

# Higher Linear Algebra

## MATH2601 UNSW

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### Contents

<b>1</b>	<b>Group and Fields</b>	<b>3</b>
1.1	Groups . . . . .	3
1.1.1	Permutation Groups . . . . .	3
1.2	Fields . . . . .	4
1.3	Subgroups and Subfields . . . . .	4
1.4	Morphisms . . . . .	5
<b>2</b>	<b>Vector Spaces</b>	<b>6</b>
2.1	Vector Spaces . . . . .	6
2.2	Standard Examples of Vector Spaces . . . . .	7
2.3	Subspaces . . . . .	8
2.4	Linear Combinations, Spans and Independence . . . . .	8
2.5	Bases . . . . .	9
2.5.1	Examples of Bases . . . . .	10
2.6	Dimension . . . . .	10
2.7	Coordinates . . . . .	11
2.8	Sums and Direct Sums . . . . .	12
<b>3</b>	<b>Linear Transformations</b>	<b>12</b>
3.1	Linear Transformations . . . . .	12
3.2	Kernel and Image . . . . .	13
3.3	Spaces Associated with Matrices . . . . .	14
3.4	The Matrix of a Linear Map . . . . .	15
3.5	Similarity . . . . .	16
3.6	Multilinear Maps . . . . .	16

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\*With some inspiration from Hussain Nawaz's Notes

<b>4</b>	<b>Inner Product Spaces</b>	<b>17</b>
4.1	The Dot product in $\mathbb{R}^p$	17
4.2	Dot product in $\mathbb{C}^p$	17
4.3	Inner Product Spaces	18
4.4	Orthogonality and Orthonormality	18
4.5	The Gram-Schmidt Process	19
4.6	Orthogonal Complements	19
4.7	Adjoint	20
4.7.1	Maps with Special Adjoints	21
4.8	QR Factorisations	21
4.9	Least Squares	22
<b>5</b>	<b>Determinants</b>	<b>22</b>
<b>6</b>	<b>Eigenvalues and Eigenvectors</b>	<b>24</b>
6.1	Eigenvalues and Eigenvectors	24
6.2	The Characteristic Polynomial	25
6.3	Multiplicities	26
6.4	Normal Operators	26
6.5	Self-Adjoint Maps and Matrices	27
6.6	Unitary and Orthogonal Maps and Matrices	28
6.7	The Singular Value Decomposition	28
<b>7</b>	<b>Canonical Forms</b>	<b>29</b>
7.1	Similarity Invariants	29
7.2	The Generalised Eigenspaces	29
7.3	Decomposition of a Space	30
7.3.1	The Technical Proofs	32
7.4	More on the Jordan Form	32
7.4.1	Matrix Polynomials	33
7.5	Calculating the Jordan Form	33
<b>8</b>	<b>Matrix Functions and ODEs</b>	<b>33</b>
8.1	Powers and the Jordan Form	33
8.2	Power Series of Matrices	34
8.3	The Matrix Exponential	35
8.4	The Column Method	36
8.5	Systems of Homogeneous Linear ODEs	36

# 1 Group and Fields

## 1.1 Groups

**Definition** A group  $G$  is a non-empty set with a binary operation defined on it. That is

1. **Closure:** for all  $a, b$  in  $G$  a composition  $a * b$  is defined and in  $G$ ,
2. **Associativity:**  $(a * b) * c = a * (b * c)$  for all  $a, b, c \in G$ ,
3. **Identity:** there is an element  $e \in G$  such that  $a * e = e * a$  for all  $a \in G$ ,
4. **Inverse:** for each  $a \in G$  there is an  $a'$  in  $G$  such that  $a * a' = a' * a = e$ ,

If  $G$  is a finite set then the order of  $G$  is  $|G|$ , the number of elements in  $G$ .

Groups are defined as  $(G, *)$ . We say this as "the group  $G$  under the operation  $*$ ".

**Abelian Groups** A group  $G$  is abelian if the operation satisfies the commutative law

$$a * b = b * a \quad \text{for all } a, b \in G$$

### Notation

- We use power notation for repeated applications:  $a * a \cdots * a = a^n$  and  $a^{-n} = (a^{-1})^n$ .
- For group operation,  $\times$  we use 1 for the identity and  $a^{-1}$  for inverse of  $a$ .
- For group operation,  $+$  we use 0 for the identity and  $-a$  for the inverse of  $a$ .
- We would then write  $na$  for  $a + a + \cdots + a$  (repeated addition, not multiplying by  $n$ ).

**Trivial Groups** The trivial group is the group consisting of exactly one element,  $\{e\}$ . It is the smallest possible group, since there has to be at least one element in a group.

### More Properties of Groups

- There is only one identity element in  $G$ .
- Each element of  $G$  only has one inverse.
- For each  $a \in G$ ,  $(a^{-1})^{-1} = a$
- For every,  $a, b \in G$ ,  $(a * b)^{-1} = b^{-1} * a^{-1}$ .
- Let  $a, b, c \in G$ . Then if  $a * b = a * c$ ,  $b = c$ .

#### 1.1.1 Permutation Groups

Let  $\Omega_n = \{1, 2, \dots, n\}$ . As an ordered set  $\Omega_n = (1, 2, \dots, n)$  has  $n!$  rearrangements. We may think of these permutations as being functions  $f : \Omega_n \rightarrow \Omega_n$ . These are bijections.

Observe that the set  $\mathcal{S}_n$  of all permutations of  $n$  objects forms a group under composition of order  $n!$ .

**Small Finite Groups** Small groups can be pictured using a multiplication table, where the row element is multiplied on the left of the column element.

In a multiplication table of finite group each row must be a permutation of the elements of the group, because:

- If we had repetition in a row (or column), so that  $xa = xb$ , then the cancellation rule will give  $a = b$ . Hence each element occurs no more than once in a row (or column).
- If  $a^2 = a$  then multiplying by  $a^{-1}$  gives  $a = e$ , so the identity is the only element that can be fixed.

## 1.2 Fields

A field  $(\mathbb{F}, +, \times)$  is a set  $\mathbb{F}$  with two binary operations on it, addition  $(+)$  and multiplication  $(\times)$ , where

1.  $(\mathbb{F}, +)$  is an abelian group,
2.  $\mathbb{F}^* = \mathbb{F} \setminus \{0\}$  is an abelian group under multiplication,
3. The distributive laws  $a \times (b + c) = a \times b + a \times c$  and  $(a + b) \times c = a \times c + b \times c$  hold.

### Additional Notes

- Our definition is equivalent to saying  $\mathbb{F}$  satisfies the  $12 = 5 + 5 + 2$  number laws.
- We use juxtaposition for the multiplication in fields and 1 for the identity under multiplication.
- The smallest possible field has two elements, and is written  $\{0, 1\}$  with  $1 + 1 = 0$ .

**Finite Fields** The only finite fields are those of size  $p^k$  for some prime  $p$  (referred to as the characteristic of the field) and positive integer  $k$ . These fields are called Galois fields of size  $p^k$ ,  $\text{GF}(p^k)$ . Note that  $\text{GF}(p^k) \neq \mathbb{Z}_{p^k}$  unless  $k = 1$ .

**Properties of Fields** Let  $\mathbb{F}$  be a field and  $a, b, c \in \mathbb{F}$ . Then

- $a0 = 0$
- $a(-b) = -(ab)$
- $a(b - c) = ab - ac$
- if  $ab = 0$  then either  $a = 0$  or  $b = 0$ .

## 1.3 Subgroups and Subfields

**Subgroups** Let  $(G, *)$  be a group and  $H$  a non-empty subset of  $G$ . If  $H$  is a group under the restriction of  $*$  to  $H$ , we call it a subgroup of  $G$ . We write this as  $H \leq G$  and say  $H$  inherits the group structure from  $G$ .

**The Subgroup Lemma** Let  $(G, *)$  be a group and  $H$  a non-empty subset of  $G$ . Then  $H$  is a subgroup of  $G$  if and only if

1. for all  $a, b \in H, a * b \in H$
2. for all  $a \in H, a^{-1} \in H$ .

i.e.  $H$  is closed under  $*$  and  $^{-1}$ .

Note that every non-trivial group  $G$  has at least two subgroups:  $\{e\}$  and  $G$ .

**General Linear Groups** Let  $n \geq 1$  be an integer. The set of invertible  $n \times n$  matrices over field  $\mathbb{F}$  is a group under matrix multiplication. This is a special case of a bijection function  $f : S \rightarrow S$  with  $S = \mathbb{F}^n$  and is non-abelian if  $n > 1$ .

It is called the general linear group,  $GL(n, \mathbb{F})$ .

The groups  $GL(n, \mathbb{R})$  and  $GL(n, \mathbb{C})$  are especially important in this course. They have many important subgroups, such as

- the special linear groups  $SL(n, \mathbb{R})$  and  $SL(n, \mathbb{C})$  of matrices with determinant 1.
- $O(n) \leq GL(n, \mathbb{R})$  the group of orthogonal matrices.
- $SO(n) = O(n) \cap SL(n, \mathbb{R})$  of special orthogonal matrices.

**Subfields** If  $(\mathbb{F}, +, \times)$  is a field and  $\mathbb{E} \subseteq \mathbb{F}$  is also a field under the same operations (restricted to  $\mathbb{E}$ ), then  $(\mathbb{E}, +, \times)$  is a subfield of  $(\mathbb{F}, +, \times)$ , usually written  $\mathbb{E} \leq \mathbb{F}$ .

**The Subfield Lemma** Let  $\mathbb{E} \neq \{0\}$  be a non-empty subset of field  $\mathbb{F}$ . Then  $\mathbb{E}$  is a subfield of  $\mathbb{F}$  if and only iff for all  $a, b \in \mathbb{E}$ :

$$a + b \in \mathbb{E}, \quad -b \in \mathbb{E}, \quad a \times b \in \mathbb{E}, \quad b^{-1} \in \mathbb{E} \quad \text{if } b \neq 0.$$

**Rational + Irrational Field** Let  $\alpha$  be any (non-rational) real or complex number. We defined  $\mathbb{Q}(\alpha)$  to be the smallest field containing both  $\mathbb{Q}$  and  $\alpha$ . Such fields are important in number theory and can clearly be generalised to e.g.  $\mathbb{Q}(\alpha, \beta)$ . For example, it can be shown

$$\mathbb{Q}(\sqrt{2}) = \{a + b\sqrt{2} : a, b \in \mathbb{Q}\}$$

## 1.4 Morphisms

A morphism is a category of "nice" maps between the members.

**Homomorphism** Let  $(G, *)$  and  $(H, \circ)$  be two groups. A (group) homomorphism from  $G$  to  $H$  is a map  $\phi : G \rightarrow H$  that respects the two operations, that is where

$$\phi(a * b) = \phi(a) \circ \phi(b) \quad \text{for all } a, b \in G.$$

**Isomorphism** A bijective homomorphism  $\phi : G \rightarrow H$  is called an isomorphism: the groups are then said to be isomorphic. That is,  $G \cong H$ .

**Isomorphism Lemmas** Let  $(G, *)$  and  $(H, \circ)$  be two groups and  $\phi$  a homomorphism between them. Then

- $\phi$  maps the identity of  $G$  to the identity of  $H$ .
- $\phi$  maps inverses to inverse, i.e.  $\phi(a^{-1}) = (\phi(a))^{-1}$  for all  $a \in G$ .
- if  $\phi$  is an isomorphism from  $G$  to  $H$  then  $\phi^{-1}$  is an isomorphism from  $H$  to  $G$ .

**Images and Kernel** Let  $\phi : G \rightarrow H$  be a group homomorphism, with  $e'$  the identity of  $H$ . The kernel of  $\phi$  is the set

$$\ker(\phi) = \{g \in G : \phi(g) = e'\}$$

The image of  $\phi$  is the set

$$\text{im}(\phi) = \{h \in H : h = \phi(g), \text{ some } g \in G\}.$$

Note that  $\ker \phi \leq G$  and  $\text{im } \phi \leq H$ .

**One-to-One Homomorphism** A homomorphism  $\phi$  is one-one if and only if  $\ker \phi = \{e\}$ , with  $e$  the identity of  $G$ . If  $\phi$  is one-one then  $\text{im}(\phi)$  is isomorphic to  $G$ .

**Linear Groups** A common use of group homomorphisms is to look for a homomorphism  $\phi : G \rightarrow \text{GL}(n, \mathbb{F})$  for some  $n$  and some field  $\mathbb{F}$ . The group  $\text{im}(\phi)$  is called a (linear) representation of  $G$  on  $\mathbb{F}^n$ . If  $\phi$  is one-one (so every element maps to a distinct matrix), we call the representation faithful.

