

Part IA - Vectors and Matrices

Theorems

Lectured by N. Peake

Michaelmas 2014

Complex numbers

Review of complex numbers, including complex conjugate, inverse, modulus, argument and Argand diagram. Informal treatment of complex logarithm, n -th roots and complex powers. de Moivre's theorem. [2]

Vectors

Review of elementary algebra of vectors in \mathbb{R}^3 , including scalar product. Brief discussion of vectors in \mathbb{R}^n and \mathbb{C}^n ; scalar product and the Cauchy-Schwarz inequality. Concepts of linear span, linear independence, subspaces, basis and dimension.

Suffix notation: including summation convention, δ_{ij} and ϵ_{ijk} . Vector product and triple product: definition and geometrical interpretation. Solution of linear vector equations. Applications of vectors to geometry, including equations of lines, planes and spheres. [5]

Matrices

Elementary algebra of 3×3 matrices, including determinants. Extension to $n \times n$ complex matrices. Trace, determinant, non-singular matrices and inverses. Matrices as linear transformations; examples of geometrical actions including rotations, reflections, dilations, shears; kernel and image. [4]

Simultaneous linear equations: matrix formulation; existence and uniqueness of solutions, geometric interpretation; Gaussian elimination. [3]

Symmetric, anti-symmetric, orthogonal, hermitian and unitary matrices. Decomposition of a general matrix into isotropic, symmetric trace-free and antisymmetric parts. [1]

Eigenvalues and Eigenvectors

Eigenvalues and eigenvectors; geometric significance. [2]

Proof that eigenvalues of hermitian matrix are real, and that distinct eigenvalues give an orthogonal basis of eigenvectors. The effect of a general change of basis (similarity transformations). Diagonalization of general matrices: sufficient conditions; examples of matrices that cannot be diagonalized. Canonical forms for 2×2 matrices. [5]

Discussion of quadratic forms, including change of basis. Classification of conics, cartesian and polar forms. [1]

Rotation matrices and Lorentz transformations as transformation groups. [1]

Contents

1	Complex numbers	3
1.1	Basic properties	3
1.2	Complex exponential function	3
1.3	Roots of unity	3
1.4	Complex logarithm and power	3
1.5	De Moivre's theorem	3
1.6	Lines and circles in \mathbb{C}	3
2	Vectors	4
2.1	Definition and basic properties	4
2.2	Scalar product	4
2.2.1	Geometric picture (\mathbb{R}^2 and \mathbb{R}^3 only)	4
2.2.2	General algebraic definition	4
2.3	Cauchy-Schwarz inequality	4
2.4	Vector product	4
2.5	Scalar triple product	4
2.6	Spanning sets and bases	4
2.6.1	2D space	4
2.6.2	3D space	4
2.6.3	\mathbb{R}^n space	4
2.6.4	\mathbb{C}^n space	4
2.7	Vector subspaces	4
2.8	Suffix notation	4
2.8.1	Spherical trigonometry	5
2.9	Geometry	5
2.9.1	Lines	5
2.9.2	Plane	5
2.10	Vector equations	5
3	Linear maps	6
3.1	Examples	6
3.1.1	Rotation in \mathbb{R}^3	6
3.1.2	Reflection in \mathbb{R}^3	6
3.2	Linear Maps	6
3.3	Rank and nullity	6
3.4	Matrices	6
3.4.1	Examples	6
3.4.2	Matrix Algebra	6
3.4.3	Decomposition of an $n \times n$ matrix	6
3.4.4	Matrix inverse	6
3.5	Determinants	6
3.5.1	Permutations	6
3.5.2	Properties of determinants	7
3.5.3	Minors and Cofactors	7

