

1.8-1.9 Matrices and Linear Transformations

Jeremy Teitelbaum

Linear Transformations and Matrices

If A is an $n \times m$ matrix, and x is any vector in \mathbf{R}^m , then Ax is a vector in \mathbf{R}^n .

So we can define a function $T : \mathbf{R}^m \rightarrow \mathbf{R}^n$ by

$$T(x) = Ax.$$

For example if

$$A = \begin{bmatrix} 0 & -4 \\ 4 & 1 \\ 3 & 3 \end{bmatrix} \text{ and } v = \begin{bmatrix} x \\ y \end{bmatrix}$$

then

$$T(v) = Av = \begin{bmatrix} -4y \\ 4x + y \\ 3x + 3y \end{bmatrix}$$

Function terminology

In general if $f : X \rightarrow Y$ is a function then f is a “rule” that associates exactly one element $y \in Y$ to each element $x \in X$. The y corresponding to x is called $f(x)$. Furthermore:

- ▶ X is called the domain of f
- ▶ Y is called the codomain of f
- ▶ the set of $y \in Y$ so that there is an $x \in X$ with $f(x) = y$ is called the *range* of f .
- ▶ if $f(x) = y$, then y is called the *image* of x under f .

If A is an $n \times m$ matrix, then the domain of $f(x) = Ax$ is \mathbf{R}^m and the codomain is \mathbf{R}^n .

Examples of matrix transformations

If

$$A = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

then

$$A \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} x \\ y \\ 0 \end{bmatrix}$$

is called a *projection*, in this case onto the xy -plane.

Rotations in 2d

If

$$A(\theta) = \begin{bmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{bmatrix}$$

then

$$A(\theta) \begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} x \cos \theta - y \sin \theta \\ x \sin \theta + y \cos \theta \end{bmatrix}$$

rotates the vector (x, y) through an angle θ counterclockwise.

To see this, write $x = r \cos \phi$ and $y = r \sin \phi$. Then:

$$r \cos \phi \cos \theta - r \sin \phi \sin \theta = r \cos(\phi + \theta)$$

$$r \cos \phi \sin \theta + r \sin \phi \cos \theta = r \sin(\phi + \theta)$$

Linear Transformations

Let $T : \mathbf{R}^m \rightarrow \mathbf{R}^n$ be a function. Then T is called a *linear transformation* if

- ▶ $T(ax) = aT(x)$ for every scalar a , and
- ▶ $T(x + y) = T(x) + T(y)$ for any two vectors $x, y \in \mathbf{R}^m$.

Any matrix transformation $T(x) = Ax$, where A is $n \times m$, is linear.

If T is linear, then $T(0) = 0$ (because $T(0x) = 0T(x) = 0$.)

Linear Transformations

Let

$$T(x) = \begin{bmatrix} 1 & 0 & -2 \\ -2 & 1 & 6 \\ 3 & -2 & -5 \end{bmatrix} x.$$

Find a vector x so that $T(x) = b$ and determine if this x is unique.

Hint: The rref form for the augmented matrix $[A \quad b]$ is

$$\begin{bmatrix} 1 & 0 & 0 & 3 \\ 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 2 \end{bmatrix}$$

Another problem

Let

$$T(x) = \begin{bmatrix} 1 & -2 & 1 \\ 3 & -4 & 5 \\ 0 & 1 & 1 \\ -3 & 5 & -4 \end{bmatrix} x.$$

Find a vector x so that $T(x) = b$ and determine if this x is unique.

Hint: The rref form for the augmented matrix $[A \quad b]$ is

$$\begin{bmatrix} 1 & 0 & 3 & 7 \\ 0 & 1 & 1 & 3 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

Linear Transformations

If $T : \mathbf{R}^m \rightarrow \mathbf{R}^n$ is linear, and v_1, \dots, v_k are vectors in \mathbf{R}^m , then if you know

$$T(v_1), \dots, T(v_k)$$

you know

$$T(a_1 v_1 + \dots + a_k v_k)$$

for any constants a_i . In other words, you can compute T for any vector in the span of v_1, \dots, v_k .

