Week 1

10 March 2021 13:30

- Matrices $\rightarrow$ Multiply them.

(1) $\rightarrow$ $\begin{bmatrix} a_1 & \cdots & a_n \end{bmatrix} \begin{bmatrix} b_1 \\ \vdots \\ b_n \end{bmatrix}$

$=$

$a_1 b_1 + \cdots + a_n b_n$

$$\begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{m1} & \cdots & a_{mn} \end{bmatrix}_{m \times n} \begin{bmatrix} b_1 \\ \vdots \\ b_n \end{bmatrix}_{n \times 1} = \begin{bmatrix} \\ \\ \end{bmatrix}_{m \times 1}$$

$$A = \begin{bmatrix} A_1 \\ \vdots \\ A_m \end{bmatrix} \qquad b = \begin{bmatrix} b_1 \\ \vdots \\ b_n \end{bmatrix}$$

$A_1, \ldots, A_m \in \mathbb{R}^{1 \times n}$

$$Ab = \begin{bmatrix} A_1 b \\ \vdots \\ A_m b \end{bmatrix}$$

$A \in \mathbb{R}^{m \times n}$ $\qquad B \in \mathbb{R}^{n \times p}$

$B = \begin{bmatrix} b_1 & \cdots & b_p \end{bmatrix}$; $b_1, \ldots, b_p \in \mathbb{R}^{n \times 1}$

$AB = \begin{bmatrix} Ab_1 & \cdots & Ab_p \end{bmatrix} \in \mathbb{R}^{m \times p}$

$\in \mathbb{R}^{m \times 1}$

$A \in \mathbb{R}^{n\times n}, \quad B \in \mathbb{R}^{n\times n}$

We say that B is an inverse of A if
$$AB = I = BA.$$

Fact. (Will see later) $AB = I \Rightarrow BA = I$
(this was not clear, a priori.)

→ Functions $f, g : X \longrightarrow X$. ($X \neq \emptyset$ is some set.)

If $(f \circ g)(x) = x \quad \forall x \in X$,

is it necessary that $(g \circ f)(x) = x \quad \forall x \in X$?

No. Find example.

$Ax = b$. —— $(*)$ $\quad A \in \mathbb{R}^{m\times n}, x \in \mathbb{R}^{n\times 1}, b \in \mathbb{R}^{m\times 1}$

If A is upper triangular, it is easy by back-substitution. (Whether consistent or not is also clear.)

Idea: Do operations on both A and b to get something as above.

→ If $Ax_0 = b$, i.e., x_0 is a particular sol^n, and $S = \{x \in \mathbb{R}^{n\times 1} : Ax = 0\}$.

Then, all solutions of $(*)$ are precisely of the form $x_0 + s$ for some $s \in S$.

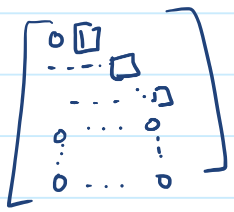
Idea: Row echelon form (REF)

(i) All zero rows at bottom. (Possibly none.)

(No zero row can be above a nonzero row.)

first $\neq 0$ element from left

(2) Pivots should be strictly from left to right as you go from top to bottom.



Week 2

17 March 2021 09:42

Outline:

$A \in \mathbb{R}^{m \times n}$

1. Recall REF. n variables, r pivots ⇒ (n - r) free variables
2. **Ax** = **0** has ***only*** the zero solution ⇔ n = r ← every column has a pivot
3. EROs
4. GEM
5. **Ax** = **0** has ***only*** the zero solution ⇔ any REF of **A** has n non-zero rows

$A \in \mathbb{R}^{n \times n}$

6. Inverse
7. **Ax** = **0** has ***only*** the zero solution ⇔ A is invertible
8. Let **A**, **B** ∈ ℝ^{n × n}. **AB** = **I** ⇔ **BA** = **I**
9. RCF. REF + pivots are 1 + the entries above the pivots are 0s
10. **A** can be transformed to **I** via EROs ⇔ **A** is invertible
11. GJM
12. Linear (in)dependence
13. Row rank
14. Given n column vectors, make a matrix with those as columns and find its row rank r. We know r ≤ n. The vectors are linearly independent ⇔ r = n.
15. EROs don't change row rank. Thus, **A** and REF(**A**) have the same row rank.
16. If **A'** is in REF, then row-rank(**A'**) = number-of-non-zero-rows(**A'**).

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3. EROs → Elementary Row operations

Type I : Interchange two rows

Type II : Add a scalar multiple of R_i to R_j where $i \neq j$.

Type III : Multiplying a row with a non-zero scalar

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4. GEM → Gauss Elimination Method

↳ Algo to convert a matrix into an REF using EROs.

