

Linear algebra explained in four pages

Excerpt from the [NO BULLSHIT GUIDE TO LINEAR ALGEBRA](#) by Ivan Savov

Abstract—This document will review the fundamental ideas of linear algebra. We will learn about matrices, matrix operations, linear transformations and discuss both the theoretical and computational aspects of linear algebra. The tools of linear algebra open the gateway to the study of more advanced mathematics. A lot of knowledge *has* awaits you if you choose to follow the path of understanding, instead of trying to memorize a bunch of formulas.

I. INTRODUCTION

Linear algebra is the math of vectors and matrices. Let n be a positive integer and let \mathbb{R} denote the set of real numbers, then \mathbb{R}^n is the set of all n -tuples of real numbers. A vector $\vec{v} \in \mathbb{R}^n$ is an n -tuple of real numbers. The notation “ $\in S$ ” is read “element of S .” For example, consider a vector that has three components:

$$\vec{v} = (v_1, v_2, v_3) \in (\mathbb{R}, \mathbb{R}, \mathbb{R}) = \mathbb{R}^3.$$

A matrix $A \in \mathbb{R}^{m \times n}$ is a rectangular array of real numbers with m rows and n columns. For example, a 3×2 matrix looks like this:

$$A = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \\ a_{31} & a_{32} \end{bmatrix} \in \begin{bmatrix} \mathbb{R} & \mathbb{R} \\ \mathbb{R} & \mathbb{R} \\ \mathbb{R} & \mathbb{R} \end{bmatrix} = \mathbb{R}^{3 \times 2}.$$

The purpose of this document is to introduce you to the mathematical operations that we can perform on vectors and matrices and to give you a feel of the power of linear algebra. Many problems in science, business, and technology can be described in terms of vectors and matrices so it is important that you understand how to work with these.

Prerequisites

The only prerequisite for this tutorial is a basic understanding of high school math concept¹ like numbers, variables, equations, and the fundamental arithmetic operations on real numbers: addition (denoted $+$), subtraction (denoted $-$), multiplication (denoted implicitly), and division (fractions).

You should also be familiar with functions that take real numbers as inputs and give real numbers as outputs, $f: \mathbb{R} \rightarrow \mathbb{R}$. Recall that, by definition, the *inverse function* f^{-1} *undoes* the effect of f . If you are given $f(x)$ and you want to find x , you can use the inverse function as follows: $f^{-1}(f(x)) = x$. For example, the function $f(x) = \ln(x)$ has the inverse $f^{-1}(x) = e^x$, and the inverse of $g(x) = \sqrt{x}$ is $g^{-1}(x) = x^2$.

II. DEFINITIONS

A. Vector operations

We now define the math operations for vectors. The operations we can perform on vectors $\vec{u} = (u_1, u_2, u_3)$ and $\vec{v} = (v_1, v_2, v_3)$ are: addition, subtraction, scaling, norm (length), dot product, and cross product:

$$\vec{u} + \vec{v} = (u_1 + v_1, u_2 + v_2, u_3 + v_3)$$

$$\vec{u} - \vec{v} = (u_1 - v_1, u_2 - v_2, u_3 - v_3)$$

$$\alpha \vec{u} = (\alpha u_1, \alpha u_2, \alpha u_3)$$

$$\|\vec{u}\| = \sqrt{u_1^2 + u_2^2 + u_3^2}$$

$$\vec{u} \cdot \vec{v} = u_1 v_1 + u_2 v_2 + u_3 v_3$$

$$\vec{u} \times \vec{v} = (u_2 v_3 - u_3 v_2, u_3 v_1 - u_1 v_3, u_1 v_2 - u_2 v_1)$$

The dot product and the cross product of two vectors can also be described in terms of the angle θ between the two vectors. The formula for the dot product of the vectors is $\vec{u} \cdot \vec{v} = \|\vec{u}\| \|\vec{v}\| \cos \theta$. We say two vectors \vec{u} and \vec{v} are *orthogonal* if the angle between them is 90° . The dot product of orthogonal vectors is zero: $\vec{u} \cdot \vec{v} = \|\vec{u}\| \|\vec{v}\| \cos(90^\circ) = 0$.

