

Chapter 1: Vector Spaces

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Problem 1.1. Let \mathcal{V} be a vector space over \mathbb{F} . Show that if $\alpha, \beta \in \mathbb{F}$ and if \mathbf{v} is a nonzero vector in \mathcal{V} , then $\alpha\mathbf{v} = \beta\mathbf{v} \implies \alpha = \beta$. [HINT: $\alpha - \beta \neq 0 \implies \mathbf{v} = (\alpha - \beta)^{-1}(\alpha - \beta)\mathbf{v}$.]

Proof. Suppose, to the contrary, that there are distinct $\alpha, \beta \in \mathbb{F}$ such that for some nonzero $\mathbf{v} \in \mathcal{V}$ we have $\alpha\mathbf{v} = \beta\mathbf{v}$. Then, $\alpha - \beta \neq 0$ and so $\mathbf{v} = (\alpha - \beta)^{-1}(\alpha - \beta)\mathbf{v}$. Hence,

$$\mathbf{v} = (\alpha - \beta)^{-1}\alpha\mathbf{v} - (\alpha - \beta)^{-1}\beta\mathbf{v} = (\alpha - \beta)^{-1}(\alpha\mathbf{v} - \beta\mathbf{v}).$$

Since $\alpha\mathbf{v} = \beta\mathbf{v}$, it follows that $\alpha\mathbf{v} - \beta\mathbf{v} = \beta\mathbf{v} - \beta\mathbf{v} = \mathbf{0}$. This implies that $\mathbf{v} = (\alpha - \beta)^{-1}\mathbf{0} = \mathbf{0}$. This is a contradiction to our assumption that \mathbf{v} was nonzero.

Another way to prove this directly is by using the fact, for some $\alpha \in \mathbb{F}$ and nonzero vector \mathbf{v} , that $\alpha\mathbf{v} = \mathbf{0} \implies \alpha = 0$. A proof reads as follows:

Let $\alpha, \beta \in \mathbb{F}$ and $\mathbf{v} \in \mathcal{V}$ be some nonzero vector such that $\alpha\mathbf{v} = \beta\mathbf{v}$. Then, $\alpha\mathbf{v} - \beta\mathbf{v} = \beta\mathbf{v} - \beta\mathbf{v} = \mathbf{0}$ and so $(\alpha - \beta)\mathbf{v} = \mathbf{0}$. Since \mathbf{v} is nonzero, it follows that $\alpha - \beta = 0$ and so $\alpha = \beta$. \square

Problem 1.2. Show that the space \mathbb{R}^3 endowed with the rule

$$\mathbf{x} \square \mathbf{y} = \begin{bmatrix} \max(x_1, y_1) \\ \max(x_2, y_2) \\ \max(x_3, y_3) \end{bmatrix}$$

for vector addition and the usual rule for scalar multiplication is not a vector space over \mathbb{R} .

Proof. We show that this space has no unique additive identity. Consider some $\mathbf{x} = (x_1, x_2, x_3)$. Then, both $\mathbf{y} = (x_1 - 1, x_2 - 1, x_3 - 1)$ and $\mathbf{z} = (x_1 - 2, x_2 - 2, x_3 - 2)$ are in \mathbb{R}^3 and they are distinct. Note that $\mathbf{x} \square \mathbf{y} = \mathbf{x}$ and $\mathbf{x} \square \mathbf{z} = \mathbf{x}$.

In fact, one can easily show that there is no vector that is an additive inverse of every vector (the zero vector $\mathbf{0}$) since one can easily construct a vector with elements lower than the ones from any other vector. \square

Problem 1.3. Let $\mathcal{C} \subset \mathbb{R}^3$ denote the set of vectors $\mathbf{a} = \begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix}$ such that the polynomial

$a_1 + a_2t + a_3t^2 \geq 0$ for every $t \in \mathbb{R}$. Show that it is closed under vector addition (i.e., $\mathbf{a}, \mathbf{b} \in \mathcal{C} \implies \mathbf{a} + \mathbf{b} \in \mathcal{C}$), but that \mathcal{C} is not a vector space over \mathbb{R} . [REMARK: A set \mathcal{C} with the indicated two properties is called a **cone**.]

