

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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Christian G. Meyer



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Table of Contents Linear Algebra For Dummies Cheat Sheet

1. Understanding the eBook Linear Algebra For Dummies Cheat Sheet
 - The Rise of Digital Reading Linear Algebra For Dummies Cheat Sheet
 - Advantages of eBooks Over Traditional Books
2. Identifying Linear Algebra For Dummies Cheat Sheet
 - Exploring Different Genres
 - Considering Fiction vs. Non-Fiction
 - Determining Your Reading Goals
3. Choosing the Right eBook Platform
 - Popular eBook Platforms
 - Features to Look for in an Linear Algebra For Dummies Cheat Sheet
 - User-Friendly Interface
4. Exploring eBook Recommendations from Linear Algebra For Dummies Cheat Sheet
 - Personalized Recommendations
 - Linear Algebra For Dummies Cheat Sheet User Reviews and Ratings
 - Linear Algebra For Dummies Cheat Sheet and Bestseller Lists
5. Accessing Linear Algebra For Dummies Cheat Sheet Free and Paid eBooks
 - Linear Algebra For Dummies Cheat Sheet Public Domain eBooks
 - Linear Algebra For Dummies Cheat Sheet eBook Subscription Services
 - Linear Algebra For Dummies Cheat Sheet Budget-Friendly Options

6. Navigating Linear Algebra For Dummies Cheat Sheet eBook Formats
 - ePub, PDF, MOBI, and More
 - Linear Algebra For Dummies Cheat Sheet Compatibility with Devices
 - Linear Algebra For Dummies Cheat Sheet Enhanced eBook Features
7. Enhancing Your Reading Experience
 - Adjustable Fonts and Text Sizes of Linear Algebra For Dummies Cheat Sheet
 - Highlighting and Note-Taking Linear Algebra For Dummies Cheat Sheet
 - Interactive Elements Linear Algebra For Dummies Cheat Sheet
8. Staying Engaged with Linear Algebra For Dummies Cheat Sheet
 - Joining Online Reading Communities
 - Participating in Virtual Book Clubs
 - Following Authors and Publishers Linear Algebra For Dummies Cheat Sheet
9. Balancing eBooks and Physical Books Linear Algebra For Dummies Cheat Sheet
 - Benefits of a Digital Library
 - Creating a Diverse Reading Collection Linear Algebra For Dummies Cheat Sheet
10. Overcoming Reading Challenges
 - Dealing with Digital Eye Strain
 - Minimizing Distractions
 - Managing Screen Time
11. Cultivating a Reading Routine Linear Algebra For Dummies Cheat Sheet
 - Setting Reading Goals Linear Algebra For Dummies Cheat Sheet
 - Carving Out Dedicated Reading Time
12. Sourcing Reliable Information of Linear Algebra For Dummies Cheat Sheet
 - Fact-Checking eBook Content of Linear Algebra For Dummies Cheat Sheet
 - Distinguishing Credible Sources
13. Promoting Lifelong Learning
 - Utilizing eBooks for Skill Development
 - Exploring Educational eBooks
14. Embracing eBook Trends
 - Integration of Multimedia Elements

- Interactive and Gamified eBooks

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