4	Matrices and linear equations	8
4.1	Simple example, 2×2	8
4.2	Inverse of an $n \times n$ matrix	8
4.3	Homogeneous and inhomogeneous equations	8
4.3.1	Gaussian elimination	8
4.4	Matrix rank	8
4.5	Homogeneous problem $A\mathbf{x} = \mathbf{0}$	8
4.5.1	Geometrical interpretation	8
4.5.2	Linear mapping view of $A\mathbf{x} = \mathbf{0}$	8
4.6	General solution of $A\mathbf{x} = \mathbf{d}$	8
5	Eigenvalues and eigenvectors	9
5.1	Preliminaries and definitions	9
5.2	Linearly independent eigenvectors	9
5.3	Transformation matrices	9
5.3.1	Transformation law for vectors	9
5.3.2	Transformation law for matrix	9
5.4	Similar matrices	9
5.5	Diagonalizable matrices	9
5.6	Canonical (Jordan normal) form	10
5.7	Cayley-Hamilton Theorem	10
5.8	Eigenvalues and eigenvectors of a Hermitian matrix	10
5.8.1	Gram-Schmidt orthogonalization (non-examinable)	10
5.8.2	Unitary transformation	10
5.8.3	Diagonalization of $n \times n$ Hermitian matrices	10
5.8.4	Normal matrices	10
6	Quadratic forms and conics	11
6.1	Quadrics and conics	11
6.1.1	Conic sections ($n = 2$)	11
6.2	Focus-directrix property	11
7	Transformation groups	12
7.1	Groups of orthogonal matrices	12
7.2	Length preserving matrices	12
7.3	Lorentz transformations	12

1 Complex numbers

1.1 Basic properties

Theorem (Triangle inequality). for all $z_1, z_2 \in \mathbb{C}$, we have

$$|z_1 + z_2| \leq |z_1| + |z_2|.$$

Alternatively, we have $|z_1 - z_2| \geq ||z_1| - |z_2||$

Proposition. $z\bar{z} = a^2 + b^2 = |z|.$

Proposition. $z^{-1} = \frac{\bar{z}}{|z|}$

1.2 Complex exponential function

Lemma.

$$\sum_{n=0}^{\infty} \sum_{m=0}^{\infty} a_{mn} = \sum_{r=0}^{\infty} \sum_{m=0}^r a_{r-m,m}$$

Theorem. $\exp(z_1)\exp(z_2) = \exp(z_1 + z_2)$

Theorem. $e^{iz} = \cos z + i \sin z$

1.3 Roots of unity

Proposition. If $\omega = \exp\left(\frac{2\pi i}{n}\right)$, then $1 + \omega + \omega^2 + \dots + \omega^{n-1} = 1$

1.4 Complex logarithm and power

1.5 De Moivre's theorem

Theorem (De Moivre's theorem).

$$\cos n\theta + i \sin n\theta = (\cos \theta + i \sin \theta)^n.$$

1.6 Lines and circles in \mathbb{C}

Theorem. The general equation of a straight line through $z_0 \in \mathbb{C}$ parallel to $w \in \mathbb{C}$ can be given by $z = z_0 + \lambda w$ for $\lambda \in \mathbb{R}$. This can be rearranged to $\lambda = \frac{z-z_0}{w}$. Taking the complex conjugate, we have $\bar{\lambda} = \frac{\bar{z}-\bar{z}_0}{\bar{w}}$. However, since λ is real, we have $\lambda = \bar{\lambda}$. Thus we have

$$\begin{aligned} \frac{z - z_0}{w} &= \frac{\bar{z} - \bar{z}_0}{\bar{w}} \\ z\bar{w} - \bar{z}w &= z_0\bar{w} - \bar{z}_0w \end{aligned}$$

The general equation of a circle with center $c \in \mathbb{C}$ and radius $\rho \in \mathbb{R}^+$ can be given by

$$\begin{aligned} |z - c| &= \rho \\ |z - c|^2 &= \rho^2 \\ (z - c)(\bar{z} - \bar{c}) &= \rho^2 \\ z\bar{z} - \bar{c}z - c\bar{z} &= \rho^2 - c\bar{c} \end{aligned}$$

2 Vectors

2.1 Definition and basic properties

2.2 Scalar product

2.2.1 Geometric picture (\mathbb{R}^2 and \mathbb{R}^3 only)

2.2.2 General algebraic definition

2.3 Cauchy-Schwarz inequality

Theorem (Cauchy-Schwarz inequality). For all $\mathbf{x}, \mathbf{y} \in \mathbb{R}$,

$$\mathbf{x} \cdot \mathbf{y} \leq |\mathbf{x}| |\mathbf{y}|$$

Corollary (Triangle inequality).

