mathbb{C})$ is similar to a direct sum of Jordan blocks, that is, there is an invertible matrix $P \in M_n(\mathbb{C})$ such that

$$P^{-1}AP = A_1 \oplus \dots \oplus A_r,$$

with each A_i a Jordan block.

$A_1 \oplus \dots \oplus A_r$ is called the Jordan normal form (JNF) of A and is unique up to the order of the A_i .

Theorem 4.24. Matrices $A, B \in M_n(\mathbb{C})$ are similar if and only if they have the same Jordan normal form, up to reordering the Jordan blocks.

Chapter 5

Duality

5.1 Dual spaces

Definition. Let V be a vector space over \mathbb{F} . The *dual space* V^* of V is

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

Elements of V^* are called *linear functionals* or (less often) *linear forms*.

Proposition 5.1. Let V be a finite-dimensional vector space with basis v_1, \dots, v_n .

Define $v_1^*, \dots, v_n^* \in V^*$ by setting

$$v_i^*(v_j) = \delta_{ij} \in \mathbb{F}$$

and extending by linearity (thus applying Proposition 1.7).

Then v_1^*, \dots, v_n^* is a basis of V^* called the dual basis to v_1, \dots, v_n .

Corollary 5.2. If V is finite-dimensional then $\dim V = \dim V^*$.

Theorem 5.3 (Sufficiency principle). Let V be a vector space and $v \in V$. Then $\alpha(v) = 0$, for all $\alpha \in V^*$, if and only if $v = 0$.

Proposition 5.4. Let V be a finite-dimensional vector space and $\alpha_1, \dots, \alpha_n$ a basis of V^* . Then there is a basis v_1, \dots, v_n of V such that

$$\alpha_i(v_j) = \delta_{ij}.$$

Thus $\alpha_i = v_i^*$, for $1 \leq i \leq n$.

Theorem 5.5. If V is a finite-dimensional vector space then $\text{ev} : V \rightarrow V^{**}$ is an isomorphism.

5.2 Solution sets and annihilators

Definition. Let $E \leq V^*$. The *solution set* of E is

$$\text{sol } E := \{v \in V \mid \alpha(v) = 0, \text{ for all } \alpha \in E\} = \bigcap_{\alpha \in E} \ker \alpha \leq V.$$

Proposition 5.6. If V is finite-dimensional and $E \leq V^*$ then

$$\dim \text{sol } E = \dim V - \dim E.$$

We say that E and $\text{sol } E$ have complementary dimension.

Corollary 5.7. Let V have dimension n and suppose that $\alpha_1, \dots, \alpha_n \in V^*$ are such that

$$\bigcap_{i=1}^n \ker \alpha_i = \{0\}.$$

Then $\alpha_1, \dots, \alpha_n$ is a basis of V^* .

Proposition 5.8. Let $E, F \leq V^*$. Then

- (1) If $E \leq F$ then $\text{sol } F \leq \text{sol } E$.
(2) sol swaps sums and intersections:

$$\begin{aligned} \text{sol}(E + F) &= (\text{sol } E) \cap (\text{sol } F) \\ (\text{sol } E) + (\text{sol } F) &\leq \text{sol}(E \cap F) \end{aligned}$$

with equality if V is finite-dimensional.

Definition. Let $U \leq V$. The annihilator of U , denoted $\text{ann } U$ or U° , is given by:

$$\text{ann } U := \{\alpha \in V^* \mid \alpha|_U = 0\} = \{\alpha \in V^* \mid \alpha(u) = 0, \text{ for all } u \in U\}.$$

Proposition 5.9. Let V be finite-dimensional and $U \leq V$. Then

$$\dim \text{ann } U = \dim V - \dim U.$$

Proposition 5.10. Let $U, W \leq V$. Then

- (1) If $U \leq W$ then $\text{ann } W \leq \text{ann } U$.
(2)
$$\begin{aligned} \text{ann}(U + W) &= (\text{ann } U) \cap (\text{ann } W) \\ (\text{ann } U) + (\text{ann } W) &\leq \text{ann}(U \cap W) \end{aligned}$$

with equality if V is finite-dimensional.

Lemma 5.11. Let $U \leq V$ and $E \leq V^*$ then $U \leq \text{sol } E$ if and only if $E \leq \text{ann } U$.

Theorem 5.12. Let $U \leq V$ and $E \leq V^*$. Then

$$\begin{aligned} U &\leq \text{sol}(\text{ann } U) \\ E &\leq \text{ann}(\text{sol } E), \end{aligned}$$

with equality if V is finite-dimensional.

5.3 Transposes

Definition. Let $\phi \in L(V, W)$ be a linear map of vector spaces. The transpose ϕ^T of ϕ is the map $\phi^T : W^* \rightarrow V^*$ given by

$$\phi^T(\alpha) := \alpha \circ \phi,$$

for all $\alpha \in W^*$.