Proof. We first show that \mathcal{C} is closed under addition. Consider any $\mathbf{a}, \mathbf{b} \in \mathcal{C}$. Then, for every $t \in \mathbb{R}$ we have $a_1 + a_2t + a_3t^2 \geq 0$ and $b_1 + b_2t + b_3t^2 \geq 0$. Then,

$$a_1 + a_2t + a_3t^2 + b_1 + b_2t + b_3t^2 = (a_1 + b_1) + (a_2 + b_2)t + (a_3 + b_3)t^2 \geq 0$$

for every $t \in \mathbb{R}$. Thus, $\mathbf{a} + \mathbf{b} = \begin{bmatrix} a_1 + b_1 \\ a_2 + b_2 \\ a_3 + b_3 \end{bmatrix} \in \mathcal{C}$. However, it is not closed under scalar

multiplication. Consider some nonzero $\mathbf{v} \in \mathcal{C}$ and let $\alpha = -1$. Since $v_1 + v_2t + v_3t^2 \geq 0$ for every $t \in \mathbb{R}$, it follows that $(-v_1) + (-v_2)t + (-v_3)t^2 < 0$ for every positive t . Hence, $(-1)\mathbf{v} \notin \mathcal{C}$ and so it is not a vector space over \mathbb{R} . \square

Problem 1.5. Let \mathcal{F} denote the set of continuous real-valued functions $f(x)$ on the interval $0 \leq x \leq 1$. Show that \mathcal{F} is a vector space over \mathbb{R} with respect to the natural rules of vector addition $((f_1 + f_2)(x) = f_1(x) + f_2(x))$ and scalar multiplication $((\alpha f)(x) = \alpha f(x))$.

Proof. (a) **Closed under vector addition**

Consider two functions $f, g \in \mathcal{F}$. Let $x \in [0, 1]$. Then, $f(x), g(x) \in \mathbb{R}$ and so $(f + g)(x) = f(x) + g(x) \in \mathbb{R}$ since \mathbb{R} is closed under addition. Therefore, $f + g$ is a real-valued function on the interval $[0, 1]$ and so $(f + g) \in \mathcal{F}$.

(b) **Closed under scalar multiplication**

Consider some function $f \in \mathcal{F}$ and real number α . Let $x \in [0, 1]$. Then, $f(x) \in \mathbb{R}$ and so $(\alpha f)(x) = \alpha f(x) \in \mathbb{R}$ since \mathbb{R} is closed under multiplication. Thus, αf is a real-valued function on the interval $[0, 1]$ and so $\alpha f \in \mathcal{F}$.

(c) **Vector addition is commutative**

Let $f, g \in \mathcal{F}$ and $x \in [0, 1]$. Then, $(f + g)(x) = f(x) + g(x) = g(x) + f(x) = (g + f)(x)$ since addition in the set of real numbers is commutative.

(d) **Vector addition is associative**

Let $f, g, h \in \mathcal{F}$ and $x \in [0, 1]$. Then, $((f + g) + h)(x) = (f + g)(x) + h(x) = f(x) + g(x) + h(x) = f(x) + (g + h)(x) = (f + (g + h))(x)$ since addition in \mathbb{R} is associative (the order of addition does not matter).

(e) **Existence of additive identity**

Let $f : [0, 1] \rightarrow \mathbb{R}$ be defined by $f(x) = 0$ for all $x \in [0, 1]$. Then, f is a continuous real-valued function and so $f \in \mathcal{F}$. Consider any $g \in \mathcal{F}$ and let $a \in [0, 1]$. Then, $(f + g)(a) = f(a) + g(a) = 0 + g(a) = g(a)$ since 0 is the additive identity of real numbers. Thus, f is an additive identity in \mathcal{F} .

(f) **Existence of additive inverse**

Consider some $f \in \mathcal{F}$. Let $g : [0, 1] \rightarrow \mathbb{R}$ be defined by $g(x) = -f(x)$ for all $x \in [0, 1]$. Consider some $x \in [0, 1]$ and so $(f + g)(x) = f(x) + g(x) = f(x) - f(x) = 0$. Hence, g is the additive inverse of f .

(g) $f \in \mathcal{F} \implies (1)f = f$

Let $f \in \mathcal{F}$. Consider any $x \in [0, 1]$ and so $f(x) = (1)f(x)$. Thus, $f = (1)f$.

