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# Linear Algebra

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# Lecture Overview

- Elements in linear algebra
- Linear system
- Linear combination, vector equation,  
Four views of matrix multiplication
- Linear independence, span, and subspace
- Linear transformation
- Least squares
- Eigendecomposition
- Singular value decomposition



# Linear Equation

- A **linear equation** in the variables  $x_1, \dots, x_n$  is an equation that can be written in the form

$$a_1x_1 + a_2x_2 + \cdots + a_nx_n = b,$$

where  $b$  and the coefficients  $a_1, \dots, a_n$  are real or complex numbers that are usually known in advance.

- The above equation can be written as

$$\mathbf{a}^T \mathbf{x} = b$$

where  $\mathbf{a} = \begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_n \end{bmatrix}$  and  $\mathbf{x} = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix}$ .



a, x :



# Linear System: Set of Equations

- A **system of linear equations** (or a **linear system**) is a collection of one or more linear equations involving the same variables - say,  $x_1, \dots, x_n$ .



# Linear System Example

- Suppose we collected persons' weight, height, and life-span (e.g., how long s/he lived)

Person ID	Weight	Height	Is_smoking	Life-span
1	60kg	5.5ft	Yes (=1)	66
2	65kg	5.0ft	No (=0)	74
3	55kg	6.0ft	Yes (=1)	78

- We want to set up the following linear system:

$$60x_1 + 5.5x_2 + 1 \cdot x_3 = 66$$

$$65x_1 + 5.0x_2 + 0 \cdot x_3 = 74$$

$$55x_1 + 6.0x_2 + 1 \cdot x_3 = 78$$

- Once we solve for  $x_1$ ,  $x_2$ , and  $x_3$ , given a new person with his/her weight, height, and is\_smoking, we can predict his/her life-span.



# Linear System Example

- The essential information of a linear system can be written compactly using a **matrix**.
- In the following set of equations,

$$60x_1 + 5.5x_2 + 1 \cdot x_3 = 66$$

$$65x_1 + 5.0x_2 + 0 \cdot x_3 = 74$$

$$55x_1 + 6.0x_2 + 1 \cdot x_3 = 78$$

- Let's collect all the coefficients on the left and form a matrix

$$A = \begin{bmatrix} 60 & 5.5 & 1 \\ 65 & 5.0 & 0 \\ 55 & 6.0 & 1 \end{bmatrix}$$

- Also, let's form two vectors:  $\mathbf{x} = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}$  and  $\mathbf{b} = \begin{bmatrix} 66 \\ 74 \\ 78 \end{bmatrix}$

# From Multiple Equations to Single Matrix Equation

- Multiple equations can be converted into a **single** matrix equations

$$\begin{aligned} 60x_1 + 5.5x_2 + 1 \cdot x_3 &= 66 \\ 65x_1 + 5.0x_2 + 0 \cdot x_3 &= 74 \\ 55x_1 + 6.0x_2 + 1 \cdot x_3 &= 78 \end{aligned} \quad \rightarrow \quad \begin{bmatrix} 60 & 5.5 & 1 \\ 65 & 5.0 & 0 \\ 55 & 6.0 & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} 66 \\ 74 \\ 78 \end{bmatrix} \quad \leftarrow \quad \begin{aligned} \mathbf{a}_1^T \mathbf{x} &= 66 \\ \mathbf{a}_2^T \mathbf{x} &= 74 \\ \mathbf{a}_3^T \mathbf{x} &= 78 \end{aligned}$$

$A \quad \mathbf{x} = \mathbf{b}$

- How can we solve for  $\mathbf{x}$ ?

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# Identity Matrix

- **Definition:** An identity matrix is a **square** matrix whose diagonal entries are all 1's, and all the other entries are zeros. Often, we denote it as  $I_n \in \mathbb{R}^{n \times n}$ .

- e.g.,  $I_3 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$

- An identity matrix  $I_n$  preserves any vector  $\mathbf{x} \in \mathbb{R}^n$  after multiplying  $\mathbf{x}$  by  $I_n$ :

$$\forall \mathbf{x} \in \mathbb{R}^n, \quad I_n \mathbf{x} = \mathbf{x}$$



# Inverse Matrix

- **Definition:** For a **square** matrix  $A \in \mathbb{R}^{n \times n}$ , its inverse matrix  $A^{-1}$  is defined such that

$$A^{-1}A = AA^{-1} = I_n.$$

- For a  $2 \times 2$  matrix  $A = \begin{bmatrix} a & b \\ c & d \end{bmatrix}$ , its inverse matrix  $A^{-1}$  is defined as

$$A^{-1} = \frac{1}{ad - bc} \begin{bmatrix} d & -b \\ -c & a \end{bmatrix}$$



# Solving Linear System via Inverse Matrix

- We can now solve  $A\mathbf{x} = \mathbf{b}$  as follows:

