Homework 1: Vector spaces

Deadline: 23rd April (23:55 JST), 2026

Exercise 0. (2 Points)

(i) Solve the exercises below and write your solutions by hand (on paper or a tablet). Typed solutions (e.g., in LaTeX) are not allowed. Create **one pdf-file** which contains your name on the first page and submit it before the deadline ends in TACT at the Assignment "Homework 1". Use precisely the following format as a filename: "**Familyname_Givenname_LA2_HW1.pdf**". Repeat this for future Homework by replacing HW1 with HW2, HW3, etc.. Points will be removed in future homeworks if this is not the case.

(ii) Read Chapter 14 of the lecture notes and compare the results and definitions with the corresponding results in Linear Algebra I (Chapters 1-13).

Exercise 1. (3+2+2+1 = 8 Points) Let $\varphi : \mathbb{R} \to \mathbb{R}$ be an injective function. Define on $V := \operatorname{im}(\varphi)$ the addition $\oplus$ and the scalar multiplication $\odot$ for $u, v \in V$ and $\lambda \in \mathbb{R}$ by

$$u \oplus v = \varphi(\varphi^{-1}(u) + \varphi^{-1}(v)),$$
$$\lambda \odot v = \varphi(\lambda \cdot \varphi^{-1}(v)).$$

Here $+$ and $\cdot$ denote the usual addition and multiplication in $\mathbb{R}$.

(i) Show that $(V, \oplus, \odot)$ is a vector space. What is the neutral element of $(V, \oplus, \odot)$?
(i.e. check that the operations $\oplus$ and $\odot$ satisfy the properties $(A.1) - (A.4)$ and $(C.1) - (C.4)$.)

(ii) Determine all subspaces of $(V, \oplus, \odot)$.

(iii) Find an isomorphism

$$F : (\mathbb{R}, +, \cdot) \longrightarrow (V, \oplus, \odot).$$

Here $(\mathbb{R}, +, \cdot)$ denotes the vector space $\mathbb{R}^1$ with the usual addition and multiplication of real numbers.

(iv) Do (ii) and (iii) explicitly for the case $\varphi(x) = e^x$.

Exercise 2. (2+2+2 = 6 Points) Define for $M \in \mathbb{R}^{2\times 2}$ the following set

$$C(M) = \left\{ A \in \mathbb{R}^{2\times 2} \mid AM = MA \right\}.$$

(i) Show that for a given fixed $M \in \mathbb{R}^{2\times 2}$ the set $C(M)$ is a subspace of $\mathbb{R}^{2\times 2}$.

(ii) For $S = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}$ determine a basis of $C(S)$.

(iii) Show that for all $M \in \mathbb{R}^{2\times 2}$ we have $2 \le \dim(C(M)) \le 4$.

Exercise 3. (2+2+2+2 = 8 Points) Let $\mathcal{P}$ denote the set of all polynomial functions from $\mathbb{R}$ to $\mathbb{R}$. Define the following subsets

$$\mathcal{P}_3 = \{ f \in \mathcal{P} \mid \deg(f) \le 3 \},$$
$$U = \{ f \in \mathcal{P}_3 \mid f(-1) = f(1) = 0 \} \subset \mathcal{P}_3.$$

(i) Show that U is a subspace of $\mathcal{P}_3$ and determine a basis $B = (b_1, \ldots, b_n)$ of U.

(ii) Determine the coordinate vector $[f]_B$ for the function $f \in U$ given by $f(x) = (x+1)x(x-1)$.

(iii) Extend the basis B to a basis $\tilde{B}$ of $\mathcal{P}_3$.
(i.e. find a basis of $\mathcal{P}_3$, which contains all the basis elements of your basis B of U)