## 2 Vector Spaces

### 2.1 Vector Spaces

**Motivation for Vector Spaces** The concept of a vector space is a natural and important generalisation of  $\mathbb{R}^n$ . It is natural to consider them whenever possible to add objects and multiply them by scalars.

It may be convenient to consider a field  $\mathbb{F}$  as a vector space over one of its subfields.

**Vector Spaces** Let  $\mathbb{F}$  be a field. A vector space over the field  $\mathbb{F}$  consists of an abelian group  $(V, +)$  plus a function from  $\mathbb{F} \times V$  to  $V$  called scalar multiplication and written  $\alpha \mathbf{v}$  where

1.  $\alpha(\beta \mathbf{v}) = (\alpha\beta) \mathbf{v}$  for all  $\alpha, \beta \in \mathbb{F}$  for all  $\mathbf{v} \in V$ .
2.  $1 \mathbf{v} = \mathbf{v}$  for all  $\mathbf{v} \in V$ .
3.  $\alpha(\mathbf{u} + \mathbf{v}) = \alpha \mathbf{u} + \alpha \mathbf{v}$  for all  $\alpha \in \mathbb{F}$  for all  $\mathbf{u}, \mathbf{v} \in V$ .
4.  $(\alpha + \beta) \mathbf{u} = \alpha \mathbf{u} + \beta \mathbf{u}$  for all  $\alpha, \beta \in \mathbb{F}$  for all  $\mathbf{u} \in V$ .

## Properties and Notation for Vector Spaces

1. There are ten axioms here: 5 from the abelian group, closure of scalar multiplication and the four explicit ones.
2. Addition in  $V$  is called vector addition to distinguish it from the addition in  $\mathbb{F}$ .
3. Being a group,  $V$  cannot be empty.
4. Bold face letters are used to distinguish elements of  $V$  from elements of  $\mathbb{F}$ .

**Vector Space Lemma** Let  $V$  be a vector space over a field  $\mathbb{F}$ . For all  $\mathbf{v}, \mathbf{w}$  in  $V$  and  $\lambda \in \mathbb{F}$ :

1.  $0\mathbf{v} = \mathbf{0}$  and  $\lambda\mathbf{0} = \mathbf{0}$ .
2.  $(-1)\mathbf{v} = -\mathbf{v}$ .
3.  $\lambda\mathbf{v} = \mathbf{0}$  implies either  $\lambda = 0$  or  $\mathbf{v} = \mathbf{0}$ .
4. if  $\lambda\mathbf{v} = \lambda\mathbf{w}$  and  $\lambda \neq 0$  then  $\mathbf{v} = \mathbf{w}$ .

## 2.2 Standard Examples of Vector Spaces

**The Space  $\mathbb{F}^n$  over  $\mathbb{F}$**  The set  $\mathbb{F}^n$  consists of all  $n$ -tuples of elements of  $\mathbb{F}$ :

$$\mathbb{F}^n = \left\{ \begin{pmatrix} \alpha_1 \\ \vdots \\ \alpha_n \end{pmatrix} : \alpha_i \in \mathbb{F} \right\}.$$

If  $\mathbf{x} = (\alpha_i)_{1 \leq i \leq n}$ ,  $\mathbf{y} = (\beta_i)_{1 \leq i \leq n}$  are elements of  $\mathbb{F}^n$ , then vector addition on  $\mathbb{F}^n$  is defined as

$$\mathbf{x} + \mathbf{y} = (\alpha_i + \beta_i)_{1 \leq i \leq n}.$$

Scalar multiplication on  $\mathbb{F}^n$  is  $\lambda\mathbf{x} = (\lambda\alpha_i)_{1 \leq i \leq n}$ .

With these operations,  $\mathbb{F}^n$  is a vector space over  $\mathbb{F}$ .

**Geometric Vectors** Geometric vectors are ordered pairs of points in  $\mathbb{R}^n$ , joined by labelled arrows. We add these objects by placing them head to tail and scalar multiplying is just stretching the vector's length while preserving the direction.

The set of all geometric vectors does not form a vector space. However, if you define 2 geometric vectors to be equivalent if one is a translation of the other then the set of equivalence classes of geometric vectors is a vector space.

**Matrices** For any positive integers  $p$  and  $q$  the set  $M_{p,q}(\mathbb{F})$  is the set of  $p \times q$  matrices with element from  $\mathbb{F}$ . Then  $M_{p,q}(\mathbb{F})$  is a vector space over  $\mathbb{F}$  with vector addition the usual addition of matrices and scalar multiplication multiplying each element of the matrix.

**Polynomials** The set of all polynomials with coefficients in  $\mathbb{F}$ ,  $\mathcal{P}(\mathbb{F})$ , is a vector space over  $\mathbb{F}$  with

$$\begin{aligned}(f + g)(x) &= f(x) + g(x) \quad \text{for all } x \in \mathbb{F} \\ (\lambda f)(x) &= \lambda f(x) \quad \text{for all } \lambda, x \in \mathbb{F}\end{aligned}$$

Similarly,  $\mathcal{P}_n(\mathbb{F})$  (polynomials of degree  $n$  or less) is a vector space over  $\mathbb{F}$ .

**Function Spaces** Let  $X$  be a non-empty set and  $\mathbb{F}$  be a field. Then define

$$\mathcal{F}[X] = \{f : X \rightarrow \mathbb{F}\}.$$

The set  $\mathcal{F}[X]$  is a vector space over  $\mathbb{F}$  if we define

- the zero in  $\mathcal{F}[X]$  to be the zero function:  $x \rightarrow 0$  for all  $x \in X$
- $(f + g)(x) = f(x) + g(x)$  for all  $x \in X$
- $(\lambda f)(x) = \lambda(f(x))$  for all  $x \in X$

**Exotic Example** Let  $V = \mathbb{R}^+$ , the set of positive real numbers. Define addition and scalar multiplication on  $V$  by

$$\mathbf{v} \oplus \mathbf{w} = \mathbf{vw}, \quad \alpha \otimes \mathbf{v} = \mathbf{v}^\alpha$$

Then with these operations,  $V$  is a vector space over  $\mathbb{R}$  whose addition and multiplication and whose scalar multiplication is exponentiation.

## 2.3 Subspaces

**Subspaces** If  $V$  is a vector space over  $\mathbb{F}$  and  $U \subseteq V$ , then  $U$  is a subspace of  $V$ , written  $U \leq V$ , if it is a vector space over  $\mathbb{F}$  with the same addition and scalar multiplication as in  $V$ .

Every vector space has  $\{\mathbf{0}\}$  (the trivial subspace) and itself as subspaces.

**Subspace Test Lemma** Suppose  $V$  is a vector space over the field  $\mathbb{F}$  and  $U$  is a non-empty subset of  $V$ . Then  $U$  is a subspace of  $V$  if and only if for all  $\mathbf{u}, \mathbf{v} \in U$  and  $\alpha \in \mathbb{F}$ ,  $\alpha\mathbf{u} + \mathbf{v} \in U$ .

## 2.4 Linear Combinations, Spans and Independence

**Linear Combination** Let  $V$  be a vector space over  $\mathbb{F}$ . A (finite) linear combination of vectors  $\mathbf{v}_1, \mathbf{v}_2, \dots, \mathbf{v}_n$  in  $V$  is any vector which can be expressed

$$\alpha_1 \mathbf{v}_1 + \alpha_2 \mathbf{v}_2 + \dots + \alpha_n \mathbf{v}_n$$

where the  $\alpha_k$  are scalars.



**Span** If  $S$  is a subset of  $V$ , then the span of is

$$\text{span}(S) = \{ \text{all finite linear combinations of vectors in } S \}.$$

We say that  $S$  spans  $V$ , or is a spanning set for  $V$ , if  $\text{span}(S) = V$ .

If  $S$  is a non-empty subset of a vector space  $V$ , then  $\text{span}(S)$  is a subspace of  $V$ .

**Linear Independence** A subset  $S$  of a vector space  $V$  is linearly independent if for all vectors  $\mathbf{v}_1, \mathbf{v}_2, \dots, \mathbf{v}_n$  in  $S$  (with  $n \geq 1$ ) the equation

$$\alpha_1 \mathbf{v}_1 + \alpha_2 \mathbf{v}_2 + \dots + \alpha_n \mathbf{v}_n = \mathbf{0}$$

with  $\alpha_i \in \mathbb{F}$ , implies  $\alpha_i = 0$  for all  $i = 1 \dots n$ .

**Linear Dependence Lemma** If  $S = \{\mathbf{v}_1, \dots, \mathbf{v}_n\}$  is a linearly dependent set of non-zero vectors in  $V$  then there is an  $i, 2 \leq i \leq n$  such that

$$\mathbf{v}_i = \sum_{j=1}^{i-1} \beta_j \mathbf{v}_j.$$

In other words in a ordered linearly dependent set at least one vector is a linear combination of its predecessors.

**Properties of Linear Independence, Dependence and Spanning Sets** In any vector space

1. Any subset of a linearly independent set is linearly independent.
2. (a) If  $\mathbf{v} \in \text{span}(S)$  and  $\mathbf{v} \notin S$ , then  $S \cup \{\mathbf{v}\}$  is linearly dependent.  
(b) If  $S$  is linearly independent and  $S \cup \{\mathbf{v}\}$  is linearly dependent then  $\mathbf{v} \in \text{span}(S)$ .
3. (a) If  $S_1 \subseteq S_2$ , then  $\text{span}(S_1) \subseteq \text{span}(S_2)$ .  
(b) If  $S_1 \subseteq \text{span}(S_2)$ , then  $\text{span}(S_1) \subseteq \text{span}(S_2)$ .
4.  $\text{span}(S \cup \{\mathbf{v}\}) = \text{span}(S)$  if and only if  $\mathbf{v} \in \text{span}(S)$ .
5. If  $S$  is linearly dependent, then there is a vector  $\mathbf{v}$  in  $S$  such that  $\text{span}(S \setminus \{\mathbf{v}\}) = \text{span}(S)$ .
6. In  $\mathbb{F}^p$ , if  $P \in \text{GL}(p, \mathbb{F})$  is an invertible matrix and  $\{\mathbf{v}_i\}$  linearly independent, then the set  $\{P\mathbf{v}_i\}$  is also linearly independent.

## 2.5 Bases

Let  $S \subseteq V$ . The set  $S$  is a basis for  $V$  over  $\mathbb{F}$  if and only if  $V = \text{span}(S)$ , and  $S$  is a linearly independent set.

### 2.5.1 Examples of Bases

**$\mathbb{F}^n$  over  $\mathbb{F}$**  The standard basis of  $\mathbb{F}^n$  as a vector space over  $\mathbb{F}$  is  $\mathcal{B} = \{\mathbf{e}_i : 1 \leq i \leq n\}$  where

$$\mathbf{e}_i = \begin{pmatrix} 0 \\ \vdots \\ 0 \\ 1 \\ 0 \\ \vdots \\ 0 \end{pmatrix} \leftarrow i\text{th place, written } \begin{pmatrix} \\ \\ \\ 1 \\ \\ \end{pmatrix} \leftarrow i$$

We also use  $\mathbf{i}, \mathbf{j}, \mathbf{k}$  as the standard basis of  $\mathbb{R}^3$ .

**Matrix Spaces** Define the matrices

$$E_{ij} = (e_{hl}) = \begin{cases} 1 & h = i \text{ and } l = j. \\ 0 & \text{otherwise.} \end{cases}$$

The set

$$\mathcal{B} = \{E_{ij} : 1 \leq i \leq p, 1 \leq j \leq q\},$$

is the standard basis of  $M_{p,q}(\mathbb{F})$  as a vector space over  $\mathbb{F}$ .

**Polynomial Spaces** The standard basis of  $\mathcal{P}_n(\mathbb{F})$  as a vector space over  $\mathbb{F}$  is

$$\mathcal{B} = \{1, t, \dots, t^n\}.$$

**Function Spaces** The space  $\mathcal{F}(X)$  has no obvious basis unless  $X$  is finite.

Let  $X = \{a_1, \dots, a_n\}$ , and for each  $i$  for  $i = 1, \dots, n$  define  $f_i : X \rightarrow \mathbb{F}$  by

$$f_i(a_j) = \delta_{ij} = \begin{cases} 1 & \text{if } i = j \\ 0 & \text{if } i \neq j \end{cases}$$

The set  $\mathcal{B} = \{f_1, f_2, \dots, f_n\}$  is a basis for  $\mathcal{F}(X)$ .

(We call the  $\delta_{ij}$  defined here the Kronecker delta symbol.)

