

An easy on Linear Transformations

Research by: Jose Portillo

$$\langle \langle K, +_g, \cdot \rangle, \langle V, +_v \rangle, \circ \rangle$$

The system above is called a *vector space* over the field K [2]. Elements of K are called *scalars*, and elements of V are called *vectors*. The operation $\circ : K \times V \rightarrow V$ is scalar multiplication, and $+_v$ is vector addition. In what follows, symbols $\alpha_1, \dots, \alpha_k$ always denote scalars in K , and symbols x_1, \dots, x_k always denote vectors in V .

Example (Coordinate n -space, [3]).

Let Γ be a field. Consider the set

$$\Gamma^n = \Gamma \times \dots \times \Gamma$$

of n -tuples (ξ^1, \dots, ξ^n) , with $\xi^i \in \Gamma$. Define addition by

$$(\xi^1, \dots, \xi^n) + (\eta^1, \dots, \eta^n) = (\xi^1 + \eta^1, \dots, \xi^n + \eta^n)$$

and scalar multiplication by

$$\lambda(\xi^1, \dots, \xi^n) = (\lambda\xi^1, \dots, \lambda\xi^n), \quad \lambda \in \Gamma.$$

With these operations, Γ^n is a vector space over Γ , called the *n -space over Γ* . In particular, Γ itself is a vector space over Γ , where scalar multiplication coincides with field multiplication.

A finite set of vectors $\{b_1, \dots, b_n\} \subset V$ is called a *basis* of the vector space V if every vector $x \in V$ can be written uniquely as a linear combination

$$x = \alpha_1 \circ b_1 + \alpha_2 \circ b_2 + \dots + \alpha_n \circ b_n, \quad \alpha_1, \dots, \alpha_n \in K.$$

A basis therefore provides a minimal and non-redundant set of building blocks for the entire space. Once a basis is fixed, every vector is completely determined by its coefficients relative to that basis.

Given vectors $x_1, \dots, x_k \in V$ and scalars $\alpha_1, \dots, \alpha_k \in K$, an expression of the form

$$\alpha_1 \circ x_1 + \alpha_2 \circ x_2 + \dots + \alpha_k \circ x_k$$

is called a *linear combination*.

Let $\langle \langle K, +_g, \cdot \rangle, \langle E, +_E \rangle, \circ_E \rangle$ and $\langle \langle K, +_g, \cdot \rangle, \langle G, +_G \rangle, \circ_G \rangle$ be vector spaces over the same field K .

A function $\psi : E \rightarrow G$ is called a *linear transformation* if it preserves linear combinations [1]:

$$\psi(\alpha_1 \circ_E x_1 + \dots + \alpha_k \circ_E x_k) = \alpha_1 \circ_G \psi(x_1) + \dots + \alpha_k \circ_G \psi(x_k).$$

Linear transformations preserve the algebraic structure of vector spaces independently of any choice of coordinates.

Let $B_E = \{e_1, \dots, e_n\}$ and $B_G = \{g_1, \dots, g_m\}$ be bases of E and G . Each image $\psi(e_i)$ can be written uniquely as $\psi(e_i) = a_{1i}g_1 + \dots + a_{mi}g_m$. The scalars a_{ji} form an $m \times n$ matrix

$$A = (a_{ji}),$$

called the *matrix of ψ relative to the chosen bases*.

Matrices thus do not define linear transformations; rather, they are concrete representations of linear transformations once bases (coordinate systems) have been chosen.

This abstract formulation is independent of geometry, yet it underlies most quantitative models in science and engineering. In modern machine learning, for example, embeddings and weight matrices are linear transformations on high-dimensional vector spaces, composed with non-linear activations. Even where non-linearity dominates, linear transformations provide the structural backbone—the universality of a man-made linear structure, even though the universe itself is not linear.

The set of all linear transformations from E into the base field K is denoted by

$$E^* = L(E, K)$$

and is called the *dual space* of E . An element $x^* \in E^*$ is called a *linear functional*. Thus,

$$x^* : E \rightarrow K$$

satisfies

$$x^*(\alpha_1 x_1 + \cdots + \alpha_k x_k) = \alpha_1 x^*(x_1) + \cdots + \alpha_k x^*(x_k).$$

Linear functionals assign scalar values to vectors while preserving linear structure.

If E is finite-dimensional with basis $B_E = \{e_1, \dots, e_n\}$, then every $x^* \in E^*$ is uniquely determined by

$$x^*(e_1), \dots, x^*(e_n).$$

These scalars form a row vector

$$[x^*(e_1) \ \dots \ x^*(e_n)].$$

In contrast, vectors in E are represented as column vectors. These two objects live in different spaces: E and E^* .

Matrix multiplication is not an arbitrary algebraic rule; it is the coordinate expression of *composition of linear maps*.

A column vector represents an element of K^n , a row vector represents an element of $(K^n)^*$, and an $m \times n$ matrix represents a linear map

$$K^n \xrightarrow{\psi} K^m.$$

A product such as

$$[x^*] A$$

is defined because it corresponds to the composition

$$K^n \xrightarrow{\psi} K^m \xrightarrow{x^*} K.$$

The dimensions match precisely because the codomain of the first map equals the domain of the second.

By contrast, a product of two row vectors would attempt to compose

$$K^n \rightarrow K \quad \text{with} \quad K^n \rightarrow K,$$

which is meaningless: the output of the first map does not lie in the domain of the second. The product is therefore undefined not by convention, but by necessity.

Matrix dimensions encode compatibility of domains and codomains. One may multiply matrices if and only if the corresponding linear maps can be composed.

Concrete numerical example.

Let

$$x^*(x, y) = 3x + 2y$$

be a linear functional on K^2 . Relative to the canonical basis, it is represented by the row vector

$$[3 \ 2].$$

Let

$$A = \begin{bmatrix} 2 & 3 \\ 5 & 4 \end{bmatrix}$$

be the matrix of a linear transformation $\psi : K^2 \rightarrow K^2$.

The product

$$[3 \ 2]A = [3 \ 2] \begin{bmatrix} 2 & 3 \\ 5 & 4 \end{bmatrix} = [19 \ 17]$$

is defined because it represents the composition

$$K^2 \xrightarrow{\psi} K^2 \xrightarrow{x^*} K.$$

The result is again a row vector, corresponding to the linear functional

$$(x, y) \mapsto 19x + 17y.$$

By contrast, the product

$$[3 \ 2][a \ b]$$

is undefined because it would attempt to compose two maps of the form

$$K^2 \rightarrow K,$$

which is impossible: the output of the first map is a scalar, not a vector in K^2 .

Note. An AI language model was used as a support tool for discussion, clarification of concepts, and stylistic refinement. All mathematical choices and final wording are the responsibility of the author.

References

- [1] Iribarren Ignacio L., *Álgebra Lineal*, Editorial Equinoccio, 2018.
- [2] Cohen, Leon and Ehrlich, Gertrude, *The Structure of the Real Number System*, D. Van Nostrand Company, 1963.
- [3] Greub, Werner, *Linear Algebra*, Springer-Verlag, 1975.