

# LINEAR ALGEBRA - Solved Exercises 2

(Real and complex finite-dimensional vector spaces)

Nicolae Cotfas, version 16 Feb. 2022 (for future updates see <https://unibuc.ro/user/nicolae.cotfas/>)

## A PARTIAL EVALUATION A

### Exercise 1

**A1** Prove that  
 $S = \{v_1 = (1, 0), v_2 = (1, 1)\}$   
 is a basis in the vector space  $\mathbb{R}^2$ .

**A2** Find the dimension of the space  
 $V = \{x = (x_1, x_2, x_3) \in \mathbb{R}^3 \mid x_1 + x_2 - x_3 = 0\}$ .

### Exercise 2

**A3** Find the eigenvalues of the linear operator  
 $A: \mathbb{R}^3 \rightarrow \mathbb{R}^3, \quad A(x_1, x_2, x_3) = (x_2, x_1, 2x_3)$ ,  
 and describe the corresponding eigenspaces.

**A4** Find the eigenvalues of the linear operator  
 $A: \mathbb{C}^2 \rightarrow \mathbb{C}^2, \quad A(z_1, z_2) = (-z_2, z_1)$ ,  
 and describe the corresponding eigenspaces.

### Exercise 3

**A5** Is the linear operator  
 $A: \mathbb{R}^3 \rightarrow \mathbb{R}^3,$   
 $A(x_1, x_2, x_3) = (2x_1 + x_2, 2x_2, 3x_3)$ ,  
 diagonalizable?

**A6** In  $\mathbb{R}^4$ , find  $\dim(W_1 + W_2)$ , where  
 $W_1 = \text{span}\{(1, -1, 0, 2), (0, 1, 1, 1), (1, 0, 1, 3)\}$ ,  
 $W_2 = \text{span}\{(1, 0, 0, 0), (1, 1, 1, 1), (0, -1, 0, 2)\}$ .

**A7** Find the eigenvalues of the operator  $A^{-1}$ , where  
 $A: \mathbb{R}^3 \rightarrow \mathbb{R}^3,$   
 $A(x_1, x_2, x_3) = (x_2 + x_3, x_1 + x_3, x_1 + x_2)$ ,  
 and describe the corresponding eigenspaces.

**A8** Let  $f(x) = x^{20} - 2x^{-15} + 1$  and  
 $A: \mathbb{C}^2 \rightarrow \mathbb{C}^2, \quad A(z_1, z_2) = (-z_2, z_1)$ .  
 Find the eigenvalues of  $f(A)$ , and describe the corresponding eigenspaces.

## Some definitions, notations and results

**1 Definition.**  $\{v_1, v_2, \dots, v_n\}$  is a  
 linearly independent set of vectors if  $\begin{cases} \alpha_1 v_1 + \alpha_2 v_2 + \dots + \alpha_n v_n = 0 \\ \alpha_1 = \alpha_2 = \dots = \alpha_n = 0 \end{cases}$

**2 Definition.** In a vector space over the field  $K = \mathbb{R}$  or  $\mathbb{C}$ ,  
 $\text{span}\{v_1, v_2, \dots, v_n\} \stackrel{\text{def}}{=} \{\alpha_1 v_1 + \alpha_2 v_2 + \dots + \alpha_n v_n \mid \alpha_k \in K\}$

**3 Definition.**  $\mathfrak{B} = \{v_1, v_2, \dots, v_n\}$  is a basis of  $V$  if  $\begin{cases} V = \text{span } \mathfrak{B} \\ \text{and} \\ \mathfrak{B} \text{ linearly indep.} \end{cases}$

**4 Definition.** Dimension of a vector space over  $K$  is  $\dim_K V \stackrel{\text{def}}{=} \begin{cases} \text{number of vectors of a basis} & \text{if } V \neq \{0\}; \\ 0 & \text{if } V = \{0\}. \end{cases}$

**5 Definition.** The sum of the subspaces  $W_1, W_2 \subset V$  is  $W_1 + W_2 \stackrel{\text{def}}{=} \left\{ w_1 + w_2 \mid \begin{matrix} w_1 \in W_1 \\ w_2 \in W_2 \end{matrix} \right\}$

**6 Definition.** Linear operator  $A: V \rightarrow V$  is diagonalizable if  $\begin{cases} \text{there exists an basis of } V \\ \text{consisting of eigenvectors of } A. \end{cases}$

**7 Definition.** In a Hilbert space  $\mathcal{H}$ :  
 An operator  $A: \mathcal{H} \rightarrow \mathcal{H}$  is a self-adjoint operator if  $\langle Ax, y \rangle = \langle x, Ay \rangle \quad \forall x, y \in \mathcal{H}$ .