(h) For any $\alpha, \beta \in \mathbb{R}$ and vector $f \in \mathcal{F}$, $\alpha(\beta f) = (\alpha\beta)f$

Let $f \in \mathcal{F}$ and $\alpha, \beta \in \mathbb{R}$. Consider any $x \in [0, 1]$ and so $\alpha(\beta f)(x) = \alpha(\beta f(x)) = (\alpha\beta)f(x)$ since multiplication in \mathbb{R} is associative. Thus, $\alpha(\beta f) = (\alpha\beta)f$

(i) For any $\alpha, \beta \in \mathbb{R}$ and vector $f \in \mathcal{F}$, $(\alpha + \beta)f = \alpha f + \beta f$

Let $f \in \mathcal{F}$ and $\alpha, \beta \in \mathbb{R}$. Consider any $x \in [0, 1]$ and so $(\alpha + \beta)f(x) = \alpha f(x) + \beta f(x) = (\alpha f + \beta f)(x)$ since multiplication over addition is distributive for real numbers. □

Lemma 1. Let \mathcal{S} be a nonempty subset of a vector space \mathcal{M} over \mathbb{F} . Then, \mathcal{S} is a vector space if and only if for every pair of vectors $\mathbf{v}, \mathbf{a} \in \mathcal{S}$ and $\alpha, \beta \in \mathbb{F}$, $\alpha\mathbf{v} + \beta\mathbf{a} \in \mathcal{S}$.

Proof. Assume that \mathcal{S} is a vector space and so it is closed under addition and scalar multiplication. Let $\mathbf{v}, \mathbf{a} \in \mathcal{S}$ and $\alpha, \beta \in \mathbb{F}$, then $\alpha\mathbf{v}, \beta\mathbf{a} \in \mathcal{S}$ and so $\alpha\mathbf{v} + \beta\mathbf{a} \in \mathcal{S}$.

Suppose, for every pair of vectors $\mathbf{v}, \mathbf{a} \in \mathcal{S}$ and $\alpha, \beta \in \mathbb{F}$, that $\alpha\mathbf{v} + \beta\mathbf{a} \in \mathcal{S}$. Let $\alpha = 0$ and $\beta \in \mathbb{F}$. Consider any vectors $\mathbf{v}, \mathbf{a} \in \mathcal{S}$. Then, $\alpha\mathbf{v} = 0$ is the additive identity of \mathcal{M} and so $\beta\mathbf{a} = \alpha\mathbf{v} + \beta\mathbf{a} \in \mathcal{S}$. Thus, \mathcal{S} is closed under scalar multiplication.

Consider some vectors $\mathbf{v}, \mathbf{a} \in \mathcal{S}$ and let $\alpha = \beta = 1$. Then, $\mathbf{v} + \mathbf{a} = (1)\mathbf{v} + (1)\mathbf{a} = \alpha\mathbf{v} + \beta\mathbf{a} \in \mathcal{S}$ since $\mathbf{v}, \mathbf{a} \in \mathcal{M}$. Therefore, \mathcal{S} is closed under addition and so it is a vector space. □

Problem 1.6. Let F_0 denote the set of continuous real-valued functions $f(x)$ on the interval $0 \leq x \leq 1$ that met the auxiliary constraints $f(0) = 0$ and $f(1) = 0$. Show that F_0 is a vector space over \mathbb{R} with respect to the natural rules of vector addition and scalar multiplication that were introduced in **Exercise 1.5** and that F_0 is a subspace of the vector space \mathcal{F} that was considered there.

Proof. By definition, $F_0 \subseteq \mathcal{F}$. Let's prove that it is closed under addition and scalar multiplication. Consider some $f, g \in F_0$ and $\alpha, \beta \in \mathbb{R}$. Then, $\alpha f + \beta g$ is a real-valued function since $f, g \in \mathcal{F}$. Particularly, $(\alpha f + \beta g)(0) = \alpha f(0) + \beta g(0) = 0 + 0 = \alpha f(1) + \beta g(1) = (\alpha f + \beta g)(1)$ and so, by condition, it is a vector in F_0 . Therefore, F_0 is a subspace of \mathcal{F} . □

Problem 1.7. Let F_1 denote the set of continuous real-valued functions $f(x)$ on the interval $0 \leq x \leq 1$ that meet the auxiliary constraints $f(0) = 0$ and $f(1) = 1$. Show that F_1 is not a vector space over \mathbb{R} with respect to the natural rules of vector addition and scalar multiplication that were introduced in **Exercise 1.5**.