$$|\mathbf{x} + \mathbf{y}| \leq |\mathbf{x}| + |\mathbf{y}|$$

2.4 Vector product

2.5 Scalar triple product

Proposition. If a parallelepiped has sides represented by vectors $\mathbf{a}, \mathbf{b}, \mathbf{c}$ that form a right-handed system, then the volume of the parallelepiped is given by $[\mathbf{a}, \mathbf{b}, \mathbf{c}]$.

Theorem. $\mathbf{a} \times (\mathbf{b} + \mathbf{c}) = \mathbf{a} \times \mathbf{b} + \mathbf{a} \times \mathbf{c}$.

2.6 Spanning sets and bases

2.6.1 2D space

Theorem. The coefficients λ, μ are unique.

2.6.2 3D space

Theorem. If $\mathbf{a}, \mathbf{b}, \mathbf{c} \in \mathbb{R}^3$ are non-coplanar, i.e. $\mathbf{a} \cdot (\mathbf{b} \times \mathbf{c}) \neq 0$, then they form a basis of \mathbb{R}^3 .

2.6.3 \mathbb{R}^n space

2.6.4 \mathbb{C}^n space

2.7 Vector subspaces

2.8 Suffix notation

Theorem. $\epsilon_{ijk}\epsilon_{ipq} = \delta_{jp}\delta_{kq} - \delta_{jq}\delta_{kp}$

Proposition.

$$\mathbf{a} \cdot (\mathbf{b} \times \mathbf{c}) = \mathbf{b} \cdot (\mathbf{c} \times \mathbf{a})$$

Theorem (Vector triple product).

$$\mathbf{a} \times (\mathbf{b} \times \mathbf{c}) = (\mathbf{a} \cdot \mathbf{c})\mathbf{b} - (\mathbf{a} \cdot \mathbf{b})\mathbf{c}$$

2.8.1 Spherical trigonometry

Proposition. $(\mathbf{a} \times \mathbf{b}) \cdot (\mathbf{b} \times \mathbf{c}) = (\mathbf{a} \cdot \mathbf{a})(\mathbf{b} \cdot \mathbf{c}) - (\mathbf{a} \cdot \mathbf{b})(\mathbf{a} \cdot \mathbf{c}).$

2.9 Geometry

2.9.1 Lines

Theorem. The equation of a straight line through a and parallel to t is

$$(\mathbf{x} - \mathbf{a}) \times \mathbf{t} = \mathbf{0} \text{ or } \mathbf{x} \times \mathbf{t} = \mathbf{a} \times \mathbf{t}.$$

2.9.2 Plane

Theorem. The equation of a plane through b with normal n is given by

$$\mathbf{x} \cdot \mathbf{n} = \mathbf{b} \cdot \mathbf{n}.$$

2.10 Vector equations

3 Linear maps

3.1 Examples

3.1.1 Rotation in \mathbb{R}^3

3.1.2 Reflection in \mathbb{R}^3

3.2 Linear Maps

Theorem. Consider a linear map $f : U \rightarrow V$, where U, V are vector spaces. Then $\text{Im}(f)$ is a subspace of V , and $\ker(f)$ is a subspace of U .

3.3 Rank and nullity

Theorem (Rank-nullity theorem). For a linear map $f : U \rightarrow V$,

$$r(f) + n(f) = \dim(U).$$

3.4 Matrices

3.4.1 Examples

3.4.2 Matrix Algebra

Proposition.

(i) $(A^T)^T = A$.

(ii) If \mathbf{x} is a column vector $\begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{pmatrix}$, \mathbf{x}^T is a row vector $(x_1 \ x_2 \ \cdots \ x_n)$.

(iii) $(AB)^T = B^T A^T$ since $(AB)_{ij}^T = (AB)_{ji} = A_{jk} B_{ki} = B_{ki} A_{jk} = (B^T)_{ik} (A^T)_{kj} = (B^T A^T)_{ij}$.