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5. # non-zero rows of A' = # pivots of A'

(A' is in REF)

5 follows from 2.

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6. If $A \in \mathbb{R}^{n \times n}$, then $B \in \mathbb{R}^{n \times n}$ is ~~an~~ the inverse of A if $AB = I = BA$.

9. RCF if (i) it is REF

(ii) it has all pivots as 1

(iii) everything above pivot are also 0

$$\begin{bmatrix} \boxed{1} & \vdots & \\ 0 & 0 & \\ \vdots & \boxed{1} & \cdots \\ 0 & 0 & \\ & \vdots & \end{bmatrix}$$

RCF is unique. (REF need not be.)

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10. A is invertible $\Leftrightarrow$ RCF of A is I

$\Leftrightarrow$ A can be transformed to I via EROs

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11. Take $A \in \mathbb{R}^{n\times n}$.

Make the augmented matrix

$$[A \mid I]$$

performs EROs to make A into its RCF (so same operations on I as well)

$$[A' \mid B]$$

If A is inv., then $A' = I$ and $B = A^{-1}$.

If A is not inv., then $A' \neq I$.

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11. Linear dependence

- $S \subset \mathbb{R}^{n\times 1}$ (or $\mathbb{R}^{1\times n}$)

(possibly infinite)

- S is linearly dependent if there exist (distinct) $v_1, \dots, v_s \in S$ and $\alpha_1, \dots, \alpha_s \in \mathbb{R}$, not all zero such that

$$\alpha_1 v_1 + \cdots + \alpha_s v_s = \mathbf{0}$$

in $\mathbb{R}^{n\times 1}$ (or $\mathbb{R}^{1\times n}$)

- For example, if $\alpha_1 \neq 0$ and $n \geq 2$, then

$$v_1 = -\frac{1}{\alpha_1}(\alpha_2 v_2 + \cdots + a_s v_s).$$

- if $\mathbf{0} \in S$, then S is lin. dep.
  Take $n=1$, $v_1 = \mathbf{0}$, $\alpha_1 = 1 \neq 0$.
  Then, $1 \cdot \mathbf{0} = \mathbf{0}$.

- If $S = \{v\}$ and $v \neq \mathbf{0}$. Then, S is not lin. dep.

- if $S = \emptyset$, then S is not lin. dep.

- S is linearly independent if S is not linearly dependent.

- $\emptyset$ is lin. indep. $\{v\}$ is lin indep iff $v \neq \mathbf{0}$.

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13. row-rank (A) = maximum no. of lin. indep rows of A.

if $A = \mathbf{O}$, then row-rank$(A) = 0$.

$$\text{row-rank}\begin{bmatrix} [1 & 1] \\ 2 & 2 \end{bmatrix} = 1$$

this is lin indep

$\{[1 \ \ 1], [2 \ \ 2]\}$ is lin. dep.

15. In general, row-rank (A) = row-rank (A')
where A' is an REF of A.

Week 4

31 March 2021 10:47

Outline:

1. Linear transformations
2. Model example
3. M^E_F(T)
4. Composite
5. Null space, image space (relate with A, T_A)
6. Eigen(value, vector, space)
7. Characteristic polynomial
8. Algebraic, geometric multiplicity
9. Similarity of square matrices
10. When is B ~ A?
11. Diagonalisable, how do we get P?

1. V, W $\longrightarrow$ vector spaces over $\mathbb{K}$

($\mathbb{K} = \mathbb{R}$ or $\mathbb{C}$)

A linear transformation from V to W is a function

$$T : V \longrightarrow W$$

with the following properties:

(i) $T(v_1 + v_2) = T(v_1) + T(v_2)$ $\forall v_1, v_2 \in V$,

(ii) $T(\alpha v) = \alpha \cdot T(v)$ $\forall \alpha \in \mathbb{K}$, $\forall v \in V$.

Consequences: (i) $T(\underset{\underset{V}{\cap}}{\mathbf{0}}) = \underset{\underset{W}{\cap}}{\mathbf{0}}$

(ii) For all $\alpha_1, \dots, \alpha_s \in \mathbb{K}$ and $v_1, \dots, v_s \in V$:

$$T(\alpha_1 v_1 + \dots + \alpha_s v_s) = T(\alpha_1 v_1) + \dots + T(\alpha_s v_s)$$
$$= \alpha_1 T(v_1) + \dots + \alpha_s T(v_s).$$

2. Let $A \in \mathbb{R}^{m \times n}$. This gives a linear transformation

$$T_A : \mathbb{R}^{n \times 1} \longrightarrow \mathbb{R}^{m \times 1}$$

defined as

$l_A(x) = Ax$

3. $\underline{M_F^E(T)}$.

