

Linear Algebra

Wenxiao Yang*

*Department of Mathematics, University of Illinois at Urbana-Champaign

2021

目录

1	Vector Space	3
1.1	Vector Space $(V, +, \times)$ (over a field \mathbb{F})	3
1.2	A field is a vector space over its subfield	3
1.3	Vector subspace	3
1.4	Linear independent, Linear combination	3
1.5	span V , basis, dimension	3
1.6	Standard basis vectors	4
1.7	Linear transformation	4
1.8	一个线性变换对应一个矩阵, 线性变换矩阵相乘仍为线性变换矩阵	4
1.9	$GL(V)$: invertible linear transformations $V \rightarrow V$	5
2	Basic Definition	5
2.1	Square Matrix $A_{n \times n}$: $\det(A)$, singular	5
2.2	Orthogonal Vectors	5
2.3	Orthonormal Vectors	5
3	Eigenvalues Related	5
3.1	Eigenvalues, Eigenvectors Definition	5
3.2	Diagonalizable Matrix	6
3.3	Eigen Decomposition of Symmetric Matrices Results	6
3.4	Diagonalization of Real Symmetric Matrices	7
3.5	Trace	7
3.6	Jacobian matrix	8
3.7	Hessian matrix	8
3.8	Positive Definite Matrices	8
3.8.1	Definition	8

3.8.2	Condition number (for PD matrix)	9
3.8.3	Diagonal matrix situation	9
3.8.4	Using eigenvalues	9
3.8.5	Sylvester's Criterion	10
3.9	Matrix Norm (Induced Norm) and Spectral Radius	11
4	Euclidean geometry basics	11
4.1	Norm	11
4.1.1	Vector's Norm	11
4.1.2	Matrix's Norm	12
4.1.3	Difference between Spectral Radius and Spectral Norm	12
4.2	Euclidean distance, inner product	12
4.3	Isometry	13
4.4	Linear isometries i.e. orthogonal group	13
4.5	Special orthogonal group	13
4.6	translation	14
4.7	All isometries can be represented by a composition of <i>a translation</i> and <i>an orthogonal transformation</i>	14
5	Algebra Computation	14
5.1	Hessian Matrix	14
5.2	Taylor expansion	14
5.3	Random Vectors	14
5.4	Matrix Multiplication	15
5.5	矩阵求导	15
5.6	Linear Regression: Least Square	16
5.6.1	Normal Equations	16
5.7	LU Decomposition (Restricted to Square)	17
5.8	SVD: Singular Value Decomposition	18
5.8.1	Pseudoinverse	18
5.8.2	Analysis about $A^T A$ and AA^T	19
5.8.3	Solve Normal Equations	19
5.8.4	Low-Rank Approximation	19

1 Vector Space

1.1 Vector Space $(V, +, \times)$ (over a field \mathbb{F})

A vector space over a field \mathbb{F} is a set V w/ an operation addition $+: V \times V \rightarrow V$ and an operation scalar multiplication $\mathbb{F} \times V \rightarrow V$

- (1) Addition is associative & commutative
- (2) $\exists 0 \in V$, additive identity: $0 + v = v \forall v \in V$
- (3) $1v = v \forall v \in V$ (where $1 \in \mathbb{F}$ is multi. id. in \mathbb{F})
- (4) $\forall \alpha, \beta \in \mathbb{F}, v \in V, \alpha(\beta v) = (\alpha\beta)v$
- (5) $\forall v \in V, (-1)v = -v$ we have $v + (-v) = 0$
- (6) $\forall \alpha \in \mathbb{F}, v, u \in V, \alpha(v + u) = \alpha v + \alpha u$
- (7) $\forall \alpha, \beta \in \mathbb{F}, v \in V, (\alpha + \beta)v = \alpha v + \beta v$

1.2 A field is a vector space over its subfield

Example 1. $\mathbb{K} \subset \mathbb{F}$ is a subfield of a field \mathbb{F} . Then \mathbb{F} is a vector space over \mathbb{K} . (Since $\mathbb{F} \subset \mathbb{F}[x]$, then $\mathbb{F}[x]$ is a vector space over \mathbb{F} .)