Proposition. $\text{tr}(BC) = \text{tr}(CB)$

Proposition. The columns of a matrix are the images of the standard basis vectors under the mapping α .

3.4.3 Decomposition of an $n \times n$ matrix

3.4.4 Matrix inverse

Proposition. $(AB)^{-1} = B^{-1} A^{-1}$

3.5 Determinants

3.5.1 Permutations

Proposition. Any q -cycle can be written as a product of 2-cycles.

Proposition.

$$\begin{vmatrix} a & b \\ c & d \end{vmatrix} = ad - bc$$

3.5.2 Properties of determinants

Proposition. $\det(A) = \det(A^T)$.

Proposition. If matrix B is formed by multiplying every element in a single row of A by a scalar λ , then $\det(B) = \lambda \det(A)$. Consequently, $\det(\lambda A) = \lambda^n \det(A)$.

Proposition. If 2 rows (or 2 columns) of A are identical, the determinant is 0.

Proposition. If 2 rows or 2 columns are linearly dependent, then the determinant is zero.

Proposition. $\det(AB) = \det(A) \det(B)$.

Corollary. If A is orthogonal, $\det A = \pm 1$.

Corollary. If U is unitary, $|\det U| = 1$

Proposition. In \mathbb{R}^3 , orthogonal matrices represent either a rotation ($\det = -1$) or a reflection ($\det = 1$).

3.5.3 Minors and Cofactors

Theorem (Laplace expansion formula). For any particular fixed i ,

$$\det A = \sum_{j=1}^n A_{j_i i} \Delta_{j_i i}.$$

4 Matrices and linear equations

4.1 Simple example, 2×2

4.2 Inverse of an $n \times n$ matrix

Lemma. $\sum A_{ik} \Delta_{jk} = \delta_{ij} \det A$

Theorem. If $\det A \neq 0$, then A^{-1} exists and is given by

$$(A^{-1})_{ij} = \frac{\Delta_{ji}}{\det A}$$

4.3 Homogeneous and inhomogeneous equations

4.3.1 Gaussian elimination

4.4 Matrix rank

Theorem. The column rank and row rank are equal for any $m \times n$ matrix.

4.5 Homogeneous problem $Ax = 0$

4.5.1 Geometrical interpretation

4.5.2 Linear mapping view of $Ax = 0$

4.6 General solution of $Ax = d$

5 Eigenvalues and eigenvectors

5.1 Preliminaries and definitions

Theorem (Fundamental theorem of algebra). Consider polynomial $p(z)$ of degree $m \geq 1$, i.e.

$$p(z) = \sum_{j=0}^m c_j z^j,$$

where $c_j \in \mathbb{C}$ and $c_m \neq 0$.

Then $p(z) = 0$ has precisely m (not necessarily distinct) roots in the complex roots, accounting for multiplicity.

Theorem. λ is an eigenvalue of A iff

$$\det(A - \lambda I) = 0.$$

5.2 Linearly independent eigenvectors

Theorem. Suppose $n \times n$ matrix A has *distinct* eigenvalues $\lambda_1, \lambda_2, \dots, \lambda_n$. Then the corresponding eigenvectors $\mathbf{x}_1, \mathbf{x}_2, \dots, \mathbf{x}_n$ are linearly independent.

5.3 Transformation matrices

5.3.1 Transformation law for vectors

Theorem. Denote vector as \mathbf{u} with respect to $\{\mathbf{e}_i\}$ and $\tilde{\mathbf{u}}$ with respect to $\{\tilde{\mathbf{e}}_i\}$. Then

$$\mathbf{u} = P\tilde{\mathbf{u}} \text{ and } \tilde{\mathbf{u}} = P^{-1}\mathbf{u}$$

5.3.2 Transformation law for matrix

Theorem.

$$\tilde{A} = P^{-1}AP.$$

5.4 Similar matrices

Proposition. Similar matrices have the following properties:

- (i) Similar matrices have the same determinant.
- (ii) Similar matrices have the same trace.
- (iii) Similar matrices have the same characteristic polynomial.