**Fields** The set  $\{1, i\}$  is a basis for  $\mathbb{C}$  as a vector space over  $\mathbb{R}$ . Similarly,  $\mathbb{Q}(\sqrt{2})$  as a vector space over  $\mathbb{Q}$  has a basis  $\{1, \sqrt{2}\}$ .

## 2.6 Dimension

**Elements of Bases** If vector space  $V$  admits a finite spanning set, it admits a finite basis and all bases contain the same number of elements.

**Basis and Spanning Sets** Let  $V$  be a vector space over  $\mathbb{F}$  and  $S$  a finite spanning set. Then  $S$  contains a finite basis for  $V$ .

**The Exchange Lemma** Suppose that  $S$  is a finite spanning set for  $V$  and that  $T$  is a (finite) linearly independent subset of  $V$  with  $|T| \leq |S|$ . Then there is a spanning set  $S'$  of  $V$  such that

$$T \subseteq S' \text{ and } |S'| = |S|.$$

**Independent Set Size** If  $S$  is a finite spanning set for a vector space  $V$  and  $T$  is a linearly independent subset of  $V$ , then  $T$  is finite and  $|T| \leq |S|$ .

In other words, independent sets are no larger than spanning sets.

**Linearly Independent Sets to Basis** Let  $V$  be a vector space over  $\mathbb{F}$  with a finite spanning set and  $T$  a linearly independent subset of  $V$ . Then there is a basis  $B$  of  $V$  which contains  $T$ .

**Dimension** The dimension of a vector space  $V$  is the size of a basis if  $V$  has a finite basis or infinity otherwise. The notation is  $\dim(V) = n$  or  $\dim(V) = \infty$ .

**Properties** Let  $V$  be a finite dimensional vector space and suppose  $\dim(V) = n$ .

1. The number of elements in any spanning set is at least  $n$ .
2. The number of elements in any independent set is no more than  $n$ .
3. If  $\text{span}(S) = V$  and  $|S| = n$  then  $S$  is a basis.
4. If  $S$  is a linearly independent set and  $|S| = n$  then  $S$  is a basis.

**Combinations, Spanning and Independence** Let  $V$  be a finite dimensional vector space over  $\mathbb{F}$ . Then  $\mathcal{B} = \{\mathbf{v}_1, \dots, \mathbf{v}_n\}$  is a basis for  $V$  if and only if every  $\mathbf{x} \in V$  can be written uniquely as  $\mathbf{x} = \sum_{i=1}^n \alpha_i \mathbf{v}_i, \alpha_i \in \mathbb{F}$ .

## 2.7 Coordinates

**Coordinate** Suppose  $V$  is a vector space of dimension  $n$  over  $\mathbb{F}$  and  $\mathcal{B} = \{\mathbf{v}_1, \dots, \mathbf{v}_n\}$  is an ordered basis of  $V$  over  $\mathbb{F}$ . If  $\mathbf{v} \in V$  then  $\mathbf{v} = \sum_{i=1}^n \alpha_i \mathbf{v}_i$  with the  $\alpha_i$  unique.

We call  $\alpha = \begin{pmatrix} \alpha_1 \\ \vdots \\ \alpha_n \end{pmatrix}$  the coordinate vector of  $\mathbf{v}$  with respect to  $\mathcal{B}$ , and refer to the  $\alpha_i$  as the coordinates of  $\mathbf{v}$ . A useful notation is

$$\alpha = [\mathbf{v}]_{\mathcal{B}} \text{ if } \mathbf{v} = \sum_{i=1}^n \alpha_i \mathbf{v}_i.$$

## Properties of Coordinates

1.  $\mathbf{u} = \mathbf{v}$  if and only if  $[\mathbf{u}]_{\mathcal{B}} = [\mathbf{v}]_{\mathcal{B}}$  for all bases  $\mathcal{B}$ .
2.  $[\mathbf{u} + \mathbf{v}]_{\mathcal{B}} = [\mathbf{u}]_{\mathcal{B}} + [\mathbf{v}]_{\mathcal{B}}$  for any basis  $\mathcal{B}$ .
3.  $[\lambda\mathbf{u}]_{\mathcal{B}} = \lambda[\mathbf{u}]_{\mathcal{B}}$  for any basis  $\mathcal{B}$ .

## 2.8 Sums and Direct Sums

**Definitions** The sum  $S + T$  of two subspaces is defined as

$$S + T = \{\mathbf{a} + \mathbf{b} : \mathbf{a} \in S, \mathbf{b} \in T\}.$$

If  $S \cap T = \{\mathbf{0}\}$  then we call the sum a direct sum and denote it as  $S \oplus T$ .

**Direct Sum** The sum of subspaces  $S$  and  $T$  is direct if and only if any vector  $\mathbf{x} \in S + T$  can be written in a unique way as  $\mathbf{x} = \mathbf{a} + \mathbf{b}$ ,  $\mathbf{a} \in S$ ,  $\mathbf{b} \in T$ .

**Dimensions of Sum of Subspaces** Suppose  $S$  and  $T$  are finite dimensional subspaces of vector spaces  $V$ . Then

$$\dim(S) + \dim(T) = \dim(S + T) + \dim(S \cap T).$$

For a direct sum of finite dimensional spaces

$$\dim(S) + \dim(T) = \dim(S \oplus T)$$

**Complementary Subspace** Let  $V$  be a finite dimensional vector space and  $X \leq V$ . Then there is a subspace  $Y$  for which  $V = X \oplus Y$ .

**External Direct Sum** Let  $X$  and  $Y$  be two vector spaces over the same field  $\mathbb{F}$ . The Cartesian product  $X \times Y$  can be made into a vector space over  $\mathbb{F}$  with the obvious definitions

$$(\mathbf{x}_1, \mathbf{y}_1) + (\mathbf{x}_2, \mathbf{y}_2) = (\mathbf{x}_1 + \mathbf{x}_2, \mathbf{y}_1 + \mathbf{y}_2) \quad \text{and} \quad \lambda(\mathbf{x}_1, \mathbf{y}_1) = (\lambda\mathbf{x}_1, \lambda\mathbf{y}_1)$$

With this structure we call the Cartesian product the (external) direct sum of  $X$  and  $Y$ ,  $X \oplus Y$ .

## 3 Linear Transformations

### 3.1 Linear Transformations

**Linear Transformation** Suppose  $V$  and  $W$  are vector spaces over the field  $\mathbb{F}$ . A function  $T : V \rightarrow W$  is a linear transformation or a linear map (or simply linear) if

- $T(\mathbf{u} + \mathbf{v}) = T(\mathbf{u}) + T(\mathbf{v})$ , and
- $T(\lambda\mathbf{v}) = \lambda T(\mathbf{v})$ ,

for all  $\mathbf{u}, \mathbf{v} \in V$  and for all  $\lambda \in \mathbb{F}$ .

**Identity Map, Zero Vector and Negatives** Let  $V$  and  $W$  be vector spaces over the field  $\mathbb{F}$ .

- The identity map,  $\text{id} : V \rightarrow V$  defined by  $\text{id}(\mathbf{v}) = \mathbf{v}$  is linear.
- If  $T : V \rightarrow W$  is linear then  $T(\mathbf{0}) = \mathbf{0}$  and  $T(-\mathbf{v}) = -T(\mathbf{v})$ .

**Linearity Test Lemma** A function  $T : V \rightarrow W$  between vector spaces over the same field  $\mathbb{F}$  is linear if and only if

$$T(\lambda \mathbf{u} + \mathbf{v}) = \lambda T(\mathbf{u}) + T(\mathbf{v})$$

for all  $\lambda \in \mathbb{F}$ , and  $\mathbf{u}, \mathbf{v} \in V$ .

**Linear Transformations are Vector Spaces** Let  $V$  and  $W$  be two vector spaces over field  $\mathbb{F}$ . The set  $L(V, W)$  of all linear transformations from  $V$  to  $W$  is a vector space under the operations

$$(S + T)(\mathbf{v}) = S(\mathbf{v}) + T(\mathbf{v}), \quad (\lambda S)(\mathbf{v}) = \lambda S(\mathbf{v}).$$

**Composition of Linear Maps** Let  $T : V \rightarrow W$  and  $S : W \rightarrow X$  be linear maps between vector spaces. Then  $S \circ T : V \rightarrow X$  is also linear.

**Linearity of Inverse** Let  $T : V \rightarrow W$  be an invertible linear map between two vector spaces over field  $\mathbb{F}$ . Then  $T^{-1} : W \rightarrow V$  is linear.

**Invertible Linear Maps are Groups** The invertible linear maps in  $L(V, V)$  form a group under compositions. Note that composition of maps is always associative so and the inverse exists by definition of  $L(V, V)$ , only closure and the identity need to be proved.

Closure exists since composition of linear transformations are vector spaces. The identity map is linear and clearly invertible and so, also exists in the group.

**Taking Coordinates is Linear** Let  $V$  be a (finite-dimensional) vector space over  $\mathbb{F}$  with a basis  $\mathcal{B} = \{\mathbf{v}_1, \dots, \mathbf{v}_p\}$ . Then the function  $S : V \rightarrow \mathbb{F}^p$  defined by  $S(\mathbf{x}) = [\mathbf{x}]_{\mathcal{B}}$  is linear.

## 3.2 Kernel and Image

**Kernel** Let  $T : V \rightarrow W$  be a linear transformation. The kernel (or nullspace) of  $T$  is the set

$$\ker T = \{\mathbf{v} \in V : T(\mathbf{v}) = \mathbf{0}\}.$$

**Image** If  $U \leq V$  then the image of  $U$  is the set

$$T(U) = \{T(\mathbf{u}) : \mathbf{u} \in U\}.$$

We also define the image of  $T$  (or range of  $T$ ),  $\text{im}(T)$  as the image of all of  $V$  :  $\text{im}(T) = T(V)$ .

**Kernal and Image of Linear Transformations** Let  $T : V \rightarrow W$  be a linear transformation between vector spaces over  $\mathbb{F}$  and  $U \leq V$ . Then

1.  $\ker T$  is a subspace of  $V$ .
2.  $T(U)$  is a subspace of  $W$ , and so  $\text{im}(T) \leq W$ .
3. If  $U$  is finite-dimensional, so is  $T(U)$ , so if  $V$  is finite dimensional, so is  $\text{im}(T)$ .

**Rank and Nullity** If  $T$  is a linear transformation, then the dimension of the kernel of  $T$  is called the nullity of  $T$ , and the dimension of its image is called the rank of  $T$ .

**Nullity - One to One** A linear map  $T : V \rightarrow W$  is one-to-one if and only if  $\text{nullity}(T) = 0$ .

**Rank-Nullity Theorem** If  $V$  is a finite dimensional vector space over  $\mathbb{F}$  and  $T : V \rightarrow W$  is linear then

$$\text{rank}(T) + \text{nullity}(T) = \dim(V).$$

**Bijective, Injective, Surjective** Let  $V, W$  be vector spaces over  $\mathbb{F}$  with  $\dim(V) = \dim(W)$  finite and  $T : V \rightarrow W$  be linear. The following are equivalent:

- $T$  is invertible (bijective).
- $T$  is one-ton-one (injective) i.e.  $\text{nullity}(T) = 0$ .
- $T$  is onto (subjective) i.e.  $\text{rank}(T) = \dim(V)$ .

**Isomorphism** An invertible linear map  $T : V \rightarrow W$  is called an isomorphism of the vector spaces  $V$  and  $W$ .

**Isomorphism + Dimensions** Finite dimension vector spaces  $V$  and  $W$  over  $\mathbb{F}$  are isomorphic if and only if they have the same dimension.

### 3.3 Spaces Associated with Matrices

**Kernel, Image, Nullity and Rank** Let  $A$  be a  $p \times q$  matrix over field  $\mathbb{F}$ , and define a map  $T : \mathbb{F}^q \rightarrow \mathbb{F}^p$  by  $T(\mathbf{x}) = A\mathbf{x}$ . The kernel, image, nullity and rank of  $A$  are by definition the same as those of this map  $T$ .

**Column Space** Suppose  $A$  has columns  $\mathbf{c}_1, \dots, \mathbf{c}_q$  (all in  $\mathbb{F}^p$ ). Then

$$\begin{aligned} \text{im}(A) &= \{A\mathbf{x} : \mathbf{x} \in \mathbb{F}^q\} \\ &= \{x_1\mathbf{c}_1 + \dots + x_q\mathbf{c}_q : x_i \in \mathbb{F}\} \\ &= (\{\mathbf{c}_1, \dots, \mathbf{c}_q\}) \end{aligned}$$

That is,  $\text{im}(A)$  is the space spanned by the columns of  $A$ : the column space of  $A$ ,  $\text{col}(A)$ , a subspace of  $\mathbb{F}^p$ . The rank of  $A$  is thus the dimension of the column space of  $A$ .