1.3 Vector subspace

Suppose that V is a vector space over \mathbb{F} . A vector subspace or just subspace is a nonempty subset $W \subset V$ closed under addition and scalar multiplication. i.e. $v + w \in W, av \in W, \forall v, w \in W, a \in \mathbb{F}$.

Example 2. $\mathbb{K} \subset \mathbb{L} \subset \mathbb{F}$, then \mathbb{L} is a subspace of \mathbb{F} over \mathbb{K} .

1.4 Linear independent, Linear combination

1.5 span V , basis, dimension

A set of elements $v_1, \dots, v_n \in V$ is said to **span** V if every vector $v \in V$ can be expressed as a linear combination of v_1, \dots, v_n . If v_1, \dots, v_n spans and is linearly independent, then we call the set a **basis** for V .

Proposition 1 (Proposition 2.4.10.). Suppose V is a vector space over a field \mathbb{F} having a basis $\{v_1, \dots, v_n\}$ with $n \geq 1$.

- (i) For all $v \in V$, $v = a_1v_1 + \dots + a_nv_n$ for exactly one $(a_1, \dots, a_n) \in \mathbb{F}^n$.
- (ii) If w_1, \dots, w_n span V , then they are linearly independent.
- (iii) If w_1, \dots, w_n are linearly independent, then they span V .

If a vector space V over \mathbb{F} has a basis with n vectors, then V is said to be n -dimensional (over \mathbb{F}) or is said to have **dimension** n .

1.6 Standard basis vectors

$$e_1 = (1, 0, \dots, 0), e_2 = (0, 1, 0, \dots, 0), \dots, e_n = (0, 0, \dots, 0, 1) \in \mathbb{F}^n$$

are a basis for \mathbb{F}^n called the **standard basis vectors**.

1.7 Linear transformation

Given two vector spaces V and W over \mathbb{F} a **linear transformation** is a function $T : V \rightarrow W$ such that for all $a \in \mathbb{F}$ and $v, w \in V$, we have

$$T(av) = aT(v) \text{ and } T(v + w) = T(v) + T(w)$$

Proposition 2 (Proposition 2.4.15.). *If V and W are vector spaces and v_1, \dots, v_n is a basis for V then any function from $\{v_1, \dots, v_n\} \rightarrow W$ extends uniquely to a linear transformation $V \rightarrow W$.*

Any $v \in V$, $\exists(a_1, \dots, a_n)$ s.t. $v = a_1v_1 + \dots + a_nv_n$. Then $T(v) = T(a_1v_1 + \dots + a_nv_n) = a_1T(v_1) + \dots + a_nT(v_n)$

1.8 一个线性变换对应一个矩阵, 线性变换矩阵相乘仍为线性变换矩阵

Corollary 1 (Corollary 2.4.16.). *If v_1, \dots, v_n is a basis for a vector space V and w_1, \dots, w_m is a basis for a vector space W (both over \mathbb{F}), then any linear transformation $T : V \rightarrow W$ determines (and is determined by) the $m \times n$ matrix:*

$$A = A(T) = \begin{bmatrix} A_{11} & A_{12} & \dots & A_{1n} \\ A_{21} & A_{22} & \dots & A_{2n} \\ \vdots & \vdots & \dots & \vdots \\ A_{m1} & A_{m2} & \dots & A_{mn} \end{bmatrix}$$

$$\begin{bmatrix} w_1 & \dots & w_m \end{bmatrix}^T = A \begin{bmatrix} v_1 & \dots & v_n \end{bmatrix}^T$$

$\mathcal{L}(V, W)$ denotes the set of all linear transformations from V to W ; $M_{m \times n}(\mathbb{F})$ the set of $m \times n$ matrix with entries in \mathbb{F} . $T \rightarrow A(T)$ defines a *bijection* $\mathcal{L}(V, W) \rightarrow M_{m \times n}(\mathbb{F})$. $A(T)$ **represents the linear transformation T** .