5.5 Diagonalizable matrices

Theorem. Let $\lambda_1, \lambda_2, \dots, \lambda_r$, with $r \leq n$ be the distinct eigenvalues of A . Let B_1, B_2, \dots, B_r be the bases of the eigenspaces $E_{\lambda_1}, E_{\lambda_2}, \dots, E_{\lambda_r}$ correspondingly.

Then the set $B = \bigcup_{i=1}^r B_i$ is linearly independent.

Proposition. A is diagonalizable iff all its eigenvalues have non-zero defect.

5.6 Canonical (Jordan normal) form

Theorem. Any 2×2 complex matrix A is similar to exactly one of

$$\begin{pmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{pmatrix}, \begin{pmatrix} \lambda & 0 \\ 0 & \lambda \end{pmatrix}, \begin{pmatrix} \lambda & 1 \\ 0 & \lambda \end{pmatrix}$$

Proposition. (Without proof) The canonical form, or Jordan normal form, exists for any $n \times n$ matrix A . i.e. Specifically, there exists a similarity transform such that A is similar to a matrix \tilde{A} that satisfies the following properties:

- (i) $\tilde{A}_{\alpha\alpha} = \lambda_\alpha$, i.e. the diagonal composes of the eigenvalues.
- (ii) $\tilde{A}_{\alpha, \alpha+1} = 0$ or 1 .
- (iii) $\tilde{A}_{ij} = 0$ otherwise.

5.7 Cayley-Hamilton Theorem

Theorem (Cayley-Hamilton theorem). Every $n \times n$ complex matrix satisfies its own characteristic equation.

5.8 Eigenvalues and eigenvectors of a Hermitian matrix

Theorem. The eigenvalues of a Hermitian matrix H are real.

Theorem. The eigenvectors of a Hermitian matrix H corresponding to distinct eigenvalues are orthogonal.

5.8.1 Gram-Schmidt orthogonalization (non-examinable)

5.8.2 Unitary transformation

5.8.3 Diagonalization of $n \times n$ Hermitian matrices

Theorem. An $n \times n$ Hermitian matrix has precisely n orthogonal eigenvectors.

5.8.4 Normal matrices

Proposition. It can be shown that:

- (i) If λ is an eigenvalue of N , then so is λ^* .
- (ii) The eigenvectors of distinct eigenvalues are orthogonal.
- (iii) A normal matrix can always be diagonalized with an orthonormal basis of eigenvectors.

6 Quadratic forms and conics

Theorem. Hermitian forms are real.

6.1 Quadrics and conics

6.1.1 Conic sections ($n = 2$)

6.2 Focus-directrix property

7 Transformation groups

7.1 Groups of orthogonal matrices

Proposition. The set of all $n \times n$ orthogonal matrices P forms a group under matrix multiplication:

0. If P, Q are orthogonal, then consider $R = PQ$. $RR^T = (PQ)(PQ)^T = P(QQ^T)P^T = PP^T = I$. So R is orthogonal.
1. I satisfies $II^T = I$. So I is orthogonal and in the group.
2. Inverse: if P is orthogonal, then $P^{-1} = P^T$ by definition, which is also orthogonal.
3. We shown previously that matrix multiplication is associative

7.2 Length preserving matrices

Theorem. Let $P \in O(n)$. Then the following are equivalent:

- (i) P is orthogonal
- (ii) $|P\mathbf{x}| = |\mathbf{x}|$
- (iii) $(P\mathbf{x})^T(P\mathbf{y}) = \mathbf{x}^T\mathbf{y}$, i.e. $(P\mathbf{x}) \cdot (P\mathbf{y}) = \mathbf{x} \cdot \mathbf{y}$.
- (iv) If $(\mathbf{v}_1, \mathbf{v}_2, \dots, \mathbf{v}_n)$ are orthonormal, so are $(P\mathbf{v}_1, P\mathbf{v}_2, \dots, P\mathbf{v}_n)$
- (v) The columns of P are orthonormal.

7.3 Lorentz transformations