Proof. We know that $F_1 \subseteq \mathcal{F}$. Consider some $f \in F_1$. Then, $(2)f$ is a continuous real-valued function since $f \in \mathcal{F}$. However, note that $(2f)(1) = (2)f(1) = 2 \neq 1$ and so $(2)f \notin F_1$. Hence, F_1 is not closed under scalar multiplication and so F_1 is not a subspace of \mathcal{F} . □

Problem 1.8. Verify the last assertion; i.e., if $\{\mathbf{v}_1, \mathbf{v}_2, \mathbf{v}_3, \dots, \mathbf{v}_k\}$ is a set of linearly independent vectors in the space \mathcal{V} over \mathbb{F} and if $\mathbf{v} = \alpha_1 \mathbf{v}_1 + \alpha_2 \mathbf{v}_2 + \dots + \alpha_k \mathbf{v}_k = \beta_1 \mathbf{v}_1 + \beta_2 \mathbf{v}_2 + \dots + \beta_k \mathbf{v}_k$, where $\alpha_j, \beta_j \in \mathbb{F}$ for $j = 1, \dots, k$, then $\alpha_j = \beta_j$ for $j = 1, \dots, k$.

Proof. Let $\{\mathbf{v}_1, \mathbf{v}_2, \dots, \mathbf{v}_k\}$ be a set of linearly independent vectors in the space \mathcal{V} over \mathbb{F} . Furthermore, assume that there is some vector $\mathbf{v} \in \mathcal{V}$ such that $\mathbf{v} = \alpha_1 \mathbf{v}_1 + \alpha_2 \mathbf{v}_2 + \dots + \alpha_k \mathbf{v}_k = \beta_1 \mathbf{v}_1 + \beta_2 \mathbf{v}_2 + \dots + \beta_k \mathbf{v}_k$, where $\alpha_j, \beta_j \in \mathbb{F}$ for $j = 1, \dots, k$. Because $\mathbf{v} \in \mathcal{V}$, it follows that

$$\begin{aligned} \mathbf{v} - \mathbf{v} &= \alpha_1 \mathbf{v}_1 + \alpha_2 \mathbf{v}_2 + \dots + \alpha_k \mathbf{v}_k - (\beta_1 \mathbf{v}_1 + \beta_2 \mathbf{v}_2 + \dots + \beta_k \mathbf{v}_k) \\ &= (\alpha_1 - \beta_1) \mathbf{v}_1 + (\alpha_2 - \beta_2) \mathbf{v}_2 + \dots + (\alpha_k - \beta_k) \mathbf{v}_k = 0. \end{aligned}$$

Since $\mathbf{v}_1, \mathbf{v}_2, \dots, \mathbf{v}_k$ are linearly independent, it follows that $\alpha_j - \beta_j = 0$ and so $\alpha_j = \beta_j$ for $j = 1, \dots, k$. \square

Problem 1.10. Show that if

$$A = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \end{bmatrix} \quad \text{and} \quad B = \begin{bmatrix} b_{11} & b_{12} & b_{13} & b_{14} \\ b_{21} & b_{22} & b_{23} & b_{24} \\ b_{31} & b_{32} & b_{33} & b_{34} \end{bmatrix}$$

then

$$AB = \begin{bmatrix} a_{11} & 0 & 0 \\ a_{21} & 0 & 0 \end{bmatrix} B + \begin{bmatrix} 0 & a_{12} & 0 \\ 0 & a_{22} & 0 \end{bmatrix} B + \begin{bmatrix} 0 & 0 & a_{13} \\ 0 & 0 & a_{23} \end{bmatrix} B$$

and hence that

$$AB = \begin{bmatrix} a_{11} \\ a_{21} \end{bmatrix} \begin{bmatrix} b_{11} & \dots & b_{14} \end{bmatrix} + \begin{bmatrix} a_{12} \\ a_{22} \end{bmatrix} \begin{bmatrix} b_{21} & b_{22} & b_{23} & b_{24} \end{bmatrix} + \begin{bmatrix} a_{13} \\ a_{23} \end{bmatrix} \begin{bmatrix} b_{31} & b_{32} & b_{33} & b_{34} \end{bmatrix}$$

