LINEAR TRANSFORMATIONS AND MATRICES

**Introduction**:

 Linear algebra is a branch of mathematics that deals with linear equations and their representations in the vector space using matrices. When information related to linear functions is presented in well organised form then it results in a matrix. The term matrix was first introduced by English mathematician James Sylvester but it was his friend, the mathematician Arthur Cayley who developed the algebraic structure of matrices in two papers in 1850s. Linear algebra facilitates the modelling of many natural phenomena and hence an integral part of engineering and physics.

**Definition:** Linear Transformation

Let U and V be two vector spaces over the same field F. Then the mapping T from U to V i.e $T:U\rightarrow V $is said to be a linear transformation ( linear mapping or vector space homomorphism) if and only if it satisfies the following conditions:

(1). $T(u+v)=T(u)+T(v) ∀u,v\in U$

(2). $T\left(αu\right)=αT\left(u\right)∀u\in U, α\in F$

The conditions (1) and (2) can be combined as

$T\left(αu+βv\right)=αT\left(u\right)+βT\left(v\right)∀u,v\in U and α,β\in F$.

A linear transformation $T:U\rightarrow U$ is called linear operator and the transformation $T:U\rightarrow F$ is called linear functional.

**Example 1**: Show that the mapping $T:R^{3}\rightarrow R^{2}$ defined by $T\left(x,y,z\right)=(x-y,y+z)$ is a linear transformation.

**Sol.** Let $u=\left(x\_{1},y\_{1},z\_{1}\right)$ and $v=\left(x\_{2},y\_{2},z\_{2}\right)\in R^{3}=U\_{3}\left(R\right)$ and $α,β$ be any two real numbers. The$ αu+βv=α\left(x\_{1},y\_{1},z\_{1}\right)+β\left(x\_{2},y\_{2},z\_{2}\right)$ $ = \left(αx\_{1}+βx\_{2},αy\_{1}+βy\_{2},αz\_{1}+βz\_{2}\right)\in R^{3}$. $T\left(αu+βv\right)=T\left(αx\_{1}+βx\_{2},αy\_{1}+βy\_{2},αz\_{1}+βz\_{2}\right)$

 $=\left(\left(αx\_{1}+βx\_{2}\right)-(αy\_{1}+βy\_{2}),\left(αy\_{1}+βy\_{2}\right)+(αz\_{1}+βz\_{2})\right)$ ( By definition of T)

 $=\left(α\left(x\_{1}-y\_{1}\right)+β\left(x\_{2}-y\_{2}\right), α\left(y\_{1}+z\_{1}\right)+ β(y\_{2}+z\_{2})\right)$ $ =α\left(x\_{1}-y\_{1},y\_{1}+z\_{1}\right)+ β\left(x\_{2}-y\_{2},y\_{2}+z\_{2}\right)$

 =$ α$T$\left(x\_{1},y\_{1},z\_{1}\right)+ βT\left(x\_{2},y\_{2},z\_{2}\right)$

 $=αT\left(u\right)+βT(v)$.

Therefore$ T\left(αu+βv\right)= αT\left(u\right)+βT\left(v\right),$ it implies that the mapping T is a linear transformation.

There are many other examples of linear transformations some of which are given below:

1. $T:R^{3}\rightarrow R$ defined by $T\left(x,y,z\right)=2x+y-3z$
2. $T:R^{2}\rightarrow R^{3}$ defined by $T\left(x,y\right)=(x+y,x,x-y)$

But the mapping $T:R^{2}\rightarrow R^{3}$ defined by $T\left(x,y\right)=(x+5,x,x-y)$ is not linear transformation because it does not satisfy the conditions. Likewise, $T:R^{2}\rightarrow R$ defined by $T\left(x,y\right)=xy and T\left(x,y\right)=\left|x-y\right|$ are not linear transformations.