The norm of the cross product is given by $\|\vec{u} \times \vec{v}\| = \|\vec{u}\| \|\vec{v}\| \sin \theta$. The cross product is not commutative: $\vec{u} \times \vec{v} \neq \vec{v} \times \vec{u}$, in fact $\vec{u} \times \vec{v} = -\vec{v} \times \vec{u}$.

B. Matrix operations

We denote by A the matrix as a whole and refer to its entries as a_{ij} . The mathematical operations defined for matrices are the following:

- addition (denoted $+$)

$$C = A + B \quad \Leftrightarrow \quad c_{ij} = a_{ij} + b_{ij}.$$

- subtraction (the inverse of addition)
- matrix product. The product of matrices $A \in \mathbb{R}^{m \times n}$ and $B \in \mathbb{R}^{n \times l}$ is another matrix $C \in \mathbb{R}^{m \times l}$ given by the formula

$$C = AB \quad \Leftrightarrow \quad c_{ij} = \sum_{k=1}^n a_{ik} b_{kj}.$$

$$\begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \\ a_{31} & a_{32} \end{bmatrix} \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix} = \begin{bmatrix} a_{11}b_{11} + a_{12}b_{21} & a_{11}b_{12} + a_{12}b_{22} \\ a_{21}b_{11} + a_{22}b_{21} & a_{21}b_{12} + a_{22}b_{22} \\ a_{31}b_{11} + a_{32}b_{21} & a_{31}b_{12} + a_{32}b_{22} \end{bmatrix}$$

- matrix inverse (denoted A^{-1})
- matrix transpose (denoted A^T):

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix}^T = \begin{bmatrix} a_{11} & a_{21} & a_{31} \\ a_{12} & a_{22} & a_{32} \\ a_{13} & a_{23} & a_{33} \end{bmatrix}.$$

- matrix trace: $\text{Tr}[A] \equiv \sum_{i=1}^n a_{ii}$
- determinant (denoted $\det(A)$ or $|A|$)

Note that the matrix product is not a commutative operation: $AB \neq BA$.

C. Matrix-vector product

The matrix-vector product is an important special case of the matrix-matrix product. The product of a 3×2 matrix A and the 2×1 column vector \vec{x} results in a 3×1 vector \vec{y} given by:

$$\vec{y} = A\vec{x} \quad \Leftrightarrow \quad \begin{bmatrix} y_1 \\ y_2 \\ y_3 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \\ a_{31} & a_{32} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} a_{11}x_1 + a_{12}x_2 \\ a_{21}x_1 + a_{22}x_2 \\ a_{31}x_1 + a_{32}x_2 \end{bmatrix} \quad (\text{C})$$

$$= x_1 \begin{bmatrix} a_{11} \\ a_{21} \\ a_{31} \end{bmatrix} + x_2 \begin{bmatrix} a_{12} \\ a_{22} \\ a_{32} \end{bmatrix}$$

$$= \begin{bmatrix} (a_{11}, a_{12}) \cdot \vec{x} \\ (a_{21}, a_{22}) \cdot \vec{x} \\ (a_{31}, a_{32}) \cdot \vec{x} \end{bmatrix}. \quad (\text{R})$$

There are two² fundamentally different yet equivalent ways to interpret the matrix-vector product. In the column picture, (C), the multiplication of the matrix A by the vector \vec{x} produces a **linear combination of the columns of the matrix**: $\vec{y} = A\vec{x} = x_1 A_{(:,1)} + x_2 A_{(:,2)}$, where $A_{(:,1)}$ and $A_{(:,2)}$ are the first and second columns of the matrix A .

In the row picture, (R), multiplication of the matrix A by the vector \vec{x} produces a column vector with coefficients equal to the **dot products of rows of the matrix with the vector \vec{x}** .

D. Linear transformations

The matrix-vector product is used to define the notion of a *linear transformation*, which is one of the key notions in the study of linear algebra. Multiplication by a matrix $A \in \mathbb{R}^{m \times n}$ can be thought of as computing a *linear transformation* T_A that takes n -vectors as inputs and produces m -vectors as outputs:

$$T_A: \mathbb{R}^n \rightarrow \mathbb{R}^m.$$

¹A good textbook to (re)learn high school math is [mathrefarrows.com](#)

²For more info see the video of Prof. Strang's MIT lecture: [bit.ly/1Qv6R0C](#)

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