**Rank-Nullity Theorem for Matrices** For  $A \in M_{p,q}(\mathbb{F})$ ,  $\text{rank}(A) + \text{nullity}(A) = q$ , the number of columns of  $A$ .

**Row Space** The row space of  $A$ ,  $\text{row}(A)$ , is defined similarly as the space spanned by the rows: it is a subspace of  $\mathbb{F}^q$ . Note that  $\text{row}(A) = \text{col}(A^T) = \text{im}(A^T)$ .

**Row and Col Spaces** Let  $A \in M_{p,q}(\mathbb{F})$ . The spaces  $\text{row}(A)$  and  $\text{col}(A)$  have the same dimension.

### 3.4 The Matrix of a Linear Map

**Matrices of Linear Maps** Let  $V, W$  be two finite dimensional vector spaces over  $\mathbb{F}$ . Suppose  $\dim(V) = q$  and  $V$  has basis  $\mathcal{B}$  and also  $\dim(W) = p$  and  $W$  has basis  $\mathcal{C}$ . If  $T : V \rightarrow W$  is linear then there is a unique  $A \in M_{p,q}(\mathbb{F})$  with

$$[T(\mathbf{v})]_{\mathcal{C}} = A[\mathbf{v}]_{\mathcal{B}}.$$

Conversely, for any  $A \in M_{p,q}(\mathbb{F})$ , the equation defines a unique linear map from  $V$  to  $W$ .

**Notation** We call  $A$  in the above theorem the matrix of  $T$  with respect to  $\mathcal{B}$  and  $\mathcal{C}$ . A useful notation is to denote this matrix by  $[T]_{\mathcal{C}}^{\mathcal{B}}$  and then the equation takes the form

$$[T(\mathbf{v})]_{\mathcal{C}} = [T]_{\mathcal{C}}^{\mathcal{B}}[\mathbf{v}]_{\mathcal{B}}.$$

**Dimension of Linear Map** If  $\dim(V) = q$  and  $\dim(W) = p$  then  $\dim(L(V, W)) = pq$ .

**Composition of Linear Maps as Matrices** Let  $T : V \rightarrow W$  and  $S : W \rightarrow X$  be linear maps between vector spaces and suppose  $V, W$  and  $X$  have bases  $\mathcal{A}, \mathcal{B}, \mathcal{C}$  respectively. Then, the matrix  $S \circ T : V \rightarrow X$  is the product of the matrices of  $T$  and  $S$ , all taken with respect to the appropriate bases:

$$[S \circ T]_{\mathcal{C}}^{\mathcal{A}} = [S]_{\mathcal{C}}^{\mathcal{B}} \cdot [T]_{\mathcal{B}}^{\mathcal{A}}.$$

**Inverting Matrices as Transformations** If  $T : V \rightarrow W$  is linear and invertible, the matrix of  $T^{-1}$  is the inverse of the matrix of  $T$ . Thus the group of invertible linear maps on an  $n$ -dimensional vector space over  $\mathbb{F}$  is isomorphic to  $\text{GL}(n, \mathbb{F})$ . Formally,

$$[T^{-1}]_{\mathcal{B}}^{\mathcal{C}} = ([T]_{\mathcal{C}}^{\mathcal{B}})^{-1}.$$

**Change of Basis Matrix** If vector space  $V$  has two bases  $\mathcal{B}$  and  $\mathcal{C}$ , the matrix  $[\text{id}]_{\mathcal{C}}^{\mathcal{B}}$  of the identity map is called the change of basis matrix (from  $\mathcal{B}$  to  $\mathcal{C}$ ). This can be used to change coordinates:

$$[\mathbf{v}]_{\mathcal{C}} = [\text{id}]_{\mathcal{C}}^{\mathcal{B}}[\mathbf{v}]_{\mathcal{B}}.$$

**Rank and Nullity of Matrices** Let  $T : V \rightarrow W$  be a linear map between finite dimensional vector spaces over  $\mathbb{F}$  and  $A$  its matrix with respect to any two bases in  $V$  and  $W$ . Then

$$\text{nullity}(A) = \text{nullity}(T) \quad \text{and} \quad \text{rank}(A) = \text{rank}(T).$$

**Invariant Subspace** Let  $V$  be a vector space over  $\mathbb{F}$  and  $T : V \rightarrow V$  a linear map. If  $X \leq V$  is such that  $T(X) \leq X$ , we call  $X$  an invariant subspace of  $T$ .

**Linear Maps of Invariant Subspaces** Let  $T : V \rightarrow V$  be a linear map on a finite dimensional vector space. Suppose  $V = X \oplus Y$  with both  $X$  and  $Y$  invariant subspaces of  $T$  with dimensions  $p$  and  $q$  respectively. Then there is a basis  $\mathcal{B}$  for  $V$  in which the matrix  $[T]_{\mathcal{B}}^{\mathcal{B}}$  of  $T$  is of the form

$$[T]_{\mathcal{B}}^{\mathcal{B}} = \begin{pmatrix} A & \mathbf{0} \\ \mathbf{0} & B \end{pmatrix}$$

with  $A$  a  $p \times p$  and  $B$  a  $q \times q$  matrix.

### 3.5 Similarity

**Definition** Matrices  $A$  and  $B$  in  $M_{p,p}(\mathbb{F})$  are similar if there exists a matrix  $P \in \text{GL}(p, \mathbb{F})$  such that  $B = P^{-1}AP$ .

**Similar Matrices over Different Bases** Matrices  $A_1$  and  $A_2$  are similar if and only if they are the matrices of the same linear transformation with respect to two choices of bases.

**Similarity Invariant** A property of matrices is called a similarity invariant if it is the same for all similar matrices.

The determinant, rank, nullity and trace of matrices are all similarity invariants.

### 3.6 Multilinear Maps

**Bilinear** Let  $V_1, V_2$  and  $W$  be vector spaces over field  $\mathbb{F}$ . A map  $T : V_1 \times V_2 \rightarrow W$  is bilinear if it is linear in each argument, that is

$$\begin{aligned} T(\lambda \mathbf{v}_1 + \mathbf{v}'_1, \mathbf{v}_2) &= \lambda T(\mathbf{v}_1, \mathbf{v}_2) + T(\mathbf{v}'_1, \mathbf{v}_2) \\ T(\mathbf{v}_1, \lambda \mathbf{v}_2 + \mathbf{v}'_2) &= \lambda T(\mathbf{v}_1, \mathbf{v}_2) + T(\mathbf{v}_1, \mathbf{v}'_2) \end{aligned}$$

for all suitable vectors and scalars. If  $V_2 = V_1$  we call  $T$  bilinear on  $V_1$ .

**Symmetric and Alternating Multilinear Maps** A multilinear map  $T$  on  $V$  is said to be symmetric if its value on any ordered set of vectors is unchanged when any two of the vectors are swapped. If such a swap always simply changes the sign of the value,  $T$  is called alternating.



## 4 Inner Product Spaces

### 4.1 The Dot product in $\mathbb{R}^p$

**Positive Definite** A bilinear  $\mathbb{F}$ -valued map,  $T$ , on  $\mathbb{F}^p$  is positive definite if for all  $\mathbf{a} \in \mathbb{F}^p$ ,  $T(\mathbf{a}, \mathbf{a}) \geq 0$  and  $T(\mathbf{a}, \mathbf{a}) = 0$  if and only if  $\mathbf{a} = 0$ .

**Cauchy-Schwarz Inequality in  $\mathbb{R}^p$**  For any  $\mathbf{a}, \mathbf{b} \in \mathbb{R}^p$  we have

$$-||\mathbf{a}||||\mathbf{b}|| \leq \mathbf{a} \cdot \mathbf{b} \leq ||\mathbf{a}||||\mathbf{b}||.$$

If  $\mathbf{a} \neq 0, \mathbf{b} \neq 0$  then

$$-1 \leq \frac{\mathbf{a} \cdot \mathbf{b}}{||\mathbf{a}||||\mathbf{b}||} \leq 1.$$

**Angle between Two Vectors** If  $\mathbf{a}, \mathbf{b} \in \mathbb{R}^n$  are non-zero then the angle  $\theta$  between  $\mathbf{a}$  and  $\mathbf{b}$  is defined by

$$\cos \theta = \frac{\mathbf{a} \cdot \mathbf{b}}{||\mathbf{a}||||\mathbf{b}||}, \quad \theta \in [0, \pi]$$

We call non-zero vectors  $\mathbf{a}$  and  $\mathbf{b}$  orthogonal if  $\mathbf{a} \cdot \mathbf{b} = 0$ .

**Orthogonal Complement** Let  $X \leq \mathbb{R}^p$  for some  $p$ . The space

$$Y = \{\mathbf{y} \in \mathbb{R}^p : \mathbf{y} \cdot \mathbf{x} = 0 \text{ for all } \mathbf{x} \in X\}$$

is called the orthogonal complement of  $X$ ,  $X^\perp$

**Orthogonal Sets** A set  $S = \{\mathbf{v}_1, \dots, \mathbf{v}_k\} \subseteq \mathbb{R}^p$  of non-zero vectors is orthogonal if  $\mathbf{v}_i \cdot \mathbf{v}_j = 0, i \neq j$ . We say  $S$  is orthonormal if  $\mathbf{v}_i \cdot \mathbf{v}_j = \delta_{ij} = \begin{cases} 0 & i \neq j \\ 1 & \text{else} \end{cases}$ .

An orthogonal set  $S$  in  $\mathbb{R}^p$  is linearly independent.

**The Triangle Inequality** For  $\mathbf{a}, \mathbf{b} \in \mathbb{R}^p$  -  $||\mathbf{a} + \mathbf{b}|| \leq ||\mathbf{a}|| + ||\mathbf{b}||$ .

### 4.2 Dot product in $\mathbb{C}^p$

**Dot Product** The standard dot product on  $\mathbb{C}^p$  is defined by

$$\mathbf{a} \cdot \mathbf{b} = \sum_{i=1}^p \overline{a_i} b_i = \overline{\mathbf{a}}^T \mathbf{b}.$$

**Notation** We will use  $\mathbf{a}^*$  as a useful shorthand for  $\overline{\mathbf{a}}^T$  from now on, so that  $\mathbf{a} \cdot \mathbf{b} = \mathbf{a}^* \mathbf{b}$ .

**Properties of the Dot Product** The standard dot product on  $\mathbb{C}^p$  has the following properties:

1.  $\mathbf{a} \cdot (\lambda \mathbf{b} + \mathbf{c}) = \lambda \mathbf{a} \cdot \mathbf{b} + \mathbf{a} \cdot \mathbf{c}$  for  $\lambda \in \mathbb{C}$ .
2.  $\mathbf{b} \cdot \mathbf{a} = \overline{\mathbf{a} \cdot \mathbf{b}}$ .
3.  $(\lambda \mathbf{b} + \mathbf{c}) \cdot \mathbf{a} = \overline{\lambda} \mathbf{b} \cdot \mathbf{a} + \mathbf{c} \cdot \mathbf{a}$  for  $\lambda \in \mathbb{C}$ .
4.  $\|\mathbf{a}\| \geq 0$  and  $\|\mathbf{a}\| = 0 \iff \mathbf{a} = \mathbf{0}$ .

### 4.3 Inner Product Spaces

**Inner Product** If  $V$  is a vector space over  $\mathbb{F}$  then an inner product on  $V$  is a function  $\langle, \rangle : V \times V \rightarrow \mathbb{F}$ , that is, for all  $\mathbf{u}, \mathbf{v} \in V$   $\langle \mathbf{u}, \mathbf{v} \rangle \in \mathbb{F}$ , such that

$$\text{IP1 } \langle \mathbf{u}, \mathbf{v} + \mathbf{w} \rangle = \langle \mathbf{u}, \mathbf{v} \rangle + \langle \mathbf{u}, \mathbf{w} \rangle.$$

$$\text{IP2 } \langle \mathbf{u}, \alpha \mathbf{v} \rangle = \alpha \langle \mathbf{u}, \mathbf{v} \rangle.$$

$$\text{IP3 } \langle \mathbf{v}, \mathbf{u} \rangle = \overline{\langle \mathbf{u}, \mathbf{v} \rangle}.$$

$$\text{IP4 } \langle \mathbf{v}, \mathbf{v} \rangle \text{ is real and } > 0 \text{ if } \mathbf{v} \neq \mathbf{0} \text{ and } = 0 \text{ if } \mathbf{v} = \mathbf{0}.$$

We call  $V$  with  $\langle, \rangle$  an inner product space.

The norm of the vector is then  $\|\mathbf{v}\| = \langle \mathbf{v}, \mathbf{v} \rangle^{1/2}$ .

