

Linear Algebra: Example Sheet 3 of 4

1. Find the eigenvalues and give bases for the eigenspaces of the following complex matrices:

$$\begin{pmatrix} 1 & 1 & 0 \\ 0 & 3 & -2 \\ 0 & 1 & 0 \end{pmatrix}, \quad \begin{pmatrix} 1 & 1 & -1 \\ 0 & 3 & -2 \\ 0 & 1 & 0 \end{pmatrix}, \quad \begin{pmatrix} 1 & 1 & -1 \\ -1 & 3 & -1 \\ -1 & 1 & 1 \end{pmatrix}.$$

The second and third matrices commute; find a basis with respect to which they are both diagonal.

2. By considering the rank or minimal polynomial of a suitable matrix, find the eigenvalues of the $n \times n$ matrix A with each diagonal entry equal to λ and all other entries 1. Hence write down the determinant of A .
3. (i) Let V be a vector space, let $\pi_1, \pi_2, \dots, \pi_k$ be endomorphisms of V such that $\text{id}_V = \pi_1 + \dots + \pi_k$ and $\pi_i \pi_j = 0$ for any $i \neq j$. Show that $V = U_1 \oplus \dots \oplus U_k$, where $U_j = \text{Im}(\pi_j)$.
(ii) Let α be an endomorphism of V satisfying the equation $\alpha^3 = \alpha$. By finding suitable endomorphisms of V depending on α , use (i) to prove that $V = V_0 \oplus V_1 \oplus V_{-1}$, where V_λ is the λ -eigenspace of α .
4. Let α be an endomorphism of a complex vector space. Show that if λ is an eigenvalue for α then λ^2 is an eigenvalue for α^2 . Show further that every eigenvalue of α^2 arises in this way. Are the eigenspaces $\text{Ker}(\alpha - \lambda I)$ and $\text{Ker}(\alpha^2 - \lambda^2 I)$ necessarily the same?
5. (Another proof of the Diagonalisability Theorem.) Let V be a vector space of finite dimension. Show that if α_1 and α_2 are endomorphisms of V , then the nullity $n(\alpha_1 \alpha_2)$ satisfies $n(\alpha_1 \alpha_2) \leq n(\alpha_1) + n(\alpha_2)$. Deduce that if α is an endomorphism of V such that $p(\alpha) = 0$ for some polynomial $p(t)$ which is a product of distinct linear factors, then α is diagonalisable.
6. Without appealing directly to the uniqueness of Jordan Normal Form show that none of the following matrices are similar:

$$\begin{pmatrix} 1 & 1 & 0 \\ 0 & 1 & 1 \\ 0 & 0 & 1 \end{pmatrix}, \quad \begin{pmatrix} 1 & 1 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}, \quad \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}.$$

Is the matrix

$$\begin{pmatrix} -2 & -2 & -1 \\ 3 & 3 & 1 \\ 3 & 2 & 2 \end{pmatrix}$$

similar to any of them? If so, which? Find a basis such that it is in Jordan Normal Form.

7. (a) Recall that the Jordan normal form of a 3×3 complex matrix can be deduced from its characteristic and minimal polynomials. Give an example to show that this is not so for 4×4 complex matrices.
(b) Let A be a 5×5 complex matrix with $A^4 = A^2 \neq A$. What are the possible minimal polynomials of A ? If A is not diagonalisable, what are the possible characteristic polynomials and JNFs of A ?
8. Let V be a vector space of dimension n and α an endomorphism of V with $\alpha^n = 0$ but $\alpha^{n-1} \neq 0$. Show that there is a vector y such that $(y, \alpha(y), \alpha^2(y), \dots, \alpha^{n-1}(y))$ is a basis for V .
Show that if β is an endomorphism of V which commutes with α , then $\beta = p(\alpha)$ for some polynomial p .
[Hint: consider $\beta(y)$.] What is the form of the matrix for β with respect to the above basis?
9. (a) Let A be an invertible square matrix. Describe the eigenvalues and the characteristic and minimal polynomials of A^{-1} in terms of those of A .
(b) Prove that the inverse of a Jordan block $J_m(\lambda)$ with $\lambda \neq 0$ has Jordan Normal Form a Jordan block $J_m(\lambda^{-1})$. Use this to find the Jordan Normal Form of A^{-1} , for an invertible square matrix A .
(c) Prove that any square complex matrix is similar to its transpose.

10. Let C be an $n \times n$ matrix over \mathbb{C} , and write $C = A + iB$, where A and B are real $n \times n$ matrices. By considering $\det(A + \lambda B)$ as a function of λ , show that if C is invertible then there exists a real number λ such that $A + \lambda B$ is invertible. Deduce that if two $n \times n$ real matrices P and Q are similar when regarded as matrices over \mathbb{C} , then they are similar as matrices over \mathbb{R} .
11. Let $f(x) = a_0 + a_1x + \dots + a_nx^n$, with $a_i \in \mathbb{C}$, and let C be the *circulant* matrix

$$\begin{pmatrix} a_0 & a_1 & a_2 & \dots & a_n \\ a_n & a_0 & a_1 & \dots & a_{n-1} \\ a_{n-1} & a_n & a_0 & \dots & a_{n-2} \\ \vdots & & & \ddots & \vdots \\ a_1 & a_2 & a_3 & \dots & a_0 \end{pmatrix}.$$

Show that the determinant of C is $\det C = \prod_{j=0}^n f(\zeta^j)$, where $\zeta = \exp(2\pi i/(n+1))$.

12. Let V denote the space of all infinitely differentiable functions $\mathbb{R} \rightarrow \mathbb{R}$ and let α be the differentiation endomorphism $f \mapsto f'$.
- (i) Show that every real number λ is an eigenvalue of α . Show also that $\ker(\alpha - \lambda\iota)$ has dimension 1.
 - (ii) Show that $\alpha - \lambda\iota$ is surjective for every real number λ .