Lemma 5.13. $\phi^T : W^* \rightarrow V^*$ is also a linear map.

Proposition 5.14. Let V, W be finite-dimensional vector spaces and $\phi \in L(V, W)$ with matrix $A \in M_{m \times n}(\mathbb{F})$ with respect to bases v_1, \dots, v_n and w_1, \dots, w_m of V and W .

Then ϕ^T has matrix A^T with respect to the dual bases w_1^*, \dots, w_m^* and v_1^*, \dots, v_n^* of W^* and V^* .

Theorem 5.15. Let $\phi \in L(V, W)$ be a linear map of vector spaces. Then

$$(1) \quad \begin{aligned} \ker \phi &= \text{sol}(\text{im } \phi^T) \\ \text{im } \phi &\leq \text{sol}(\ker \phi^T) \end{aligned}$$

with equality if V, W are finite-dimensional.

$$(2) \quad \begin{aligned} \ker \phi^T &= \text{ann}(\text{im } \phi) \\ \text{im } \phi^T &\leq \text{ann}(\ker \phi) \end{aligned}$$

with equality if V, W are finite-dimensional.

Corollary 5.16. *Let $\phi \in L(V, W)$ be a linear map of finite-dimensional vector spaces. Then*

$$\text{rank } \phi = \text{rank } \phi^T.$$

Proposition 5.17. *Let $\phi \in L(V, W)$ be a linear map of finite-dimensional vector spaces. Then*

- (1) ϕ injects if and only if ϕ^T surjects.
- (2) ϕ^T injects if and only if ϕ surjects.

Chapter 6

Bilinearity

6.1 Bilinear maps

6.1.1 Definitions and examples

Definition. Let U, V, W be vector spaces over a field \mathbb{F} . A map $B : U \times V \rightarrow W$ is *bilinear* if it is linear in each slot separately:

$$\begin{aligned} B(\lambda u_1 + u_2, v) &= \lambda B(u_1, v) + B(u_2, v) \\ B(u, \lambda v_1 + v_2) &= \lambda B(u, v_1) + B(u, v_2), \end{aligned}$$

for all $u, u_1, u_2 \in U$, $v, v_1, v_2 \in V$ and $\lambda \in \mathbb{F}$.

A bilinear map $U \times V \rightarrow \mathbb{F}$ is called a *bilinear pairing*.

A bilinear map $V \times V \rightarrow \mathbb{F}$ is called a *bilinear form on V* .

Notation. We let $\text{Bil}(U, V; W)$ denote the set of bilinear maps $U \times V \rightarrow W$.

6.1.2 Bilinear forms and matrices

Definition. Let V be a vector space over \mathbb{F} with basis $\mathcal{B} = v_1, \dots, v_n$ and let $B : V \times V \rightarrow \mathbb{F}$ be a bilinear form. The *matrix of B with respect to \mathcal{B}* is $A \in M_{n \times n}(\mathbb{F})$ given by

$$A_{ij} = B(v_i, v_j),$$

for $1 \leq i, j \leq n$.

Proposition 6.1. Let $B : V \times V \rightarrow \mathbb{F}$ be a bilinear form with matrix A with respect to $\mathcal{B} = v_1, \dots, v_n$. Then B is completely determined by A : if $v = \sum_{i=1}^n x_i v_i$ and $w = \sum_{j=1}^n y_j v_j$ then

$$B(v, w) = \sum_{i,j=1}^n x_i y_j A_{ij},$$

or, equivalently, for all $x, y \in \mathbb{F}^n$,

$$B(\phi_{\mathcal{B}}(x), \phi_{\mathcal{B}}(y)) = B_A(x, y) = \mathbf{x}^T \mathbf{A} \mathbf{y}.$$

Proposition 6.2. Let $B : V \times V \rightarrow \mathbb{F}$ be a bilinear form with matrices A and A' with respect to bases \mathcal{B} and \mathcal{B}' of V . Then

$$A' = P^T A P$$

where P is the change of basis matrix¹ from \mathcal{B} to \mathcal{B}' : thus $\phi_P = \phi_{\mathcal{B}}^{-1} \circ \phi_{\mathcal{B}'}$.

¹Algebra 1B, Definition 1.6.1.

Definition. We say that matrices $A, B \in M_{n \times n}(\mathbb{F})$ are *congruent* if there is $P \in \text{GL}(n, \mathbb{F})$ such that

$$B = P^T A P.$$

6.2 Symmetric bilinear forms

Definition. A bilinear form $B : V \times V \rightarrow \mathbb{F}$ is *symmetric* if, for all $v, w \in V$,

$$B(v, w) = B(w, v)$$

6.2.1 Rank and radical

Definitions. Let $B : V \times V \rightarrow \mathbb{F}$ be a symmetric bilinear form.