Linear Transformations

In particular if

$$T\left(\begin{bmatrix} 1 \\ 0 \end{bmatrix}\right) = \begin{bmatrix} a \\ b \end{bmatrix}$$

and

$$T\left(\begin{bmatrix} 0 \\ 1 \end{bmatrix}\right) = \begin{bmatrix} c \\ d \end{bmatrix}$$

then

$$T\left(\begin{bmatrix} x \\ y \end{bmatrix}\right) = T\left(x \begin{bmatrix} 1 \\ 0 \end{bmatrix} + y \begin{bmatrix} 0 \\ 1 \end{bmatrix}\right) = xT\left(\begin{bmatrix} 1 \\ 0 \end{bmatrix}\right) + yT\left(\begin{bmatrix} 0 \\ 1 \end{bmatrix}\right) = \begin{bmatrix} ax + cy \\ bx + dy \end{bmatrix}$$

and $T(x) = Ax$ where

$$A = \begin{bmatrix} a & c \\ b & d \end{bmatrix}$$

Matrices and Linear Transformations

We have seen that, given a matrix A , then $T(x) = Ax$ is a linear transformation.

Now suppose $T : \mathbf{R}^m \rightarrow \mathbf{R}^n$ is a linear transformation.

Let $e_i \in \mathbf{R}^m$ be the vector

$$e_i = \begin{bmatrix} 0 \\ \vdots \\ 1 \\ \vdots \\ 0 \end{bmatrix}$$

where the 1 is in row i of e_i .

Matrices and Linear Transformations

Let

$$A(T) = [T(e_1) \quad T(e_2) \cdots T(e_m)]$$

whose columns are the $T(e_i)$. This is an $n \times m$ matrix because each $T(e_i) \in \mathbf{R}^n$.

Notice that $Ae_i = T(e_i)$ for $i = 1, \dots, m$. As a result, by linearity, $Av = T(v)$ for any vector $v \in \mathbf{R}^m$.

Therefore *every linear transformation comes from multiplication by a matrix.*

The identity map

The map $T : \mathbf{R}^m \rightarrow \mathbf{R}^m$ given by $Tx = x$ is called the identity map.

Since $T(e_i) = e_i$ for $i = 1, \dots, m$ the matrix of T is the $m \times m$ matrix with 1's on the diagonal and zeros elsewhere.

$$\begin{bmatrix} 1 & 0 & 0 & \cdots & 0 \\ 0 & 1 & 0 & \cdots & 0 \\ 0 & 0 & \ddots & 1 & 0 \\ 0 & 0 & \cdots & 0 & 1 \end{bmatrix}$$

Matrices and Linear Transformations

If $T : \mathbf{R}^m \rightarrow \mathbf{R}^n$ is linear, then T is determined by what it does to the standard basis vectors e_i .

For example, if $m = n = 2$, and T is the reflection map $T(x, y) = (y, x)$, then $T(e_1) = e_2$ and $T(e_2) = e_1$ and therefore $Tx = Ax$ where

$$A = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}.$$

Reflections

TABLE 1 Reflections

| Transformation | Image of the Unit Square | Standard Matrix |
|--|--------------------------|--|
| Reflection through the x_2 -axis | | $\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$ |
| Reflection through the x_1 -axis | | $\begin{bmatrix} -1 & 0 \\ 0 & 1 \end{bmatrix}$ |
| Reflection through the line $x_2 = x_1$ | | $\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$ |
| Reflection through the line $x_2 = -x_1$ | | $\begin{bmatrix} 0 & -1 \\ -1 & 0 \end{bmatrix}$ |
| Reflection through the origin | | $\begin{bmatrix} -1 & 0 \\ 0 & -1 \end{bmatrix}$ |

Figure 1: reflections

Shears

TABLE 3 Shears

| Transformation | Image of the Unit Square | Standard Matrix |
|------------------|---|--|
| Horizontal shear |  <p style="text-align: center;">$k < 0$</p>  <p style="text-align: center;">$k > 0$</p> | $\begin{bmatrix} 1 & k \\ 0 & 1 \end{bmatrix}$ |
| Vertical shear |  <p style="text-align: center;">$k < 0$</p>  <p style="text-align: center;">$k > 0$</p> | $\begin{bmatrix} 1 & 0 \\ k & 1 \end{bmatrix}$ |