Let $T: \overset{\dim = n}{V} \to \overset{\dim = m}{W}$ be a lin. transf.
Fix ordered bases E of V and F of W.

Say, $E = (v_1, \ldots, v_n)$ and
$F = (w_1, \ldots, w_m)$.

The matrix $M = M_F^E(T)$ is defined as:
εW

(i) Compute $T(v_1)$ and write it as a lin. combination of F. (Can do this since F is a basis of W.)
(This combination is unique.)

$$T(v_1) = a_{11} w_1 + a_{21} w_2 + \cdots + a_{m1} w_m.$$

The first column of M is $\begin{bmatrix} a_{11} \\ a_{21} \\ \vdots \\ a_{m1} \end{bmatrix}$.

(ii) Do the same for $T(v_2)$.
$\vdots$
(n) Do it for $T(v_n)$.

$M^{\text{dom}}_{\text{codomain}}$

4. v. spaces $V \xrightarrow{T} W \xrightarrow{S} U$

4. v. spaces $V \xrightarrow{T} W \xrightarrow{S} U$

(ordered!) bases $\quad E \subseteq V$, $F \subseteq W$, $G \subseteq U$

T and S are lin. transf.

Note $S \circ T : V \longrightarrow U$ is also linear. (Check!)

$$M_G^E(S \circ T) = M_G^F(S) M_F^E(T).$$

5. $T : V \longrightarrow W$ lin. transf.

$$\mathcal{N}(T) := \{ v \in V : T(v) = \underset{W}{\mathbf{0}} \} \subseteq V$$

vector subspaces of V and W

$$\mathcal{I}(T) := \{ w \in W : \exists v \in V \text{ s.t. } T(v) = w \} \subseteq W$$

If $V = \mathbb{R}^{n \times 1}$, $W = \mathbb{R}^{m \times 1}$, $A \in \mathbb{R}^{m \times n}$, then

$$\mathcal{N}(T_A) = \mathcal{N}(A) \text{ and}$$
$$\mathcal{I}(T_A) = \mathcal{C}(A).$$

6. Let $A \in \mathbb{K}^{m \times n}$.

Suppose $v \in \mathbb{K}^{n \times 1} \setminus \{\mathbf{0}\}$ and $\lambda \in \mathbb{K}$ is such that

$$Av = \lambda v.$$

Then, v is called an eigenvector of A and λ an eigenvalue.

The eigenspace of λ is defined as

$$\mathcal{N}(A-\lambda I) = \{ v \in \mathbb{R}^{n\times 1} : Av = \lambda v \}.$$

All eigenvectors along with $\mathbf{0}$.

7. Let $p_A(t) := \det(A - tI)$.

This is the characteristic polynomial of A.

<u>Thm.</u> $\lambda \in \mathbb{K}$ is an e-val of $A \Leftrightarrow p_A(\lambda) = 0$.

8. geometric multiplicity of $\lambda := \dim(\mathcal{N}(A-\lambda I))$
algebraic multiplicity of $\lambda :=$ largest m s.t. $(t-\lambda)^m$ is a factor of $p_A(t)$.

9. Let $A, B \in \mathbb{K}^{n\times n}$.

$A \sim B \overset{\text{defn}}{\iff} \exists P \in \mathbb{K}^{n\times n}$ invertible such that $P^{-1}AP = B$

<u>Check</u>: $\sim$ is an equivalence relation.

11. $A \in \mathbb{K}^{n\times n}$ is said to be diagonalisable if A is similar to a diagonal matrix.

Proposition

A matrix $\mathbf{A} \in \mathbb{K}^{n\times n}$ is diagonalizable if and only if there is a basis for $\mathbb{K}^{n\times 1}$ consisting of eigenvectors of $\mathbf{A}$. In fact,

$$\begin{aligned} & \mathbf{P}^{-1}\mathbf{A}\mathbf{P} = \mathbf{D}, \text{ where } \mathbf{P}, \mathbf{D} \in \mathbb{K}^{n\times n} \text{ are of the form} \\ & \mathbf{P} = \begin{bmatrix} \mathbf{x}_1 & \cdots & \mathbf{x}_n \end{bmatrix} \text{ and } \mathbf{D} = \operatorname{diag}(\lambda_1, \ldots, \lambda_n) \\ \iff \quad & \{\mathbf{x}_1, \ldots, \mathbf{x}_n\} \text{ is a basis for } \mathbb{K}^{n\times 1} \text{ and} \\ & \mathbf{A}\mathbf{x}_k = \lambda_k \mathbf{x}_k \text{ for } k = 1, \ldots, n. \end{aligned}$$