**Properties of the Inner Product** Let  $V$  be an inner product space. Then for  $\mathbf{u}, \mathbf{v}, \mathbf{w} \in V$  and  $\alpha \in \mathbb{C}$ :

1.  $\|\mathbf{u}\| > 0$  if and only if  $\mathbf{u} \neq \mathbf{0}$ .
2.  $\langle \mathbf{u} + \mathbf{v}, \mathbf{w} \rangle = \langle \mathbf{u}, \mathbf{w} \rangle + \langle \mathbf{v}, \mathbf{w} \rangle$ .
3.  $\langle \alpha \mathbf{u}, \mathbf{v} \rangle = \alpha \langle \mathbf{u}, \mathbf{v} \rangle$  and  $\|\alpha \mathbf{u}\| = |\alpha| \|\mathbf{u}\|$ .
4.  $\langle \mathbf{x}, \mathbf{u} \rangle = 0$  for all  $\mathbf{u}$  if and only if  $\mathbf{x} = \mathbf{0}$ .
5.  $|\langle \mathbf{u}, \mathbf{v} \rangle| \leq \|\mathbf{u}\| \|\mathbf{v}\|$  (Cauchy - Schwarz inequality).
6.  $\|\mathbf{u} + \mathbf{v}\| \leq \|\mathbf{u}\| + \|\mathbf{v}\|$  (The Triangle Inequality).

### 4.4 Orthogonality and Orthonormality

**Orthogonal** Let  $V$  be an inner product space. Non-zero vectors  $\mathbf{u}$  and  $\mathbf{v}$  are orthogonal if  $\langle \mathbf{u}, \mathbf{v} \rangle = 0$ ; we will use the notation  $\mathbf{u} \perp \mathbf{v}$  for this.

A set  $S = \{\mathbf{v}_1, \dots, \mathbf{v}_k\} \subseteq V$  of non-zero vectors is orthogonal if  $\langle \mathbf{v}_i, \mathbf{v}_j \rangle = 0, i \neq j$ .

**Orthonormal** We say  $S$  is orthonormal if  $\langle \mathbf{v}_i, \mathbf{v}_j \rangle = \delta_{ij} = \begin{cases} 1 & i = j \\ 0 & i \neq j \end{cases}$ .

**Projection** In inner product space  $V$  let  $\mathbf{v} \neq \mathbf{0}$ . The projection of  $\mathbf{u} \in V$  onto  $\mathbf{v}$  is defined as

$$\text{proj}_{\mathbf{v}}(\mathbf{u}) = \frac{\langle \mathbf{v}, \mathbf{u} \rangle}{\langle \mathbf{v}, \mathbf{v} \rangle} \mathbf{v}.$$

Note:  $\mathbf{u} - \alpha \mathbf{v} \perp \mathbf{v} \iff \mathbf{u} - \alpha \mathbf{v} = \mathbf{u} - \text{proj}_{\mathbf{v}} \mathbf{u}$ .

**Orthogonal and Orthonormal Sets** If  $S = \{\mathbf{v}_1, \dots, \mathbf{v}_k\}$  is an orthogonal set of non-zero vectors in inner product space  $V$  and  $\mathbf{v} \in \text{span}(S)$  then  $\mathbf{v} = \sum_{i=1}^k \text{proj}_{\mathbf{v}_i} \mathbf{v}$ .

If  $S$  is an orthonormal set  $\mathbf{v} = \sum_{i=1}^k \langle \mathbf{v}_i, \mathbf{v} \rangle \mathbf{v}_i$ .

**Orthonormal Basis** If  $\{\mathbf{e}_1, \dots, \mathbf{e}_n\}$  is an orthonormal basis for  $V$  then  $\mathbf{v} = \sum_{i=1}^n \langle \mathbf{e}_i, \mathbf{v} \rangle \mathbf{e}_i$ .

## 4.5 The Gram-Schmidt Process

**Gram-Schmidt Process** Every finite dimensional inner product space has an orthonormal basis.

The process uses this idea to transform any basis into an orthonormal basis. Suppose  $S = \{\mathbf{v}_1, \dots, \mathbf{v}_p\}$  is a basis for  $V$  over  $\mathbb{F}$ . Then

$$\begin{aligned} \mathbf{w}_1 &= \mathbf{v}_1 \\ \mathbf{w}_2 &= \mathbf{v}_2 - \text{proj}_{\mathbf{w}_1}(\mathbf{v}_2) \\ \mathbf{w}_3 &= \mathbf{v}_3 - \text{proj}_{\mathbf{w}_1}(\mathbf{v}_3) - \text{proj}_{\mathbf{w}_2}(\mathbf{v}_3) \\ &\vdots \quad \vdots \quad \dots \quad \vdots \\ \mathbf{w}_{k+1} &= \mathbf{v}_{k+1} - \sum_{j=1}^k \text{proj}_{\mathbf{w}_j}(\mathbf{v}_{k+1}) \end{aligned}$$

where  $W = \{\mathbf{w}_1, \dots, \mathbf{w}_k\}$  forms an orthonormal basis.

## 4.6 Orthogonal Complements

**Orthogonal Complement** Let  $X \leq V$  for some inner product space  $V$ . The space

$$Y = \{\mathbf{y} \in V : \langle \mathbf{y}, \mathbf{x} \rangle = 0 \text{ for all } \mathbf{x} \in X\}$$

is called the orthogonal complement of  $X$ ,  $X^\perp$ .

**Existence of Orthogonal Complement** Suppose  $V$  is a finite dimensional inner product space,  $W \leq V$  and  $\mathbf{v} \in V$  then

$$\mathbf{v} = \mathbf{a} + \mathbf{b}, \mathbf{a} \in W, \mathbf{b} \in W^\perp$$

where  $\mathbf{a}$  and  $\mathbf{b}$  are unique.

**Properties of the Projection** In finite dimensional product space  $V$  with  $W \leq V$ :

- If  $\mathbf{v} \in V$  then  $\mathbf{v} - \text{proj}_W(\mathbf{v})$  is in  $W^\perp$ .
- If  $\mathbf{w} \in W$  then  $\text{proj}_W(\mathbf{w}) = \mathbf{w}$ . Consequently, the projection mapping is idempotent: that is,  $(\text{proj}_W) \circ (\text{proj}_W) = \text{proj}_W$ .
- For all  $\mathbf{w} \in V$  we have  $\|\text{proj}_W(\mathbf{v})\| \leq \|\mathbf{v}\|$ .
- The function  $\text{proj}_W + \text{proj}_{(W^\perp)}$  is the identity function of  $V$ .

**Length Inequality** Let  $W$  be a subspace of a finite-dimensional inner product space  $V$ , and let  $\mathbf{v} \in V$ . For every  $\mathbf{w} \in W$  we have

$$\|\mathbf{v} - \mathbf{w}\| \geq \|\mathbf{v} - \text{proj}_W(\mathbf{v})\|,$$

with equality if and only if  $\mathbf{w} = \text{proj}_W(\mathbf{v})$ , i.e.  $\mathbf{v} - \mathbf{w} \in W^\perp$ .

## 4.7 Adjoints

**Linear Maps** If  $(V, \langle, \rangle)$  is a finite dimensional inner product space and  $T : V \rightarrow \mathbb{F}$  is linear then there is a unique vector  $\mathbf{t} \in V$  such that for all  $\mathbf{v} \in V$ ,  $T(\mathbf{v}) = \langle \mathbf{t}, \mathbf{v} \rangle$ .

**Adjoint Linear Maps** For any linear map  $T : V \rightarrow W$  between finite-dimensional inner product spaces, there is a unique linear map  $T^* : W \rightarrow V$  called the adjoint of  $T$  with

$$\langle \mathbf{w}, T(\mathbf{v}) \rangle = \langle T^*(\mathbf{w}), \mathbf{v} \rangle$$

for all  $\mathbf{v} \in V$  and  $\mathbf{w} \in W$ .

**Identity Adjoint** For any inner product space,  $V$ , the identity map on  $V$  is its own adjoint.

**Adjoint Properties** Suppose that  $V$  and  $W$  are finite-dimensional inner product spaces; let  $S$  and  $T$  be linear transformations from  $V$  to  $W$ . Then

1.  $(S + T)^* = S^* + T^*$
2. for any scalar  $\alpha$  we have  $(\alpha T)^* = \overline{\alpha} T^*$ ;
3.  $(T^*)^* = T$ .
4. if  $U : W \rightarrow X$  is linear then  $(U \circ T)^* = T^* \circ U^*$

**Change of Basis** Let  $V$  and  $W$  be finite-dimensional inner product spaces with orthonormal bases  $\mathcal{B}$  and  $\mathcal{C}$  respectively. If  $A$  is the matrix of the linear transformation  $T : V \rightarrow W$  with respect to bases  $\mathcal{B}$  and  $\mathcal{C}$ , then the matrix of  $T^* : W \rightarrow V$  with respect to bases  $\mathcal{C}$  and  $\mathcal{B}$  is the adjoint of  $A$ .

### 4.7.1 Maps with Special Adjoints

**Unitary, Isometry and Self-Adjoint** Let  $T : V \rightarrow V$  be a linear map on a finite-dimensional inner product space  $V$ . The  $T$  is said to be

- unitary if  $T^* = T^{-1}$
- an isometry if  $\|T(\mathbf{v})\| = \|\mathbf{v}\|$  for all  $\mathbf{v} \in V$ ;
- self-adjoint or Hermitian if  $T^* = T$ .

### Unitary Properties

1. A map  $T$  is unitary if and only if  $T^*$  is unitary.
2. The set of all unitary transformations on  $V$  forms a group under composition.

**Unitary and Isometry Maps** Let  $T$  be a linear map on a finite-dimensional inner product space  $V$ . Then the following are equivalent:

1.  $T$  is an isometry;
2.  $\langle T(\mathbf{v}), T(\mathbf{w}) \rangle = \langle \mathbf{v}, \mathbf{w} \rangle$  for all  $\mathbf{v}, \mathbf{w} \in V$  (i.e.  $T$  preserves inner products);
3.  $T$  is unitary (i.e.  $T^* \circ T$  is the identity);
4.  $T^*$  is an isometry;
5. if  $\{\mathbf{e}_1, \dots, \mathbf{e}_n\}$  is an orthonormal basis for  $V$  then so is  $\{T(\mathbf{e}_1), \dots, T(\mathbf{e}_n)\}$ .

**Unitary, Hermitian, Orthogonal and Symmetric Matrices** A matrix  $A \in M_{p,p}(\mathbb{C})$  is called unitary if  $A^* = A^{-1}$  and Hermitian if  $A^* = A$ . A matrix  $A \in M_{p,p}(\mathbb{R})$  is called orthogonal if  $A^T = A^{-1}$  and symmetric if  $A^T = A$ .

**Orthonormal Basis and Unitary** The columns of a  $p \times p$  matrix are an orthonormal basis of  $\mathbb{C}^p$  if and only if  $A$  is unitary. The columns of a  $p \times p$  matrix are an orthonormal basis of  $\mathbb{R}^p$  if and only if  $A$  is orthogonal. The same result apply to rows.

## 4.8 QR Factorisations

**QR Factorisation** If  $A$  is  $p \times q$  of rank  $q$  so ( $p \geq q$ ) then we can write  $A = QR$  where  $Q$  is an  $p \times q$  matrix with orthonormal columns, and  $R$  is an  $q \times q$  invertible upper triangular matrix.

**QR Factorisation with  $\tilde{Q}$  Square Matrix** Let  $A \in M_{p,q}(\mathbb{F})$  with  $p > q$  and  $\text{rank}(A) = q$ . Then we can write  $A = \tilde{Q}\tilde{R}$ , with  $\tilde{Q}$  being  $p \times p$  unitary (or orthogonal), and  $\tilde{R}$  being  $p \times q$ , of rank  $q$  and in echelon form.

## 4.9 Least Squares

**Normal Equations** A least squares solution to the system of equations  $A\mathbf{x} = \mathbf{b}$  is a solution to the equations  $A^*A\mathbf{x} = A^*\mathbf{b}$  which are known as the normal equations.

## 5 Determinants

**Odd and Even Permutations** If a permutation  $\sigma = [p_1, p_2, \dots, p_n]$  of  $\Omega_n$  contains  $k$  inversions then its sign,  $\text{sign}(\sigma) = (-1)^k$ . A permutation is called even or odd depending on whether the number of inversions is even or odd.

