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Chapter 1

Linear Equations in Linear Algebra

1.1 Systems of Linear Equations

Definition 1.1.1. A Linear Equation is the variables x_1, x_2, \dots, x_n is an equation that can be written in the form $a_1x_1 + a_2x_2 + \dots + a_nx_n = b$ where a_1, a_2, \dots, a_n are real coefficient and b is a real number (and known)

Definition 1.1.2. A System of Linear Equations
$$\begin{cases} a_{11}x_1 + a_{12}x_2 + \dots + a_{1n}x_n = b_1 \\ a_{21}x_1 + a_{22}x_2 + \dots + a_{2n}x_n = b_2 \\ \vdots \\ a_{m1}x_1 + a_{m2}x_2 + \dots + a_{mn}x_n = b_m \end{cases}$$
 m number of equations, n number of unknowns (standard form) (first index row number, second index col number)

Definition 1.1.3. A solution of the system is a list (s_1, s_2, \dots, s_n) of numbers that makes each equation a true statement when the values are substituted for x_1, x_2, \dots, x_n

Definition 1.1.4. Solution Set is the set of all possible solutions

Geometric Interpretations Example) Find the Solution set of the system

(a) $\begin{cases} x_1 - x_2 = 5 \\ 2x_1 + x_2 = 7 \end{cases}$

(b) $\begin{cases} x_1 - 2x_2 = 4 \\ -2x_1 + 4x_2 = -8 \end{cases}$

(c) $\begin{cases} x_1 + 3x_2 = 1 \\ 2x_1 + 6x_2 = 5 \end{cases}$

Definition 1.1.5. A linear system is consistent if it has either one solution or infinitely many solutions

Definition 1.1.6. Matrix of Coefficients
$$\begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \dots & a_{mn} \end{bmatrix}$$

Definition 1.1.7. Augmented Matrix of the System

$$\left[\begin{array}{cccc|c} a_{11} & a_{12} & \dots & a_{1n} & b_1 \\ a_{21} & a_{22} & \dots & a_{2n} & b_2 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ a_{m1} & a_{m2} & \dots & a_{mn} & b_m \end{array} \right]$$

1.2 Row Reduction and Echelon Forms

Definition 1.2.1. A leading of a row in a matrix is the left most non-zero entry

Example)
$$\left[\begin{array}{cccccc} 0 & 0 & \textcircled{7} & 3 & 4 & 1 \\ \textcircled{2} & 4 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \textcircled{-2} & 0 \end{array} \right]$$

Definition 1.2.2. A rectangular matrix is in echelon form if it has the following three properties:

1. All non-zero rows are above any zero rows.
2. Each leading entry of a row is in a column to the right of the leading entry above it.
3. All entries in a column below a leading entry are zero.

1.3 Vector Equations

Definition 1.3.1. Vectors

In R^2 , $\vec{v} = \begin{bmatrix} v_1 \\ v_2 \end{bmatrix}$, in R^3 , $\vec{v} = \begin{bmatrix} v_1 \\ v_2 \\ v_3 \end{bmatrix}$, in R^n , $\vec{v} = \begin{bmatrix} v_1 \\ v_2 \\ \vdots \\ v_n \end{bmatrix}$

Definition 1.3.2. Alebraic Operations of Vectors.

$$\vec{u} = \begin{bmatrix} u_1 \\ u_2 \\ \vdots \\ u_n \end{bmatrix} \quad \vec{v} = \begin{bmatrix} v_1 \\ v_2 \\ \vdots \\ v_n \end{bmatrix}$$

Addition: $\vec{u} + \vec{v} = \begin{bmatrix} u_1 + v_1 \\ u_2 + v_2 \\ \vdots \\ u_n + v_n \end{bmatrix}$

Multiply by Scaler: $c \in R \quad c\vec{v} = \begin{bmatrix} cv_1 \\ cv_2 \\ \vdots \\ cv_n \end{bmatrix}$