Proof. By the definition of addition of matrices

$$A = \begin{bmatrix} a_{11} & 0 & 0 \\ a_{21} & 0 & 0 \end{bmatrix} + \begin{bmatrix} 0 & a_{12} & 0 \\ 0 & a_{22} & 0 \end{bmatrix} + \begin{bmatrix} 0 & 0 & a_{13} \\ 0 & 0 & a_{23} \end{bmatrix}$$

and so

$$AB = \begin{bmatrix} a_{11} & 0 & 0 \\ a_{21} & 0 & 0 \end{bmatrix} B + \begin{bmatrix} 0 & a_{12} & 0 \\ 0 & a_{22} & 0 \end{bmatrix} B + \begin{bmatrix} 0 & 0 & a_{13} \\ 0 & 0 & a_{23} \end{bmatrix} B$$

since the multiplication of matrices is distributive over addition. By the definition of matrix multiplication, each entry $c_{kl} = \sum_{j=1}^q a_{kj} b_{jl}$, for the rows $k = 1, \dots, p$ and columns $l = 1, \dots, r$. Note that each matrix component of A has just one nonzero column m and so each entry $c_{kl} = a_{km} b_{ml}$. Thus

$$\begin{aligned} AB &= \begin{bmatrix} a_{11}b_{11} & a_{11}b_{12} & a_{11}b_{13} & a_{11}b_{14} \\ a_{21}b_{11} & a_{21}b_{12} & a_{21}b_{13} & a_{21}b_{14} \end{bmatrix} + \begin{bmatrix} a_{12}b_{21} & a_{12}b_{22} & a_{12}b_{23} & a_{12}b_{24} \\ a_{22}b_{21} & a_{22}b_{22} & a_{22}b_{23} & a_{22}b_{24} \end{bmatrix} \\ &+ \begin{bmatrix} a_{13}b_{31} & a_{13}b_{32} & a_{13}b_{33} & a_{13}b_{34} \\ a_{23}b_{31} & a_{23}b_{32} & a_{23}b_{33} & a_{23}b_{34} \end{bmatrix} \\ &= \begin{bmatrix} a_{11} \\ a_{21} \end{bmatrix} \begin{bmatrix} b_{11} & \dots & b_{14} \end{bmatrix} + \begin{bmatrix} a_{12} \\ a_{22} \end{bmatrix} \begin{bmatrix} b_{21} & b_{22} & b_{23} & b_{24} \end{bmatrix} + \begin{bmatrix} a_{13} \\ a_{23} \end{bmatrix} \begin{bmatrix} b_{31} & b_{32} & b_{33} & b_{34} \end{bmatrix} \end{aligned}$$

\square

Problem 1.12. Show that if A and B are invertible matrices of the same size, then AB is invertible and $(AB)^{-1} = B^{-1}A^{-1}$.

Proof. Let $A, B \in \mathbb{F}^{p \times p}$ be invertible matrices. Then, A^{-1} and B^{-1} are left-right inverses of A and B , respectively. Therefore,

$$\begin{aligned}(AB)(B^{-1}A^{-1}) &= A(BB^{-1})A^{-1} \\ &= A(I_p A^{-1}) = AA^{-1} \\ &= I_p\end{aligned}$$

and

$$\begin{aligned}(B^{-1}A^{-1})(AB) &= B^{-1}(A^{-1}A)B \\ &= B^{-1}(I_p B) = B^{-1}B \\ &= I_p,\end{aligned}$$

since matrix multiplication is associative. Thus, $B^{-1}A^{-1}$ is the **inverse** of AB and so AB is invertible. \square

Problem 1.13. Show that the matrix $A = \begin{bmatrix} 1 & 0 & 1 \\ 1 & 1 & 0 \\ 1 & 1 & 0 \end{bmatrix}$ has no left inverses and no right inverses.

Proof. Suppose to the contrary, that A has some right inverse B . Then, $B \in \mathbb{F}^{3 \times 3}$ and $AB = C = I_3$. Therefore, $c_{22} = 1 \cdot b_{12} + 1 \cdot b_{22} + 0 \cdot b_{32} = 1$ and $c_{32} = 1 \cdot b_{12} + 1 \cdot b_{22} + 0 \cdot b_{32} = 0$, which is a contradiction.

Now, assume, to the contrary, that A has some left inverse B . Then, $B \in \mathbb{F}^{3 \times 3}$ and $BA = C = I_3$. Hence, $c_{11} = b_{11} \cdot 1 + b_{12} \cdot 1 + b_{13} \cdot 1 = 1$, $c_{12} = b_{11} \cdot 0 + b_{12} \cdot 1 + b_{13} \cdot 1 = 0$ and $c_{13} = b_{11} \cdot 1 + b_{12} \cdot 0 + b_{13} \cdot 0 = 0$. This leads to the contradiction $1 = 0$. \square

Problem 1.15. Show that if a matrix $A \in \mathbb{C}^{p \times q}$ has two right inverse B_1 and B_2 , then $\lambda B_1 + (1 - \lambda)B_2$ is also a right inverse for every choice of $\lambda \in \mathbb{C}$.