The *radical* $\text{rad } B$ of B is given by

$$\text{rad } B := \{v \in V \mid B(v, w) = 0, \text{ for all } w \in V\}.$$

We shall shortly see that $\text{rad } B \leq V$.

We say that B is *non-degenerate* if $\text{rad } B = \{0\}$.

If V is finite-dimensional, the *rank* of B is $\dim V - \dim \text{rad } B$ (so that B is non-degenerate if and only if $\text{rank } B = \dim V$).

Lemma 6.3. *Let $B : V \times V \rightarrow \mathbb{F}$ be a symmetric bilinear form on a finite-dimensional vector space V with matrix A with respect to some basis of V . Then*

$$\text{rank } B = \text{rank } A.$$

In particular, B is non-degenerate if and only if $\det A \neq 0$.

6.2.2 Classification of symmetric bilinear forms

Convention. In this section, we work with a field \mathbb{F} where $1 + 1 \neq 0$ so that $\frac{1}{2} = (1 + 1)^{-1}$ makes sense. This excludes, for example, the 2-element field \mathbb{Z}_2 .

Lemma 6.4. *Let $B : V \times V \rightarrow \mathbb{F}$ be a symmetric bilinear form such that $B(v, v) = 0$, for all $v \in V$. Then $B \equiv 0$.*

Theorem 6.5 (Diagonalisation Theorem). *Let B be a symmetric bilinear form on a finite-dimensional vector space over \mathbb{F} . Then there is a basis v_1, \dots, v_n of V with respect to which the matrix of B is diagonal:*

$$B(v_i, v_j) = 0,$$

for all $1 \leq i \neq j \leq n$. We call v_1, \dots, v_n a diagonalising basis for B .

Corollary 6.6. *Let $A \in M_{n \times n}(\mathbb{F})$ be symmetric. Then there is an invertible matrix $P \in \text{GL}(n, \mathbb{F})$ such that $P^T A P$ is diagonal.*

6.2.3 Sylvester's Theorem

Definitions. Let B be a symmetric bilinear form on a *real* vector space V .

Say that B is *positive definite* if $B(v, v) > 0$, for all $v \in V \setminus \{0\}$.

Say that B is *negative definite* if $-B$ is positive definite.

If V is finite-dimensional, the *signature* of B is the pair (p, q) where

$$\begin{aligned} p &= \max\{\dim U \mid U \leq V \text{ with } B|_{U \times U} \text{ positive definite}\} \\ q &= \max\{\dim W \mid W \leq V \text{ with } B|_{W \times W} \text{ negative definite}\}. \end{aligned}$$

Theorem 6.7 (Sylvester's Law of Inertia). *Let B be a symmetric bilinear form of signature (p, q) on a finite-dimensional real vector space. Then:*

- $p + q = \text{rank } B$;
- any diagonal matrix representing B has p positive entries and q negative entries (necessarily on the diagonal!).

6.3 Application: Quadratic forms

Convention. We continue working with a field \mathbb{F} where $1 + 1 \neq 0$.

Definition. A *quadratic form* on a vector space V over \mathbb{F} is a function $Q : V \rightarrow \mathbb{F}$ of the form

$$Q(v) = B(v, v),$$

for all $v \in V$, where $B : V \times V \rightarrow \mathbb{F}$ is a symmetric bilinear form.

Lemma 6.8. *Let $Q : V \rightarrow \mathbb{F}$ be a quadratic form with $Q(v) = B(v, v)$ for a symmetric bilinear form B . Then*

$$B(v, w) = \frac{1}{2}(Q(v + w) - Q(v) - Q(w)),$$

for all $v, w \in V$.

B is called the *polarisation* of Q .

Definitions. Let Q be a quadratic form on a finite-dimensional vector space V over \mathbb{F} .

The *rank* of Q is the rank of its polarisation.

If $\mathbb{F} = \mathbb{R}$, the *signature* of Q is the signature of its polarisation.

Theorem 6.9. *Let Q be a quadratic form with rank r polarisation on a finite-dimensional vector space over \mathbb{F} .*

(1) *When $\mathbb{F} = \mathbb{C}$, there is a basis v_1, \dots, v_n of V such that*

$$Q\left(\sum_{i=1}^n x_i v_i\right) = x_1^2 + \dots + x_r^2.$$

(2) *When $\mathbb{F} = \mathbb{R}$ and Q has signature (p, q) , there is a basis v_1, \dots, v_n of V such that*

$$Q\left(\sum_{i=1}^n x_i v_i\right) = x_1^2 + \dots + x_p^2 - x_{p+1}^2 - \dots - x_r^2.$$