Definition 1.3.3. Linear Combination of Vectors $\vec{v}_1, \vec{v}_2, \dots, \vec{v}_p$ vectors in R^n c_1, c_2, \dots, c_n scalarsLinear Combination: $c_1\vec{v}_1 + c_2\vec{v}_2 + \dots + c_n\vec{v}_n$ **Definition 1.3.4.** Vector Form of a System of Linear Equations

$$a_{11}x_1 + a_{12}x_2 + \dots + a_{1n}x_n = b_1$$

$$a_{21}x_1 + a_{22}x_2 + \dots + a_{2n}x_n = b_2$$

$$\vdots \quad \quad \quad \vdots$$

$$a_{m1}x_1 + a_{m2}x_2 + \dots + a_{mn}x_n = b_m$$

$$\vec{a}_1 \quad \quad \quad \vec{a}_2 \quad \quad \quad \vec{a}_n \quad \quad \quad \vec{b}_n$$

Short Vector Form: $\vec{a}_1x_1 + \vec{a}_2x_2 + \dots + \vec{a}_nx_n = \vec{b}_n$

$$\text{Long Vector Form: } \begin{bmatrix} a_{11} \\ a_{21} \\ \vdots \\ a_{m1} \end{bmatrix} x_1 + \begin{bmatrix} a_{12} \\ a_{22} \\ \vdots \\ a_{m2} \end{bmatrix} x_2 + \dots + \begin{bmatrix} a_{1n} \\ a_{2n} \\ \vdots \\ a_{mn} \end{bmatrix} x_n = \begin{bmatrix} b_1 \\ b_2 \\ \vdots \\ b_m \end{bmatrix}$$

Example 1.3.1.

$$\text{Standard Form: } \begin{cases} 2x_1 + 3x_2 - 4x_3 = 5 \\ x_1 \quad \quad \quad + 2x_3 = 1 \\ \quad \quad \quad x_2 - x_3 = 4 \end{cases}$$

$$\text{Augmented Matrix: } \left[\begin{array}{ccc|c} 2 & 3 & -4 & 5 \\ 1 & 0 & 2 & 1 \\ 0 & 1 & -1 & 4 \end{array} \right]$$

$$\text{Vector Form: } \begin{bmatrix} 2 \\ 1 \\ 0 \end{bmatrix} x_1 + \begin{bmatrix} 3 \\ 0 \\ 1 \end{bmatrix} x_2 + \begin{bmatrix} -4 \\ 2 \\ -1 \end{bmatrix} x_3 = \begin{bmatrix} 5 \\ 1 \\ 4 \end{bmatrix}$$

Definition 1.3.5.

If $\vec{v}_1, \vec{v}_2, \dots, \vec{v}_p$ are vectors in R^N then the set of all linear combinations of $\vec{v}_1, \vec{v}_2, \dots, \vec{v}_p$ is denoted by $\text{Span}\{\vec{v}_1, \vec{v}_2, \dots, \vec{v}_p\}$ and is called a subset of R^N spanned (or generated) by $\vec{v}_1, \vec{v}_2, \dots, \vec{v}_p$.

Example 1.3.2.

$$\text{for } R^3, \text{ describe } \text{Span}\left\{ \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \right\}$$

All Linear Combinations we get the x_1x_3 -plane

Remark: A system of linear equations is consistent if \vec{b} is in $\text{Span}\{\vec{a}_1, \vec{a}_2, \dots, \vec{a}_n\}$

Example 1.3.3.

$$\text{Determine if } \vec{b} = \begin{bmatrix} 11 \\ -5 \\ 9 \end{bmatrix} \text{ is in the } \text{Span}\left\{ \begin{bmatrix} 1 \\ 0 \\ 1 \end{bmatrix}, \begin{bmatrix} -2 \\ 1 \\ 2 \end{bmatrix}, \begin{bmatrix} -6 \\ 7 \\ 5 \end{bmatrix} \right\}$$

$$\begin{bmatrix} 1 \\ 0 \\ 1 \end{bmatrix} x_1 + \begin{bmatrix} -2 \\ 1 \\ 2 \end{bmatrix} x_2 + \begin{bmatrix} -6 \\ 7 \\ 5 \end{bmatrix} x_3 = \begin{bmatrix} 11 \\ -5 \\ 9 \end{bmatrix}$$

$$\left[\begin{array}{ccc|c} 1 & -2 & -6 & 11 \\ 0 & 1 & 7 & -5 \\ 1 & 2 & 5 & 9 \end{array} \right] \text{RowOperations} \rightarrow \left[\begin{array}{ccc|c} 1 & -2 & -6 & 11 \\ 0 & 1 & 7 & -5 \\ 0 & 0 & -17 & -18 \end{array} \right]$$

Yes it is in Span because it is consistent!