## B PARTIAL EVALUATION B

### Exercise 1

Solve the differential equations

**B1**  $y'' + 2y' - 3y = 0$ .

**B2**  $y'' + 2y' + y = 0$ .

**B3**  $y'' + 2y' + 3y = 0$ .

### Exercise 2

**B4** Prove that the linear operator  
 $A: \mathbb{C}^3 \rightarrow \mathbb{C}^3, \quad A(x_1, x_2, x_3) = (x_3, x_2, x_1)$ ,  
 is self-adjoint, and find its eigenvalues/eigenvectors.

**B5** Prove that the linear operator  
 $U: \mathbb{C}^2 \rightarrow \mathbb{C}^2, \quad U(x_1, x_2) = \frac{1}{\sqrt{2}}(x_1 + x_2, x_1 - x_2)$ ,  
 is unitary, and find its eigenvalues/eigenvectors.

### Exercise 3

Let  $s \in \{1, 2, 3, \dots\}$ ,  $d = 2s + 1$ , and  $\mathcal{H}$  be the complex Hilbert space of all the functions  
 $\psi: \{-s, -s+1, \dots, s-1, s\} \rightarrow \mathbb{C}$   
 with the usual scalar product

$$\langle \psi, \phi \rangle = \sum_{n=-s}^s \overline{\psi(n)} \phi(n).$$

**B6** Prove that the parity operator  
 $\Pi: \mathcal{H} \rightarrow \mathcal{H}: \psi \mapsto \Pi\psi, \quad (\Pi\psi)(n) = \psi(-n)$ ,  
 is a self-adjoint operator.

**B7** Find the eigenvalues of  $\Pi$  and the dimension of the corresponding eigenspaces.

**B8** Prove that the Fourier transform  
 $F: \mathcal{H} \rightarrow \mathcal{H}: \psi \mapsto F[\psi],$   
 $(F[\psi])(k) = \frac{1}{\sqrt{2}} \sum_{n=-s}^s e^{-i\frac{\pi}{2}kn} \psi(n),$   
 is a unitary transform.

**B9** Prove that the operators  
 $Q: \mathcal{H} \rightarrow \mathcal{H}: \psi \mapsto Q\psi, \quad (Q\psi)(n) = n\psi(n),$   
 $P: \mathcal{H} \rightarrow \mathcal{H}, \quad P = F^2 Q F,$   
 are self-adjoint, and find their eigenvalues and the corresponding eigenfunctions.

**8 Definition.** In a Hilbert space  $\mathcal{H}$ :  
 An operator  $A: \mathcal{H} \rightarrow \mathcal{H}$  is a unitary operator if  $\langle Ax, Ay \rangle = \langle x, y \rangle \quad \forall x, y \in \mathcal{H}$ .

**9 Definition.** In the case of vector space over  $K = \mathbb{R}$  or  $\mathbb{C}$ ,  
 $\lambda$  is an eigenvalue of a linear operator if  $\begin{cases} \lambda \in K \quad \text{and} \\ \text{there exists } v \in V, v \neq 0 \\ \text{(eigenvector corresp. to } \lambda) \\ \text{such that } Ax = \lambda v. \end{cases}$

The eigenspace corresponding to  $\lambda$  is  $\{x \mid Ax = \lambda x\}$ .

**10 Theorem.** In the case of vector space over  $K = \mathbb{R}$  or  $\mathbb{C}$ ,

$\lambda$  is an eigenvalue of a linear operator  $A: V \rightarrow V$   $\Leftrightarrow$   $\begin{cases} \lambda \in K \quad \text{and} \\ \lambda \text{ is a root of the equation} \\ \begin{vmatrix} a_1^1 - \lambda & a_1^2 & \dots & a_1^n \\ a_2^1 & a_2^2 - \lambda & \dots & a_2^n \\ \vdots & \vdots & \ddots & \vdots \\ a_n^1 & a_n^2 & \dots & a_n^n - \lambda \end{vmatrix} = 0 \end{cases}$

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