Figure 2: shears

Contractions/Expansions

TABLE 2 Contractions and Expansions

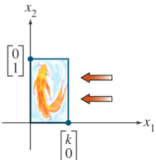
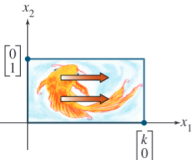
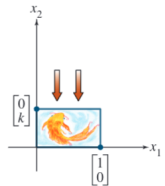
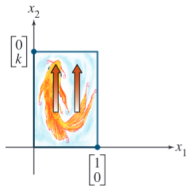
| Transformation | Image of the Unit Square | | Standard Matrix |
|--------------------------------------|---|---|--|
| Horizontal contraction and expansion |  |  | $\begin{bmatrix} k & 0 \\ 0 & 1 \end{bmatrix}$ |
| | $0 < k < 1$ | $k > 1$ | |
| Vertical contraction and expansion |  |  | $\begin{bmatrix} 1 & 0 \\ 0 & k \end{bmatrix}$ |
| | $0 < k < 1$ | $k > 1$ | |

Figure 3: contractions and expansions

Projections

TABLE 4 Projections

| Transformation | Image of the Unit Square | Standard Matrix |
|---------------------------------|---|--|
| Projection onto the x_1 -axis |  | $\begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}$ |
| Projection onto the x_2 -axis |  | $\begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix}$ |

Figure 4: projections

One-to-one and onto maps

A function $T : A \rightarrow B$ is *one-to-one* if the only way that $T(x) = T(y)$ is if $x = y$.

Eg the function $f(x) = x^2$ is *not* one-to-one, because $f(-1) = f(1)$ even though $-1 \neq 1$. But the function $f(x) = 3x$ is one-to-one, because if $3x = 3y$ then x and y must be equal.

A function $T : A \rightarrow B$ is *onto* if, for any $b \in B$, there is an $a \in A$ so that $T(a) = b$.

The function $f(x) = x^2$ is not *onto*, because the equation $-1 = x^2$ does not have a solution (at least in real numbers.) The function $f(x) = 3x$ is *onto*, because the equation $y = 3x$ always has a solution ($x = y/3$).

One-to-one linear maps

If T is linear, then $T(x) = T(y)$ if and only if $T(x) - T(y) = T(x - y) = 0$. So T is one-to-one if the only solution to $T(v) = 0$ is $v = 0$.

Since T comes from a matrix A , the map is one-to-one if and only if the matrix equation $Ax = 0$ has only zero as its solution.

This happens if and only if *the columns of A are linearly independent*.

Onto linear maps

If $T : \mathbf{R}^m \rightarrow \mathbf{R}^n$ is linear, then $T(x)$ is onto if only if $T(x) = b$ has a solution for any $b \in \mathbf{R}^n$. This means that the matrix equation

$$Ax = b$$

has a solution for any $b \in \mathbf{R}^n$.

Since Ax is a linear combination of the columns of A , every equation $Ax = b$ has a solution only if every b is a linear combination of the columns of A . In other words, A is onto if and only if the columns of A span \mathbf{R}^n .

Theorem 12

Theorem 12 in the book summarizes these two key facts.

Theorem: Let $T(x) = Ax$ be a linear map from \mathbf{R}^m to \mathbf{R}^n , where A is an $n \times m$ matrix.

1. T is one-to-one if and only if the columns of A are linearly independent vectors in \mathbf{R}^n .
2. T is onto if and only if the columns of A span \mathbf{R}^n .

Algebraic version

Algebraically:

1. $T(x) = Ax$ is one-to-one if and only if the rref of A has no free variables - in other words, if every column has a pivot.
2. $T(x) = Ax$ is onto if and only if every row of A has a pivot.

Note that if A is an $n \times m$ matrix, then:

- ▶ if $m > n$, the map cannot be one-to-one.
- ▶ if $n > m$, the map cannot be onto.