Remark:

- 1) If the question is determine wheter the system is consistent or not. Then usually it is enough to get Echelon Form of the Augmented Matrix.
- 2) If the question is to solve the system, then we need Reduced Echelon Form of the Augmented Matrix

Example 1.3.4.

$$\begin{array}{rcl} x_1 + x_2 - 2x_3 & = & 5 \\ x_1 - x_2 + x_3 & = & 7 \\ 5x_1 - x_2 - x_3 & = & 31 \end{array} = \left[\begin{array}{ccc|c} 1 & 1 & -2 & 5 \\ 1 & -1 & 1 & 7 \\ 5 & -1 & -1 & 31 \end{array} \right] \text{RowOperations} \rightarrow$$

$$\left[\begin{array}{ccc|c} 1 & 1 & -2 & 5 \\ 0 & 1 & -\frac{3}{2} & -1 \\ 0 & 0 & 0 & 0 \end{array} \right] \Rightarrow \begin{array}{l} x_1 = -x_2 + 2x_3 + 5 \\ x_2 = \frac{3}{2}x_3 - 1 \\ x_3 = \text{Parameter} \end{array}$$

Wrong Because $-x_2$ is not a parameter. If it's a pivot column, it can't be a parameter.

$$\text{RowOperations} \rightarrow \left[\begin{array}{ccc|c} 1 & 0 & -\frac{1}{2} & 6 \\ 0 & 1 & -\frac{3}{2} & -1 \\ 0 & 0 & 0 & 0 \end{array} \right] \Rightarrow \begin{array}{l} x_1 = \frac{1}{2}x_3 + 6 \\ x_2 = \frac{3}{2}x_3 - 1 \\ x_3 = \text{Parameter} \end{array}$$

Remember: Echelon Form of a matrix is not unique. Reduced Echelon Form IS unique.

1.4 The Matrix Equation $A\vec{x} = \vec{b}$

$$\begin{array}{rcl} a_{11}x_1 & + & a_{12}x_2 + \dots + a_{1n}x_n = b_1 \\ a_{21}x_1 & + & a_{22}x_2 + \dots + a_{2n}x_n = b_2 \\ \vdots & & \vdots \\ a_{m1}x_1 & + & a_{m2}x_2 + \dots + a_{mn}x_n = b_m \end{array}$$

$$\text{Matrix Form: } \underbrace{\begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \dots & a_{mn} \end{bmatrix}}_A \underbrace{\begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_m \end{bmatrix}}_{\vec{x}} = \underbrace{\begin{bmatrix} b_1 \\ b_2 \\ \vdots \\ b_m \end{bmatrix}}_{\vec{b}}$$

Theorem: The system $A\vec{x} = \vec{b}$ has a solution Iff \vec{b} is a linear combination of $A, \vec{b} \in \text{Span}\{\text{column vectors of } A\}$

$$\text{Example 1.4.1. } A = \begin{bmatrix} 3 & 5 & -1 \\ 2 & 0 & 4 \\ 0 & 1 & 2 \end{bmatrix} \vec{b} = \begin{bmatrix} 4 \\ 2 \\ -1 \end{bmatrix}$$

$$\text{Standard Form: } \begin{cases} 3x_1 + 5x_2 - 1x_3 = 4 \\ 2x_1 + 4x_3 = 2 \\ 1x_2 + 2x_3 = -1 \end{cases}$$

$$\begin{aligned} \text{Matrix Form: } & \begin{bmatrix} 3 & 4 & -1 \\ 2 & 0 & 4 \\ 0 & 1 & 2 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} 4 \\ 2 \\ -1 \end{bmatrix} \\ \text{Vector Form: } & \begin{bmatrix} 3 \\ 2 \\ 0 \end{bmatrix} x_1 + \begin{bmatrix} 5 \\ 0 \\ 1 \end{bmatrix} x_2 + \begin{bmatrix} -1 \\ 4 \\ 2 \end{bmatrix} x_3 = \begin{bmatrix} 4 \\ 2 \\ -1 \end{bmatrix} \end{aligned}$$