**Definition: Matrix.** A matrix is the arrangement of numbers in rows and columns or when the numbers are arranged in rows and columns so as to form a rectangulat array, the pattern so formed is called a matrix.The numbers are called entries or elements of the matrix. In common notation, matrix is denoted by a capital letter and the small letters with double subscript describes the entries of the matrix. If a matrix has m rows and n columns then $m×n$ is defined as the order of the matrix.

**Matrix associated with linear transformation**

A matrix represents a linear transformation under a fixed basis and vice-versa.

Let $T:U\rightarrow V $be a linear transformation where U and V are two finite dimensional vector spaces over the same field F and $dimU=n$ and $dimV=m.$ Let$ B\_{1}=\left\{u\_{1},u\_{2},…,u\_{n}\right\}$ and $ B\_{2}=\left\{v\_{1},v\_{2},…,v\_{n}\right\}$ be the ordered bases of U and V respectively.

Since $T:U\rightarrow V $is a linear transformation so for every $u\in U$, we have $T(u)\in V$. Since $ B\_{2}$ is a basis of V, so each element $T(u)\in V$ can be expressed as the linear combination of elements of $ B\_{2}$. It implies each $T(u\_{j})\in V$ where $j=1,2,…n.$ Therefore, we have

$$T\left(u\_{1}\right)=a\_{11}v\_{1}+a\_{21}v\_{2}+…+a\_{m1}v\_{m}$$

$$T\left(u\_{2}\right)=a\_{12}v\_{1}+a\_{22}v\_{2}+…+a\_{m2}v\_{m}$$

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$$T\left(u\_{n}\right)=a\_{1n}v\_{1}+a\_{2n}v\_{2}+…+a\_{mn}v\_{m}$$

i.e. $T\left(u\_{j}\right)=\sum\_{i=1}^{m}a\_{ij}v\_{i}$ where $a\_{ij}\in F for i=1,2,…,m and j=1,2,…,n$. Then the above equations can be expressed in matrix form as follows:

 $\left[\begin{matrix}T\left(u\_{1}\right)\\T\left(u\_{2}\right)\\\vdots \\T\left(u\_{n}\right)\end{matrix}\right]=\left[\begin{matrix}a\_{11}&a\_{21}&…&a\_{m1}\\a\_{12}&a\_{22}&…&a\_{m2}\\\vdots &\vdots &\ddots &\vdots \\a\_{1n}&a\_{2n}&…&a\_{mn}\end{matrix}\right]\left[\begin{matrix}v\_{1}\\v\_{2}\\\vdots \\v\_{m}\end{matrix}\right]$.

So, the coefficient matrix in above form is

 $\left[\begin{matrix}a\_{11}&a\_{21}&…&a\_{m1}\\a\_{12}&a\_{22}&…&a\_{m2}\\\vdots &\vdots &\ddots &\vdots \\a\_{1n}&a\_{2n}&…&a\_{mn}\end{matrix}\right]$.

The transpose of the above coefficient matrix is defined as the matrix associated with linear transformation T, relative to basis $B\_{1} $and $ B\_{2}$.

Conversely, for any matrix say $A=\left(a\_{ij}\right)\_{m×n}$, $a\_{ij}\in R$ we define a mapping $T:R^{n}\rightarrow R^{m}$ by $T\left(u\right)=v $where $u=\left\{x\_{1},x\_{2},…,x\_{n}\right\}$ $\in R^{n}$ and $v=\left\{y\_{1},y\_{2},…,y\_{m}\right\}\in R^{m}$ such that
$$y\_{1}=a\_{11}x\_{1}+a\_{12}x\_{2}+…+a\_{1n}x\_{n}$$

$$y\_{2}=a\_{21}x\_{1}+a\_{22}x\_{2}+…+a\_{2n}x\_{n}$$

$$\cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots $$

$$y\_{m}=a\_{m1}v\_{1}+a\_{m2}x\_{2}+…+a\_{mn}x\_{n}$$

or $Y=AX$. So it is clear that the mapping $T:R^{n}\rightarrow R^{m} $defined by matrix A is a linear transformation. It implies that corresponds to any given matrix A, there exists a unique linear transformation T. It also comes out that if T is any linear transformation which maps $R^{n}$ to $R^{m}$, there is always an $m×n$ matrix say A with the property that $T\left(X\right)=AX$. The important conclusion is that every linear transformation is associated with a matrix and vice-versa. We show this by means of an example.