**Determinant** The determinant of an  $n \times n$  matrix  $A = (a_{ij})_{ij=1, \dots, n}$  is

$$\det(A) = \sum_{\sigma \in S_n} \text{sign}(\sigma) a_{1\sigma(1)} a_{2\sigma(2)} \cdots a_{n\sigma(n)}.$$

**Difference Product** Define the  $n$ th difference product  $\Delta_n$  by

$$\begin{aligned} \Delta_n &= \prod_{i=1, j>1}^n (i - j) \\ &= (1 - 2)(1 - 3) \cdots (1 - n)(2 - 3)(2 - 4) \cdots ((n - 1) - n) \end{aligned}$$

**Signs Changed Equal Inversions** For any  $\sigma \in S_n$ ,  $\sigma(\Delta_n) = \text{sign}(\sigma)\Delta_n$ .

**Sign of Compositions** If  $\alpha, \beta \in S_n$  then  $\text{sign}(\alpha \circ \beta) = \text{sign}(\alpha)\text{sign}(\beta)$ , and  $\text{sign}(\alpha^{-1}) = \text{sign}(\alpha)$ .

**Transpositions are Odd** Every transposition (i.e. swap of two elements) in  $f_n$  is odd.

**Properties of Determinant** Let  $A \in M_{p,p}$ . Then

1.  $\det(A) = \sum_{\sigma \in S_n} \text{sign}(\sigma) a_{\sigma(1)1} a_{\sigma(2)2} \cdots a_{\sigma(n)n}$ .
2.  $\det(A) = \det(A^T)$  and  $\det(A^*) = \overline{\det(A)}$
3. If any row or column of  $A$  is zero  $\det(A) = 0$ .
4. If a permutation is applied to the rows or columns of  $A$ , then the determinant is multiplied by the sign of the permutation.
5. If  $A$  has two rows or two columns the same, then  $\det(A) = 0$ .
6. If any row or column of  $A$  has a multiple of another row or column (respectively) added to it, the determinant is unchanged.

**Multilinear and Alternating** If  $\det$  is considered as a map on the rows or columns of a matrix (that is, from  $p$  copies of  $\mathbb{F}^p$  to  $\mathbb{F}$ ), then it is multilinear and alternating.

We note a useful special case of this last result, namely if any row or column of  $A$  is multiplied by a constant  $\alpha$ , then the determinant is multiplied by  $\alpha$ .

**Matrix Minors** For  $A \in M_{p,p}(\mathbb{F})$  let  $A_{ij}$  be the matrix obtained by deleting row  $i$  and column  $j$ . We call  $A_{ij}$  the  $(i, j)$ -minor of  $A$ .

**Determinant Minor Property** Suppose that row  $i$  of matrix  $A \in M_{p,p}(\mathbb{F})$  is zero except for entry  $a_{ij}$ . Then

$$\det(A) = (-1)^{i+j} a_{ij} \det(A_{ij}).$$

**Determinant of Triangular Matrices** The determinant of an upper or lower triangular matrix is the product of its diagonal elements.

**Elementary Row Operations and Matrices** An elementary row operation on a matrix is one of the following:

1. swapping two rows
2. multiplying one row by a non-zero scalar
3. adding a multiple of one row to another

An elementary matrix is a matrix obtained from an identity matrix after an elementary row operation.

**Invertible Matrices with Sequence of Elementary Matrices** If  $A$  is invertible there is a sequence of elementary matrices  $E_1, E_2, \dots, E_k$  such that

$$A = E_1 E_2 \cdots E_k \text{ and } \det(A) = \prod_{i=1}^k \det(E_i).$$

**Determinant of Invertible Matrices** A matrix  $A$  is invertible if and only if  $\det(A) \neq 0$ . If  $A$  is invertible, then  $\det(A^{-1}) = \frac{1}{\det(A)}$ .

**Determinant of Products** For any two matrices  $A$  and  $B$ ,  $\det(AB) = \det(A) \det(B)$ .

**Zero Determinant** A matrix  $A$  has determinant zero if and only if it has linearly dependent columns and hence if and only if it has linearly dependent rows.

**Cofactor** In matrix  $A$  the number  $c_{ij} = (-1)^{i+j} \det(A_{ij})$  is called the cofactor of element  $a_{ij}$ .

**Cofactor Expansion** For any  $A \in M_{p,p}(\mathbb{F})$  and any fixed  $j$ ,

$$\det(A) = \sum_{i=1}^p a_{ij}c_{ij}.$$

**Adjugate** For  $A \in M_{p,p}(\mathbb{F})$  the adjugate (also called the classical adjoint and adjunct) of  $A$ ,  $\text{adj}(A)$  is the transpose of the matrix of cofactors  $\text{adj}(A)_{ij} = c_{ji}$ .

For an invertible matrix,  $A$ ,  $A^{-1} = \frac{\text{adj}(A)}{\det(A)}$ .

## 6 Eigenvalues and Eigenvectors

### 6.1 Eigenvalues and Eigenvectors

**Definitions** Suppose  $T \in L(V, V)$  :

1. if  $T(\mathbf{v}) = \alpha\mathbf{v}$ ,  $\mathbf{v} \in V$ ,  $\alpha \in \mathbb{F}$ ,  $\mathbf{v} \neq 0$  then  $\alpha$  is an eigenvalue of  $T$ ,  $\mathbf{v}$  is an eigenvector for  $T$  corresponding to  $\alpha$ .
2. If  $\lambda$  is an eigenvalue of  $T$ , then the eigenspace of  $T$ ,  $E_\lambda(T) = \{\mathbf{v} \in V : T(\mathbf{v}) = \lambda\mathbf{v}\}$ .
3. We call the set of all eigenvalues of  $T$  the spectrum of  $T$ .

**Notes**

1. Eigenvectors are never zero.
2.  $E_\lambda(T) = \{\mathbf{0}\} \cup \{\text{all eigenvectors corresponding to } \lambda\}$ .
3. Each eigenspace is invariant under  $T$ .

**Properties of Eigenvalues** Let  $T : V \rightarrow V$  be linear. Then

1.  $E_\lambda(T) = \ker(\lambda \text{id} - T)$ .
2. If  $\lambda_1, \dots, \lambda_k$  are distinct eigenvalues and  $T(\mathbf{v}_i) = \lambda_i\mathbf{v}_i$ , then  $\mathbf{v}_1, \dots, \mathbf{v}_k$  are linearly independent.
3. If  $\lambda \neq \mu$  then  $E_\lambda(T) \cap E_\mu(T) = \{\mathbf{0}\}$ .

**Diagonalisable** A matrix  $A \in M_{p,p}(\mathbb{F})$  is diagonalisable over  $\mathbb{F}$  if there is an invertible matrix  $P \in \text{GL}(p, \mathbb{F})$  such that  $P^{-1}AP$  is diagonal - that is,  $A$  is similar over  $\mathbb{F}$  to a diagonal matrix. A linear map  $T : V \rightarrow V$  is diagonalisable if there is a basis of  $V$  with respect to which the matrix of  $T$  is diagonal.



**Diagonalisability Regarding Basis** If  $T \in L(V, v)$  where  $V$  is a finite dimensional vector space over  $\mathbb{F}$ , then  $T$  is diagonalisable if and only if  $V$  has a basis whose elements are all eigenvectors of  $T$ . Similarly,  $A \in M_{p,p}(\mathbb{F})$  is diagonalisable if and only if  $\mathbb{F}^p$  has a basis consisting of eigenvectors of  $A$ .

**Diagonalisability Regarding Eigenvalues** A  $p \times p$  matrix with  $p$  distinct eigenvalues is diagonalisable.

## 6.2 The Characteristic Polynomial

**Definition** If  $A$  is a  $p \times p$  matrix over  $\mathbb{F}$  then the characteristic polynomial of  $A$  is

$$\text{cp}_A(t) = \det(tI - A).$$

**Similarity Invariant** The characteristic polynomial is a similarity invariant.

**Characteristic Polynomials of Maps** If  $V$  is finite dimensional and  $T \in L(V, V)$  the characteristic polynomial of  $T$ ,  $\text{cp}_T(t)$ , is defined to be  $\text{cp}_A(t)$  for any matrix  $A$  of  $T$ .

**Properties with Linear Maps** Suppose  $T \in L(V, V)$ , with  $\dim V = n$ . Then

1.  $\lambda$  is an eigenvalue if and only if  $\text{cp}_T(\lambda) = 0$ .
2.  $W \leq E_\lambda(T)$  implies  $W$  is  $T$ -invariant.
3.  $\lambda$  is an eigenvalue if and only if  $\text{nullity}(T - \lambda \text{id}) > 0$ .

**Eigenvalues with Basis** Let  $T : V \rightarrow V$  be linear on finite dimensional space  $V$ , and  $\mathcal{B}$  be a basis for  $V$ . Let  $A$  be the matrix of  $T$  with respect to  $\mathcal{B}$ . The following are equivalent:

- $\mathbf{v}$  is an eigenvector of  $T$  corresponding to eigenvalue  $\lambda$ ;
- the coordinate vector  $[\mathbf{v}]_{\mathcal{B}}$  is an eigenvector of  $A$  corresponding to eigenvalue  $\lambda$ .

**Diagonalisation Algorithm** Given matrix  $A$

1. Calculate  $\text{cp}_A(t)$ .
2. Find all roots  $\alpha$  of  $\text{cp}_A(t)$ .
3. For each  $\alpha$ , calculate  $\dim(E_\alpha(A))$ .
4. If  $\sum_\alpha \dim(E_\alpha(A)) = n$  then  $A$  is diagonalizable.
5. If  $A$  is diagonalisable construct  $P$ , whose columns are a basis of  $V$  consisting of eigenvectors of  $A$  so that  $D = P^{-1}AP$  is diagonal.

## 6.3 Multiplicities

**Geometric and Algebraic Multiplicity** Suppose  $T$  is a linear map on finite dimensional vector space  $V$ . Suppose further that  $\lambda$  is an eigenvalue of  $T$  so that  $t - \lambda$  is a factor of the characteristic polynomial of  $T$ .

- The geometric multiplicity (g.m.) of  $\lambda$  is  $\dim(E_\lambda(T))$ .
- The algebraic multiplicity (a.m.) of  $\lambda$  is its multiplicity as a factor of  $\text{cp}_T(t)$ .

Let  $T : V \rightarrow V$  be linear on finite dimensional space  $V$  and  $\lambda$  an eigenvalue of  $T$ . Then

$$1 \leq \text{geometric multiplicity } \lambda \leq \text{algebraic multiplicity } \lambda.$$

**Solutions, Determinant and Trace with Eigenvalues** Suppose  $A \in M_{p,p}(\mathbb{C})$ . Then  $A$  has  $p$  eigenvalues  $\alpha_1, \dots, \alpha_p$  counting algebraic multiplicities. Also

$$\det(A) = \prod_{i=1}^p \alpha_i \text{ and } \text{tr}(A) = \sum_{i=1}^p \alpha_i.$$

**Equivalent Properties** Let  $T : V \rightarrow V$  be linear on finite dimensional space  $V$ . The following four statements are equivalent:

1.  $T$  is diagonalisable.
2. There is a basis for  $V$  consisting of eigenvectors for  $T$ .
3.  $V = E_{\lambda_1}(T) \oplus E_{\lambda_2}(T) \oplus \dots \oplus E_{\lambda_k}(T)$  where  $\lambda_1, \dots, \lambda_k$  are the distinct eigenvalues of  $T$ .
4. The sum of the geometric multiplicities of the distinct eigenvalues is  $\dim V$ . That is,

$$\sum_{j=1}^k \dim E_{\lambda_j}(T) = \dim V.$$

**Diagonalizable Distinct Roots** Linear map  $T$  on a  $p$ -dimensional space  $V$  over  $\mathbb{F}$  is diagonalizable if  $\text{cp}_T(t)$  has  $p$  distinct roots in  $\mathbb{F}$ .

## 6.4 Normal Operators

**Normal Definition** A linear transformation on an inner product space is normal if and only if  $T^* \circ T = T \circ T^*$  and an  $n \times n$  matrix is normal if and only if  $A^*A = AA^*$ .

**Inner Product Spaces and Normal Linear Maps** Let  $V$  be a finite dimensional inner product space and  $T$  a normal linear map on  $V$ . Then

- (a) For all  $\mathbf{v} \in V$ ,  $\|T(\mathbf{v})\| = \|T^*(\mathbf{v})\|$
- (b) For any scalar,  $\alpha$ ,  $(T - \alpha \text{id})$  is also normal.
- (c) If  $T$  has eigenvalue  $\lambda$  then  $\bar{\lambda}$  is an eigenvalue of  $T^*$ .
- (d)  $E_\lambda(T) = E_{\bar{\lambda}}(T^*)$ .
- (e) If  $\lambda \neq \mu$  then  $E_\lambda(T) \perp E_\mu(T)$ .

