

## 5 2025-09-05 | Week 02 | Lecture 05

*The nexus question of this lecture: What is a matrix, and what are the fundamental algebraic operations we can do with it?*

*This lecture is based on section 1.2 in the textbook.*

### 5.1 Matrices and matrix notation

A **matrix** is a rectangular array of objects, usually numbers, which are called **entries**. If the number of rows and the number of columns are equal, the matrix is said to be a **square matrix**.

For example,

$$\begin{bmatrix} 1 & 0 & 3 \\ 2 & 5 & -3 \end{bmatrix} \quad \text{or} \quad \underbrace{\begin{bmatrix} 1 & 0 & -7 & 5 \end{bmatrix}}_{\text{a row vector}} \quad \text{or} \quad \underbrace{\begin{bmatrix} 1 \\ 4 \\ 0 \end{bmatrix}}_{\text{a column vector}} \quad \text{or} \quad \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$$

A matrix with  $m$  rows and  $n$  columns takes the form

$$A = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \vdots & \vdots & & \vdots \\ a_{m1} & a_{m2} & \dots & a_{mn} \end{bmatrix}.$$

Such a matrix is said to be an  $m \times n$  **matrix**. The pair  $(m, n)$  is called the **dimensions** of the matrix (i.e., the number of rows and number of columns). If  $m = n$ , then the matrix is said to be a **square matrix**.

The set of all  $m \times n$  matrices with real entries is denoted

$$M_{m \times n}(\mathbb{R})$$

For example, in set notation

$$M_{2 \times 3}(\mathbb{R}) = \left\{ \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \end{bmatrix} : a_{11}, a_{12}, a_{13}, a_{21}, a_{22}, a_{23} \in \mathbb{R} \right\}$$

**Notation 14.** It is common to denote a matrix compactly using the notation

$$A = [a_{ij}] \quad \text{or} \quad A = (a_{ij})$$

To denote the entry at row  $i$ , column  $j$ , we write either

$$\text{ent}_{ij}(A) \quad \text{or more simply,} \quad a_{ij}$$

For example, if

$$A = (a_{ij}) = \begin{bmatrix} -1 & 2 & 1 \\ 5 & 4 & -9 \\ 3 & -4 & 7 \end{bmatrix}$$

then  $a_{23} = \text{ent}_{23}(A) = -9$ , and  $a_{21} = \text{ent}_{21}(A) = 5$ .

Vectors are a special case of matrices. An  $n$ -dimensional vector is an  $n \times 1$  matrices (a column matrix, typically).

## 5.2 Matrix operations: scaling, addition and multiplication

We can **multiply matrices by a scalar**, in the obvious way:  $10 \times \begin{bmatrix} 3 & 4 \\ -2 & 0 \end{bmatrix} = \begin{bmatrix} 30 & 40 \\ -20 & 0 \end{bmatrix}$ .

We can **add matrices**, also in the obvious way:

$$\begin{bmatrix} 3 & 4 \\ -2 & 0 \end{bmatrix} + \begin{bmatrix} 1 & 5 \\ 2 & 10 \end{bmatrix} = \begin{bmatrix} 4 & 9 \\ 0 & 10 \end{bmatrix}.$$

But note that we can only add two matrices if they have the same dimensions:

$$\begin{bmatrix} 5 & 2 \\ -2 & -1 \end{bmatrix} + \begin{bmatrix} -1 & 10 \\ 4 & 7 \\ 2 & 5 \end{bmatrix} = \text{undefined}.$$

We can also **multiply** matrices, but before defining matrix multiplication, it will be helpful to recall the notion of dot product. Suppose we have two vectors of the same length:

$$X = [x_1 \quad x_2 \quad \cdots \quad x_n] \quad \text{and} \quad Y = [y_1 \quad y_2 \quad \cdots \quad y_n],$$

then the **dot product** of  $X$  and  $Y$ , denoted  $X \cdot Y$ , is

$$X \cdot Y = x_1 y_1 + x_2 y_2 + \cdots + x_n y_n = \sum_{i=1}^n x_i y_i.$$

**Matrix multiplication** is defined in the following way:

### Matrix Multiplication

If  $A = (a_{ij})$  is a  $p \times n$  matrix and  $B = (b_{ij})$  is an  $n \times q$  matrix, then we can think of  $A$  and  $B$  as