Example 1.4.2. How many rows have pivot positions?

$$A = \begin{bmatrix} 1 & 3 & -2 & -2 \\ 0 & 1 & -1 & 5 \\ -1 & -2 & 1 & 7 \\ 1 & 1 & 0 & -6 \end{bmatrix} \xrightarrow{\text{RowOperations}} \begin{bmatrix} \textcircled{1} & 3 & -2 & -2 \\ 0 & \textcircled{1} & -1 & 5 \\ 0 & 0 & 0 & \textcircled{6} \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

A as above

$A\vec{x} = \vec{b}$ Assume system is consistent

Q_1 : On how many parameters does the solution depend?

Answer: One (x_3)

Q_2 : Is it true that $A\vec{x} = \vec{b}$ has a solution for any $\vec{b} \in R^4$?

Answer: Only if there is a pivot position in each row. - So it's False.

$$\textbf{Example 1.4.3.} \quad \text{Do the vectors } \vec{v}_1 = \begin{bmatrix} 1 \\ 3 \\ 4 \\ -1 \end{bmatrix} \vec{v}_2 = \begin{bmatrix} 0 \\ 7 \\ 5 \\ -1 \end{bmatrix} \vec{v}_3 = \begin{bmatrix} -1 \\ 4 \\ 2 \\ 1 \end{bmatrix} \text{ Span } R^4?$$

Only 3 vectors, need at least 4 vectors to span R^4 (Still it is not enough, in general)

Theorem: Let A be an m row by n column matrix then the following statements are equivalent.

a) For each \vec{b} in R^m , the system $A\vec{x} = \vec{b}$ has a solution.

b) The columns of A span R^m .

c) A has a pivot position in every row.

$$\textbf{Example 1.4.4.} \quad \text{Do the columns of } A = \begin{bmatrix} 1 & -1 & 5 & 0 \\ 2 & 0 & 4 & 2 \\ 4 & 1 & 5 & 5 \end{bmatrix} \text{ span } R^3?$$

$$A \xrightarrow[\widetilde{R_3 - 4R_1}]{\widetilde{R_2 - 2R_1}} \begin{bmatrix} 1 & -1 & 5 & 0 \\ 0 & 2 & -6 & 2 \\ 0 & 5 & -15 & 5 \end{bmatrix} \xrightarrow{\widetilde{R_3 - \frac{5}{2}R_2}} \begin{bmatrix} \textcircled{1} & -1 & 5 & 0 \\ 0 & \textcircled{2} & -6 & 2 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

NO, the columns of A do NOT span R^3 because all the vectors lie in a plane (no z component)

Notation of Matrices

1.5 Section 1.5

1.6 Section 1.6

1.7 Section 1.7

1.8 Introduction to Linear Transformations

Example 1.8.1.

$$A = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$$
$$T(\vec{x}) = A\vec{x} = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} x_1 \\ -x_2 \end{bmatrix}$$

Definition 1.8.1. Transformation

A transformation (or function or mapping) T from R^n to R^m is a rule that assigns to each vector \vec{x} in R^n a vector $T(\vec{x})$ in R^m .

The set R^n is called the Domain of T

The set R^m is called the Co-Domain of T

$T(\vec{x})$ is called the image of \vec{x} (under T)

$\{T(\vec{x}), \vec{x} \in R^n\}$ is called the range of T (the set of all images)

Definition 1.8.2. Linear Transformation

A transformation $T : R^n \rightarrow R^m$ is linear if:

- (i) $T(\vec{u} + \vec{v}) = T(\vec{u}) + T(\vec{v})$ for any \vec{u}, \vec{v} from the domain of T
- (ii) $T(c\vec{u}) = cT(\vec{u})$ for any \vec{u} and any scalar $c \in R$

Example 1.8.2. .

1.9 Solution Sets of Linear Systems

Chapter 2

Matrix Algebra

2.1 Matrix Operations