**Algebraic and Geometric Multiplicity** If  $T$  is normal with eigenvalue  $\lambda$  then the algebraic multiplicity of  $\lambda$  equals the geometric multiplicity of  $\lambda$ .

**The Spectral Theorem for Normal Operators** If  $V$  is a finite dimensional inner product space over  $\mathbb{C}$  and  $T \in L(V, V)$  is normal then there is an orthonormal basis  $\mathcal{B}$  of  $V$  consisting of eigenvectors of  $T$ . Hence if  $A \in M_{p,p}(\mathbb{C})$  is normal there is a unitary  $P$  such that  $P^{-1}AP = P^*AP$  is diagonal. Conversely if  $[T]_{\mathcal{B}}^{\mathcal{B}} = A = PDP^{-1}$ , with  $D$  diagonal and  $P$  unitary (so  $\mathcal{B}$  is orthonormal) then both  $A$  and  $T$  are normal.

**Normal Operators and Matrices** If  $A$  is normal with eigenvalues  $\lambda_i$ , then there are matrices  $P_i$  with

$$\begin{aligned} A &= \sum_i \lambda_i P_i, & P_i^2 &= P_i = P_i^*, \\ P_i P_j &= 0 \quad i \neq j, & \sum_i P_i &= \text{id}. \end{aligned}$$

## 6.5 Self-Adjoint Maps and Matrices

**Self-Adjoint, Hermitian and Symmetric** Suppose  $V$  is a finite dimensional inner product space over field  $\mathbb{F}$  (where  $\mathbb{F}$  is  $\mathbb{R}$  or  $\mathbb{C}$ ) and  $T \in L(V, V)$ .

- a) If  $T$  is self-adjoint (that is Hermitian if  $\mathbb{F} = \mathbb{C}$  or symmetric if  $\mathbb{F} = \mathbb{R}$ ) then the eigenvalues of  $T$  are real.
- b) If  $\mathbb{F} = \mathbb{C}$  and  $T$  is Hermitian there is a unitary basis for  $V$  consisting of eigenvectors of  $T$ .
- c) If  $\mathbb{F} = \mathbb{R}$  and  $T$  is symmetric, then there is a real orthonormal basis of  $V$  consisting of eigenvectors of  $T$ .

## 6.6 Unitary and Orthogonal Maps and Matrices

**Eigenvalues and Eigenvectors of a Unitary Map** Suppose  $V$  is a  $p$ -dimensional inner product space over field  $\mathbb{F}$  (where  $\mathbb{F}$  is  $\mathbb{R}$  or  $\mathbb{C}$ ), with  $T \in L(V, V)$  a unitary map. Then the eigenvalues of  $T$  lie on the unit circle in  $\mathbb{C}$ , that is are  $e^{i\alpha_k}$  for real  $\alpha_k$  and  $V$  has a unitary basis of eigenvectors of  $T$ .

**Isometries** Suppose  $T$  is an isometry on a real inner product space  $V$ . Then its characteristic polynomial is of the form

$$\text{cp}_T(t) = (t-1)^a(t+1)^b \prod_{j=1}^k (t - e^{i\alpha_j})(t - e^{-i\alpha_j})$$

where  $a+b+2k = \dim(V)$  and  $\alpha_j \in (0, \pi)$ . Also there is an orthonormal basis of  $V$  in which the matrix of  $T$  is of the form

$$I_a \oplus (-I_b) \bigoplus_{j=1}^k R(\alpha_j).$$

## 6.7 The Singular Value Decomposition

**Singular Value Decomposition (SVD)** Let  $A \in M_{p,q}(\mathbb{C})$ . A singular value decomposition of  $A$  is a factorization of  $A$  as  $U \Sigma V^*$  where  $U$  and  $V$  are square and unitary and  $\Sigma$  is a  $p \times q$  matrix with zero off diagonal terms and diagonal entries called the singular values satisfy

$$\sigma_1 \geq \sigma_2 \geq \cdots \geq \sigma_q \geq 0.$$

The columns of  $U$  are called left singular vectors and the columns of  $V$  right singular vectors.

**Kernel and Rank** Let  $A \in M_{p,q}(\mathbb{F})$  for  $\mathbb{F}$  either  $\mathbb{R}$  or  $\mathbb{C}$ . Then

- a)  $\ker(A * A) = \ker(A)$
- b)  $\text{rank}(A * A) = \text{rank}(A)$

**Existence of SVD** For any matrix  $A$  an  $SVD$  exists and the singular values are unique.

**Reduced Singular Value Decomposition** If  $A \in M_{p,q}(\mathbb{C})$  is rank  $k$  then the reduced singular value decomposition is the decomposition

$$A = \hat{U} \hat{\Sigma} \hat{V}^*$$

where  $\hat{U}$  and  $\hat{V}$  have orthonormal columns and  $\hat{\Sigma}$  is  $k \times k$  invertible and diagonal.

**Orthonormal Basis** For any  $p \times q$  matrix of rank  $k$ :

- a) The last  $q - k$  right singular vectors are an orthonormal basis of  $\ker(A)$ .
- b) The first  $k$  left singular vectors are an orthonormal basis of  $\text{im}(A)$ .
- c)  $\sum_{i=1}^k \omega_i^2 = \text{tr}(\mathbf{A}^* \mathbf{A}) = \sum_{i=1}^p \sum_{j=1}^q |a_{ij}|^2$ .

**Pseudoinverse** For an arbitrary  $A$  with reduced SVD  $\hat{U}\hat{\Sigma}\hat{V}^*$  we define the pseudoinverse of  $A$ ,  $A^+$  by

$$A^+ = \hat{V}\hat{\Sigma}^{-1}\hat{U}^*.$$

**Least Squares** The least squares solution to  $A\mathbf{x} = \mathbf{b}$  for  $A$  of full rank is given by  $\mathbf{x} = A^+\mathbf{b}$ .

## 7 Canonical Forms

### 7.1 Similarity Invariants

**Generalised Eigenvector** Let  $A \in M_{p,p}(\mathbb{C})$  and  $\lambda$  be an eigenvalue of  $A$ . Then  $\mathbf{v} \in \mathbb{C}^p$  is a generalised eigenvector (for eigenvalue  $\lambda$ ) iff

$$\mathbf{v} \in \ker(A - \lambda I)^k, \text{ for some integer } k \geq 1.$$

**Generalised Eigenspace** The generalised eigenspace of  $\lambda$ ,  $\text{GE}_\lambda(A)$ , is the space of all generalised eigenvectors of eigenvalue  $\lambda$ .

**Complete Set of Similarity Invariants** The collection of all the integers  $\text{nullity}(A - \lambda I)^k$  for all the eigenvalues  $\lambda$  and all integers  $k \geq 1$  is a complete set of similarity invariants of  $A$ .

### 7.2 The Generalised Eigenspaces

**Notation for Eigen Subspaces** Let  $T \in L(V, V)$  and suppose  $\lambda$  is an eigenvalue of  $T$ . For each integer  $j$ , define the spaces  $V_j(\lambda) = \ker(T - \lambda \text{id})^j$ .

**Maximum Growth of  $V_m$**  If for  $T \in L(V, v)$  and some eigenvalue  $\lambda$  and integer  $m \geq 1$  we have  $V_{m+1}(\lambda) = V_m(\lambda)$  then  $V_{m+\ell}(\lambda) = V_m(\lambda)$  for all integers  $\ell \geq 1$ .

**Height of Eigenspace** Let  $\lambda$  be an eigenvalue of  $T \in L(V, V)$ , where  $\dim(V) = p$  is finite. Then there is a least a integer  $h$ , the height of  $\lambda$ , with  $1 \leq h \leq p$  such that

$$\text{GE}_\lambda(T) = \ker(T - \lambda \text{id})^h.$$

**Increasing Dimension of Generalised Eigenspaces** Let  $\lambda$  be an eigenvalue of  $T \in L(V, V)$ , where  $\dim(V) = p$  is finite. Define

$$d_k = \dim(V_k(\lambda)) = \text{nullity}(T - \lambda \text{id})^k,$$

then

$$0 = d_0 < d_1 < d_2 < \cdots < d_{h-1} < d_h = d_{h+\ell} \leq \dim(V),$$

for all positive integers  $\ell$ .

**Transformation in Subspace** With the previous notation for  $k > 1$  if

$$\mathbf{v} \in Z_k(\lambda) \setminus \{\mathbf{0}\} \text{ then } (T - \lambda \text{id})(\mathbf{v}) \in V_{k-1}(\lambda) \setminus V_{k-2}(\lambda).$$

**Definition of  $Z_k$**  We can find non-trivial Subspaces  $Z_k(\lambda)$  of  $V$  such that

$$V_k(\lambda) = V_{k-1}(\lambda) \oplus Z_k(\lambda) \quad \text{for } k = 2, 3, \dots, h,$$

and we define  $Z_1(\lambda) = V_1(\lambda) = \ker(T - \lambda \text{id})$ .

**Difference in Dimension** With the same notation as above

$$d_1 - d_0 \geq d_2 - d_1 \geq d_3 - d_2 \geq \dots,$$

i.e.

$$\dim(Z_1(\lambda)) \geq \dim(Z_2(\lambda)) \geq \dim(Z_3(\lambda)) \geq \dots.$$

**Jordan Chain** A ordered set of non-zero vectors  $\{\mathbf{v}_1, \mathbf{v}_2, \dots, \mathbf{v}_k\}$  such that

$$T(\mathbf{v}_1) = \lambda \mathbf{v}_1 \text{ and } T(\mathbf{v}_i) = \lambda \mathbf{v}_i + \mathbf{v}_{i-1} \text{ if } 1 < i \leq k$$

is called a Jordan chain (of length  $k$ ) for eigenvalue  $\lambda$ . We will call a Jordan chain maximal if it is not part of a longer chain.

**Jordan Blocks** A matrix of the shape of  $J_k(\lambda)$  below is called Jordan block (for eigenvalue  $\lambda$ ).

$$J_k(\lambda) = \begin{pmatrix} \lambda & 1 & \cdots & 0 & 0 \\ 0 & \lambda & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & \lambda & 1 \\ 0 & 0 & \cdots & 0 & \lambda \end{pmatrix}$$

**Jordan Matrix** A matrix consisting of a direct sum of Jordan blocks is called a Jordan matrix.

**Jordan Basis** A basis with respect to which the matrix of  $T \in L(V, V)$  is a Jordan matrix is called a Jordan basis of  $T$ .

**Properties of the Span of a Jordan Chain** Let  $U = \text{span}\{\mathbf{v}_1, \mathbf{v}_2, \dots, \mathbf{v}_k\}$  be the space spanned by a Jordan chain of length  $k$  for eigenvalue  $\lambda$ . Then  $U$  is invariant under  $T$ , i.e.  $T(U) \subseteq U$ . Furthermore, if we write  $U = X \oplus Y$  for some  $X$  and  $Y$  both invariant under  $T$  then either  $X$  or  $Y$  is trivial.

## 7.3 Decomposition of a Space

**Invariant Kernel and Image** Let  $S$  and  $T$  be linear transformations on a vector space  $V$ , and suppose that  $S \circ T = T \circ S$ . Then the kernel and image of  $S$  are invariant under  $T$ .

**Indecomposable Invariant Subspace** Let  $T : V \rightarrow V$  be a linear map and  $U \leq V$  be an invariant subspace. If  $U$  is indecomposable with respect to  $T$  then it is indecomposable with respect to  $T|_U$ , with the restriction of  $T$  to  $U$ .

**Properties by Subtracting Multiplies of the Identity** Let  $T : V \rightarrow V$  be a linear map and  $\lambda$  be a scalar. Define  $S = T - \lambda \text{id}$ . Then  $U \leq V$  is

- a) invariant under  $S$  if and only if it is invariant under  $T$ ;
- b) decomposable with respect to  $S$  if and only if it is decomposable with respect to  $T$ .

**The Decomposition Lemma** Let  $T$  be a linear transformation on a vector space  $V$  of non-zero finite dimension. Then for some integer  $m \geq 1$ , there exist  $T$ -invariant subspaces  $U_1, \dots, U_m$ , each indecomposable with respect to  $T$ , such that

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

**Kernel-Image Decomposition** If  $T$  is a linear map on a finite-dimensional space  $V$ , then there exists a positive integer  $m$  such that

$$V = (\ker T^m) \oplus (\text{im } T^m).$$

**The Jordan Form** Let  $T$  be a linear transformation on a non-zero, finite-dimensional complex vector space  $V$ . Then there is a basis of  $V$  with respect to which the matrix of  $T$  is a Jordan matrix.

**Definition of Jordan Form** The matrix of  $T$  in a Jordan basis is called a Jordan (canonical) form of  $T$ .

**Jordan Chains as Similarity Invariants** The number and lengths of the maximal Jordan chains are similarity invariants.