 **Example 1.** Let $T:R^{2}\rightarrow R^{3}$ defined by $T\left(x,y\right)=(x+5y,y,2x-y)$ is a linear transformation. To find the matrix associated with T, Let $T\left(x\_{1},x\_{2}\right)=(y\_{1},y\_{2},y\_{3})$ where $\left(x\_{1},x\_{2}\right)\in R^{2}$ and $=(y\_{1},y\_{2},y\_{3})\in R^{3}$. It gives $\left(y\_{1},y\_{2},y\_{3}\right)=T\left(x\_{1},x\_{2}\right)=(x\_{1}+5x\_{2},x\_{2},2x\_{1}-x\_{2})$

Therefore, we get $ y\_{1}=x\_{1}+5x\_{2}$

 $y\_{2}=0x\_{1}+x\_{2}$

$ y\_{3}=2x\_{1}-x\_{2}$

The above system of equations can be expressed as

$$\left[\begin{matrix}y\_{1}\\y\_{2}\\y\_{3}\end{matrix}\right]=\left[\begin{matrix}1&5\\0&1\\2&-1\end{matrix}\right]\left[\begin{matrix}x\_{1}\\x\_{2}\end{matrix}\right]$$

So the matrix associated with the linear transformation T is $\left[\begin{matrix}1&5\\0&1\\2&-1\end{matrix}\right].$ Conversely , one can easily find the linear transformation T associated with matrix A by using similar arguments. **Example 2**. To find the linear transformation say $T:R^{3}\rightarrow R^{3}$ corresponding to the matrix

 $A=\left[\begin{matrix}2&0&-4\\-5&1&-1\\2&-7&3\end{matrix}\right]$ .

Let $ Y=T$(X) where X=$\left(x\_{1},x\_{2},x\_{3}\right)\in R^{3}$ and $Y=(y\_{1},y\_{2},y\_{3})\in R^{3}$.

Then $Y=A$X.

$⇒ \left[\begin{matrix}y\_{1}\\y\_{2}\\y\_{3}\end{matrix}\right]=\left[\begin{matrix}2&0&-4\\-5&1&-1\\2&-7&3\end{matrix}\right]\left[\begin{matrix}x\_{1}\\x\_{2}\\x\_{3}\end{matrix}\right]=\left[\begin{matrix}2x\_{1}-4x\_{3}\\-5x\_{1}+x\_{2}-x\_{3}\\2x\_{1}-7x\_{2}+3x\_{3}\end{matrix}\right]$.

 $∴$ $y\_{1}=2x\_{1}-4x\_{3}, y\_{2}=-5x\_{1}+x\_{2}-x\_{3}, y\_{3}=2x\_{1}-7x\_{2}+3x\_{3}.$

So the linear transformation corresponding to matrix A is

 $T\left(x\_{1},x\_{2},x\_{3}\right) =(2x\_{1}-4x\_{3}, -5x\_{1}+x\_{2}-x\_{3}, 2x\_{1}-7x\_{2}+3x\_{3}).$

**Example 3**. Find a matrix representation of linear transformation T on $R^{3}$ defined as

$$T\left(x,y,z\right) =(7y+z, x-5y, 3x-z).$$

 **References:**

1. Introduction to Engineering Mathematics, vol- I by H.K Dass and Dr. Rama Verma, S. Chand publishers, 2014.
2. Linear Algebra by Anil Makkar, Jagdeep singh, Nishant Juneja and Baljit Singh, Sharma Publications, 2017.
3. Higher Engineering Mathematics by B.S. Grewal, Khanna Publishers, 40th Edition, 2007.