$$A\mathbf{x} = \mathbf{b}$$

$$A^{-1}A\mathbf{x} = A^{-1}\mathbf{b}$$

$$I_n\mathbf{x} = A^{-1}\mathbf{b}$$

$$\mathbf{x} = A^{-1}\mathbf{b}$$



# Solving Linear System via Inverse Matrix

- **Example:**

$$\begin{bmatrix} 60 & 5.5 & 1 \\ 65 & 5.0 & 0 \\ 55 & 6.0 & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} 66 \\ 74 \\ 78 \end{bmatrix} \quad \xrightarrow{\hspace{1cm}} \quad A^{-1} = \begin{bmatrix} 0.0870 & 0.0087 & -0.0870 \\ -1.1304 & 0.0870 & 1.1314 \\ 2.0000 & -1.0000 & -1.0000 \end{bmatrix}$$

$A \qquad \mathbf{x} = \mathbf{b}$

- One can verify

$$A^{-1}A = AA^{-1} = I_n.$$

- $\mathbf{x} = A^{-1}\mathbf{b} = \begin{bmatrix} 0.0870 & 0.0087 & -0.0870 \\ -1.1304 & 0.0870 & 1.1314 \\ 2.0000 & -1.0000 & -1.0000 \end{bmatrix} \begin{bmatrix} 66 \\ 74 \\ 78 \end{bmatrix} = \begin{bmatrix} -0.4 \\ 20 \\ -20 \end{bmatrix}$



# Solving Linear System via Inverse Matrix

- Now, the life-span can be written as

$$\begin{aligned}(\text{life-span}) = & -0.4 \times (\text{weight}) + 20 \times (\text{height}) \\& - 20 \times (\text{is\_smoking}).\end{aligned}$$



# Non-Invertible Matrix $A$ for $A\mathbf{x} = \mathbf{b}$

- Note that if  $A$  is invertible, the solution is uniquely obtained as
$$\mathbf{x} = A^{-1}\mathbf{b}.$$
- What if  $A$  is non-invertible, i.e., the inverse does not exist?
  - E.g., For  $A = \begin{bmatrix} 1 & 2 \\ 2 & 4 \end{bmatrix}$ , in  $A^{-1} = \frac{1}{ad-bc} \begin{bmatrix} d & -b \\ -c & a \end{bmatrix}$ , the denominator  $ad - bc = 0$ , so  $A$  is not invertible.
- For  $A = \begin{bmatrix} a & b \\ c & d \end{bmatrix}$ ,  $ad - bc$  is called the determinant of  $A$ , or  $\det A$ .



# Does a Matrix Have an Inverse Matrix?

- $\det A$  determines whether  $A$  is invertible (when  $\det A \neq 0$ ) or not (when  $\det A = 0$ ).
- For more details on how to compute the determinant of a matrix  $A \in \mathbb{R}^{n \times n}$  where  $n \geq 3$ , you can study the following:
  - <https://ocw.mit.edu/courses/mathematics/18-06-linear-algebra-spring-2010/video-lectures/lecture-18-properties-of-determinants/>
  - <https://ocw.mit.edu/courses/mathematics/18-06-linear-algebra-spring-2010/video-lectures/lecture-19-determinant-formulas-and-cofactors/>



# Inverse Matrix Larger than $2 \times 2$

- If invertible, is there any formula for computing an inverse matrix of a matrix  $A \in \mathbb{R}^{n \times n}$  where  $n \geq 3$ ?
- No, but one can compute it.
- We skip details, but you can study Gaussian elimination in Lay Ch1.2 and then study Lay Ch2.2.



# Non-Invertible Matrix $A$ for $Ax = b$

- Back to the linear system, if  $A$  is non-invertible,  $Ax = b$  will have either **no solution** or **infinitely many solutions**.

# Rectangular Matrix $A$ in $Ax = b$

- What if  $A$  is a rectangular matrix, e.g.,  $A \in \mathbb{R}^{m \times n}$ , where  $m \neq n$ ?

Person ID	Weight	Height	Is_smoking	Life-span
1	60kg	5.5ft	Yes (=1)	66
2	65kg	5.0ft	No (=0)	74
3	55kg	6.0ft	Yes (=1)	78

$$\rightarrow \begin{bmatrix} 60 & 5.5 & 1 \\ 65 & 5.0 & 0 \\ 55 & 6.0 & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} 66 \\ 74 \\ 78 \end{bmatrix}$$

- Recall  $m = \#\text{equations}$  and  $n = \#\text{variables}$ .  $A$        $x = b$
- $m < n$ : more variables than equations
  - Usually infinitely many solutions exist (under-determined system).
- $m > n$ : more equations than variables
  - Usually no solution exists (over-determined system). ML
- To study how to compute the solution in these general cases, check out Lay Ch1.2 and Lay Ch1.5.