**Splitting Spaces Equals Independent Eigenvectors Equals Maximal Jordan Chains** The number of splitting spaces in The Decomposition Lemma, is the same as the number of Independent eigenvectors, which is the same as the number of maximal Jordan chains in any Jordan basis.

**Jordan Form Similarity Invariant** The Jordan form is a complete similarity invariant for complex matrices.

### 7.3.1 The Technical Proofs

Recall the following definition and results:

- a) For  $T : V \rightarrow V$ ,  $U \leq V$  is indecomposable and invariant w.r.t  $T$ ;
- b)  $T|_U : U \rightarrow U$  is thus well defined and has an eigenvalue  $\lambda$ ;
- c)  $S : U \rightarrow U$  is defined as  $S = T|_U - \lambda \text{id}$ ;
- d)  $k$  is the smallest positive integer such that  $S^k$  is the zero map on  $U$ ;
- e)  $\mathbf{u} \in U$  is some vector with  $S^{k-1}(\mathbf{u}) \neq \mathbf{0}$ ;
- f)  $\mathcal{B} = \{\mathbf{u}, S(\mathbf{u}), S^2(\mathbf{u}), \dots, S^{k-1}(\mathbf{u})\}$  is independent.
- g)  $W = \text{span}(\mathcal{B})$

**Existence of  $S(\mathbf{v}) \in X$**  With the given notation, if  $X$  is a subspace of  $U$  such that

$$S(X) \subseteq X, \quad W \cap X = \{\mathbf{0}\}, \quad W \oplus X \neq U,$$

then there exists  $\mathbf{v} \in U$  such that

$$\mathbf{v} \in W \oplus X \quad \text{and} \quad S(\mathbf{v}) \in X.$$

**$W$  is equal to  $U$**  With the above notation,  $W = U$ .

## 7.4 More on the Jordan Form

### Properties of the Jordan Form

- a) The eigenvalues of  $T$  are the  $\lambda_i$  in its Jordan form and conversely.
- b) The number of Jordan blocks for each eigenvalue  $\lambda_i$  is the geometric multiplicity of  $\lambda_i$ .
- c) The algebraic multiplicity of an eigenvalue is the sum of the sizes of all the Jordan blocks for that eigenvalue.
- d) The height,  $h_i$ , of eigenvalue  $\lambda_i$  is the size of the largest Jordan block for  $\lambda_i$ ,  $h_i \leq a_i$  and  $(T - \lambda_i \text{id})^{h_i}$  is the zero map on each splitting space for  $\lambda_i$ .
- e) Each of the splitting spaces for  $T$  consists of generalised eigenvectors.
- f)  $\ker(T - \lambda_i \text{id})^k$  for  $k \geq h_i$  is the generalised eigenspace of  $\lambda_i$ .
- g)  $\text{GE}_\lambda(T)$  is spanned by the union of the Jordan chains for eigenvalue  $\lambda$ , and  $\dim \text{GE}_\lambda(T)$  is the algebraic multiplicity of  $\lambda$ .
- h)  $V$  is the direct sum of all the generalised eigenspaces for  $T \in L(V, V)$ .

All these results have equivalent matrix formulations.



### 7.4.1 Matrix Polynomials

**The Cayley-Hamilton Theorem** For any matrix  $A \in M_{p,p}(\mathbb{C})$ ,  $\text{cp}_A(A)$  is zero.

**Maximal Dimension of Matrix Powers** The space spanned by  $\{I, A, A^2, A^3, \dots\}$  is at most  $p$ -dimensional.

**Minimal Polynomial** The polynomial  $\text{mp}_A(t) = \prod_{i=1}^m (t - \lambda_i)^{h_i}$  is called the minimal polynomial of  $A$ .

It is the monic polynomial of least degree for which this is true.

## 7.5 Calculating the Jordan Form

### Properties for Finding Jordan Form

- We know  $d_1 - d_0 = d_1 = \text{nullity}(A - \lambda I)$  is the number of Jordan blocks.
- The value of  $d_2 - d_1$  will tell us how many chains of length at least 2 we have.
- Generalising  $d_k - d_{k-1}$  tells us how many chains of length at least  $k$  we have.
- The horizontal layers correspond to the spaces  $Z_j$  and the vertical stacks correspond to the Jordan chains.

**Matrices with One Eigenvalue** If matrix  $A \in M_{p,p}(\mathbb{C})$  has only one eigenvalue,  $\lambda$ , then  $\text{GE}_\lambda(A) = \mathbb{C}^p$ . Furthermore, if such an  $A$  is diagonalisable then it is  $\lambda I$ .

## 8 Matrix Functions and ODEs

### 8.1 Powers and the Jordan Form

#### Powers of Matrices

- If  $A = PBP^{-1}$ , then  $A^n = PB^nP^{-1}$ .
- If  $M = A \oplus B$  then  $M^n = A^n \oplus B^n$ .
- If  $A\mathbf{v} = \lambda\mathbf{v}$  then  $A^n\mathbf{v} = \lambda^n\mathbf{v}$ .

**Binomial Theorem for Commuting Matrices** Let  $A$  and  $B$  be  $p \times p$  matrices for which  $AB = BA$ . Then for any integer  $n \geq 0$  we have

$$(A + B)^n = A^n + \binom{n}{1} A^{n-1} B + \binom{n}{2} A^{n-2} B^2 + \dots + B^n.$$

## 8.2 Power Series of Matrices

**Convergence Entrywise Definition** Suppose  $A^{(k)} = (a_{ij}^{(k)})$  for  $k = 1, 2, 3, \dots$  is a sequence of  $p \times q$  matrices then we say  $A^{(k)}$  converges entrywise to  $A$  as  $k \rightarrow \infty$  iff  $a_{ij}^{(k)} \rightarrow a_{ij}$  as  $k \rightarrow \infty$  for all  $i, j$ .

**Norms on Matrices** Let  $A \in M_{p,p}(\mathbb{C})$ .

The  $\infty$ -norm of  $A$  is defined by

$$\|A\|_{\infty} = \max\{|a_{ij}| : 1 \leq i, j \leq p\}.$$

The operator norm (or 2-norm) of  $A$  is defined as

$$\|A\|_{\text{op}} = \max\{\|A\mathbf{v}\| : \mathbf{v} \in \mathbb{C}^p \text{ and } \|\mathbf{v}\| = 1\},$$

The Frobenius norm of  $A$  is defined as  $\|A\|_F = \sqrt{\text{tr}(A^* A)}$ , which is the same as  $\sqrt{\sum_{i,j} |a_{ij}|^2}$ .

**Operator and Forenius Norm Relationship** Suppose  $A \in M_{p,p}(\mathbb{C})$  has non-zero singular values  $\sigma_1 \geq \sigma_2 \geq \dots \geq \sigma_k \geq 0$ . Then  $\|A\|_{\text{op}} = \sigma_1$  and  $\|A\|_F = \sqrt{\sigma_1^2 + \dots + \sigma_k^2}$ . It follows that for all such  $A$ ,

$$\|A\|_{\text{op}} \leq \|A\|_F \leq \sqrt{p} \|A\|_{\text{op}}.$$

**Forenius and Infinity Norm** For any matrix  $A \in M_{p,p}(\mathbb{C})$  we have

$$\|A\|_F \geq \|A\|_{\infty} \geq \frac{1}{p} \|A\|_F.$$

**Convergence in Norm** Suppose  $N$  is some norm on  $p \times p$  matrices and  $A^{(k)}$  is a sequence of  $p \times p$  matrices. Then we say  $A^{(k)}$  converges to  $A$  in the norm  $N$  iff  $N(A^{(k)} - A) \rightarrow 0$  as  $k \rightarrow \infty$ .

**Norm Equivalence** A sequence of  $p \times p$  matrices  $A^{(k)}$  converges to  $A$  in the  $\infty$ -norm iff it converges to  $A$  in the Frobenius norm iff it converges to  $A$  in the operator norm.

**Convergence Entrywise by  $\infty$ -norm** A sequence  $A^{(k)}$  tends to  $A$  entrywise if and only if it converges to  $A$  in the  $\infty$ -norm.

**$\infty$ -norm Products** Let  $A$  and  $B$  be  $p \times p$  complex matrices. Then

$$\|AB\|_{\infty} \leq p \|A\|_{\infty} \|B\|_{\infty}.$$

**Convergence is Preserved Under Similarity** Suppose sequence  $A^{(k)} \in M_{p,p}(\mathbb{C})$  converges to  $A$  and  $P$  is  $p \times p$  and invertible. Then the sequence  $B^{(k)} = P^{-1}A^{(k)}P$  converges to  $B = P^{-1}AP$ .

**Convergence of Power Series** Suppose  $f : \mathbb{C} \rightarrow \mathbb{C}$  has a power series expansion  $f(t) = \sum_{k=0}^{\infty} a_k t^k$  with a radius of convergence  $R$ , ( $R$  possibly  $\infty$ ). Then if  $A \in M_{p,p}(\mathbb{C})$ ,  $\sum a_k A^k$  converges provided  $p\|A\|_{\infty} < R$ . The limit is then called  $f(A)$ .

**Power Series Properties** Suppose  $f : \mathbb{C} \rightarrow \mathbb{C}$  has a power series expansion. Then

1. If  $f(A)$  is defined and  $B = PAP^{-1}$ , then  $f(B)$  is defined and  $f(B) = Pf(A)P^{-1}$ .
2. If  $M = A \oplus B$  and  $f(A)$  and  $f(B)$  are defined, so is  $f(M)$  and  $f(M) = f(A) \oplus f(B)$ .
3. If  $f(A)$  is defined and  $A\mathbf{v} = \lambda\mathbf{v}$  then  $f(\lambda)$  is defined and  $f(A)\mathbf{v} = f(\lambda)\mathbf{v}$ .

### 8.3 The Matrix Exponential

**Matrix Exponential Definition** Suppose  $A \in M_n(\mathbb{C})$ . Then

$$e^A = \exp(A) = I + A + \frac{1}{2!}A^2 + \cdots = \sum_{k=0}^{\infty} \frac{1}{k!}A^k.$$

**Derivative of The Matrix Exponential** For any  $A \in M_{p,p}(\mathbb{C})$ ,  $\exp(tA)$  is differentiable and

$$\frac{d}{dt}\exp(tA) = A\exp(tA) = \exp(tA)A.$$

**Solution to Initial Value Problem** Let  $A \in M_{p,p}(\mathbb{C})$  and  $\mathbf{c} \in \mathbb{C}^p$ ; then

$$\mathbf{y}(t) = e^{tA}\mathbf{c}$$

is a solution of the initial value problem

$$\mathbf{y}' = A\mathbf{y}, \quad \mathbf{y}(0) = \mathbf{c}.$$

**Invertible is Inverse** For each  $t$  and any  $A$ ,  $e^{tA}$  is invertible and has inverse  $e^{-tA}$ .

**Uniqueness of Solution** Let  $A \in M_{p,p}(\mathbb{C})$ . Then

1. If  $\mathbf{y}' = A\mathbf{y}$  and  $\mathbf{y}(0) = \mathbf{0}$ , then  $\mathbf{y} \equiv \mathbf{0}$ .
2. The set of solutions of  $\mathbf{y}' = A\mathbf{y}$  is a vector space of dimension  $p$  and the columns of  $e^{tA}$  form a basis for this space.
3. The initial value problem  $\mathbf{y}' = A\mathbf{y}$ ,  $\mathbf{y}(0) = \mathbf{c}$  has a unique solution  $\mathbf{y} = e^{tA}\mathbf{c}$ .

**Commutativity** If  $A, B$  in  $M_{p,p}(\mathbb{C})$  commute ( $AB = BA$ ) then

$$\exp(A + B) = \exp(A) \cdot \exp(B).$$

## 8.4 The Column Method

For a generalised eigenvector,  $\mathbf{v}$ , finding  $e^{tA}\mathbf{v}$  only involves a finite summation.

If  $A$  has only one eigenvalue,  $\lambda$  say, then

$$e^{tA} = e^{\lambda t} \left( I + t(A - \lambda I) + \cdots + \frac{1}{(k-1)!} t^{k-1} (A - \lambda I)^{k-1} \right)$$

where the largest Jordan block is  $k \times k$ , since every vector is a generalised eigenvector and in  $\ker((A - \lambda I)^k)$ .

## 8.5 Systems of Homogeneous Linear ODEs

**Fundamental Matrix** A square matrix whose columns are independent as functions of  $t$  and are solutions of  $\mathbf{y}' = \mathbf{A}\mathbf{y}$  is called a fundamental matrix for the system and is denoted by  $\phi(t)$ .