$$A = \begin{bmatrix} \text{---} A_1 \text{---} \\ \text{---} A_2 \text{---} \\ \vdots \\ \text{---} A_p \text{---} \end{bmatrix} \quad \text{and} \quad B = \begin{bmatrix} \begin{array}{c} | \\ B_1 \\ | \end{array} & \begin{array}{c} | \\ B_2 \\ | \end{array} & \cdots & \begin{array}{c} | \\ B_q \\ | \end{array} \end{bmatrix}$$

where  $A_1, \dots, A_p$  are the  $1 \times n$  row vectors

$$A_i = [a_{i1} \quad a_{i2} \quad \cdots \quad a_{in}] \quad (i = 1, \dots, p)$$

and  $B_1, \dots, B_q$  are  $n \times 1$  column vectors:

$$B_j = \begin{bmatrix} b_{1j} \\ b_{2j} \\ \vdots \\ b_{nj} \end{bmatrix} \quad (j = 1, 2, \dots, q)$$

Then the product  $P = AB$  is a  $p \times q$  matrix  $P = (p_{ij})$ , whose entries are

$$\begin{aligned} p_{ij} &= A_i \cdot B_j \\ &= \sum_{k=1}^n a_{ik} b_{kj}. \end{aligned}$$

For example,

$$\begin{bmatrix} 1 & 2 \\ 3 & 4 \end{bmatrix} \begin{bmatrix} 5 & 6 \\ 7 & 8 \end{bmatrix} = \begin{bmatrix} 1 \cdot 5 + 2 \cdot 7 & 1 \cdot 6 + 2 \cdot 8 \\ 3 \cdot 5 + 4 \cdot 7 & 3 \cdot 6 + 4 \cdot 8 \end{bmatrix} = \begin{bmatrix} 19 & 22 \\ 43 & 50 \end{bmatrix}$$

**Dimensionality requirement for matrix multiplication:** we can only multiply two matrices if their dimensions match in the right way. If  $A$  is a  $p \times n$  matrix, and  $B$  is an  $\tilde{n} \times q$  matrix, then the product  $AB$  is defined if and only if  $n = \tilde{n}$ . That is,

$$AB \text{ is } \begin{cases} \text{a } p \times q \text{ matrix} & \text{if } n = \tilde{n} \\ \text{undefined} & \text{if } n \neq \tilde{n} \end{cases}$$

**Properties of matrix multiplication:** Perhaps surprisingly, despite matrix multiplication's complicated definition, it nonetheless behaves sort of like regular multiplication in that the **associative property** and **distributed property** both hold. That is,

$$ABC = (AB)C = A(BC) \quad (\text{associative property})$$

and

$$\begin{aligned} A(B + C) &= AB + AC & (\text{left distributive property}) \\ (B + C)A &= BA + CA & (\text{right distributive property}) \end{aligned}$$

It's not obvious why the properties always hold; they require proof. For now, we will take them as a given.

## 5.3 Special classes of matrices

### 5.3.1 Diagonal matrices

If  $A = (a_{ij})$  is a square (i.e.,  $n \times n$ ) matrix, then the entries  $a_{11}, a_{22}, a_{33}, \dots, a_{nn}$  are called the **diagonal entries**. A square matrix of the form

$$A = \begin{bmatrix} a_{11} & 0 & 0 & \dots & 0 \\ 0 & a_{22} & 0 & \dots & 0 \\ 0 & 0 & a_{33} & \dots & 0 \\ \vdots & \vdots & & \ddots & \\ 0 & 0 & 0 & \dots & a_{nn} \end{bmatrix}.$$

is called a **diagonal** matrix, and the notation used for such matrices is  $A = \text{diag}(a_{11}, \dots, a_{nn})$ .

### 5.3.2 Identity matrix

An **identity matrix** is a diagonal matrix with 1's on its diagonal (and 0's everywhere else). For example,

$$\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \quad \text{or} \quad \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad \text{or} \quad \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad \text{et cetera}$$

Identity matrices are always square. The notation for an  $n \times n$  identity matrix is  $I_n$ , or more simply  $I$ .

An identity matrix has the property that when you multiply it by another matrix, it doesn't change the other matrix. For example,

$$\begin{bmatrix} 5 & 6 \\ 2 & 7 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} 5 & 6 \\ 2 & 7 \end{bmatrix}$$

It's like multiplying a number by 1.

### 5.3.3 Zero matrices

A matrix whose entries are all zeros is called a *zero matrix*, like

$$\begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix} \quad \text{or} \quad \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad \text{or} \quad \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad \text{et cetera}$$

The book uses the notation  $\mathbf{O}_{m \times n}$  to denote an  $m \times n$  zero matrix, or sometimes even just  $\mathbf{O}$ .