Proposition 3 (Proposition 2.4.19). *Suppose that V , W , and U are vector spaces over \mathbb{F} , with fixed chosen bases. If $T : V \rightarrow W$ and $S : W \rightarrow U$ are linear transformations represented by matrices $A = A(T)$ and $B = B(S)$, then $ST = S \circ T : V \rightarrow U$ is a linear transformation represented by the matrix $BA = B(S)A(T)$.*

1.9 $GL(V)$: invertible linear transformations $V \rightarrow V$

Given a vector space V over F , we let $GL(V) \subset \mathcal{L}(V, V)$ denote the subset of **invertible linear transformations**.

$$GL(V) = \{T \in \mathcal{L}(V, V) | T \text{ is a bijection}\} = \mathcal{L}(V, V) \cap Sym(V)$$

2 Basic Definition

2.1 Square Matrix $A_{n \times n}$: $\det(A)$, singular

1. A is singular if $\det(A) = 0$, else non-singular.
2. If $\det(A) \neq 0$, A^{-1} exists and $A^{-1} = \frac{adj(A)}{\det(A)}$
3. $\det(AB) = \det(A)\det(B)$

2.2 Orthogonal Vectors

Two vectors a and b are orthogonal, if their dot product is equal to zero (they are perpendicular).

$$a \cdot b = 0$$

2.3 Orthonormal Vectors

Two vectors a and b are orthonormal, if they are orthogonal **unit vectors**.

3 Eigenvalues Related

3.1 Eigenvalues, Eigenvectors Definition

A vector x is an **eigenvector** of a matrix A if Ax is parallel to x , that is if $Ax = \lambda x$ for some number $\lambda \in \mathbb{R}$. The number λ is called an **eigenvalue** of A .

i.e. the root of $(A - \lambda I_n)x = 0 \Leftrightarrow \det(A - \lambda I_n) = 0$

3.2 Diagonalizable Matrix

A $n \times n$ matrix A with n linearly independent eigenvalues u is said to be *diagonalizable*.

$$\begin{aligned}
 AU &= A \begin{bmatrix} | & | & \cdots & | \\ u_1 & u_2 & \cdots & u_n \\ | & | & \cdots & | \end{bmatrix} \\
 &= \begin{bmatrix} | & | & \cdots & | \\ \lambda_1 u_1 & \lambda_2 u_2 & \cdots & \lambda_n u_n \\ | & | & \cdots & | \end{bmatrix} \\
 &= \begin{bmatrix} | & | & \cdots & | \\ u_1 & u_2 & \cdots & u_n \\ | & | & \cdots & | \end{bmatrix} \begin{bmatrix} \lambda_1 & & & \\ & \lambda_2 & & \\ & & \ddots & \\ & & & \lambda_n \end{bmatrix} \\
 &= UD \\
 \Rightarrow A &= UDU^{-1}
 \end{aligned}$$

Theorem 1. If an $n \times n$ matrix A has n linearly independent eigenvectors u_1, \dots, u_n corresponding to eigenvalues $\lambda_1, \dots, \lambda_n$, then $A = UDU^{-1}$ where D is diagonal with entries $\lambda_1, \dots, \lambda_n$, and U has columns u_1, \dots, u_n .

A is **similar** to D ($\exists P$ s.t. $A = PDP^{-1}$).

Not *diagonalizable* is also called *defective*.

Theorem 2. An $n \times n$ matrix with n distinct eigenvalues is diagonalizable.

(Because the n associated eigenvectors are always linearly independent.)

3.3 Eigen Decomposition of Symmetric Matrices Results

Let A be a symmetric $n \times n$ matrix, i.e. $A^T = A$

Proposition 4. All eigenvalues of A are real.

Proposition 5. Eigenvectors corresponding to distinct eigenvalues are orthogonal.

证明.

Let λ_1, λ_2 be eigenvalues s.t. $\lambda_1 \neq \lambda_2$.

$$\begin{aligned}
 Au_1 &= \lambda_1 u_1; \quad Au_2 = \lambda_2 u_2 \\
 \lambda_1 u_1^T u_2 &= (Au_1)^T u_2 = u_1^T A^T u_2 \\
 &= u_1^T Au_2 = u_1^T (\lambda_2 u_2) = \lambda_2 u_1^T u_2 \\
 \Rightarrow u_1^T u_2 &= 0 \text{ Since } \lambda_1 \neq \lambda_2
 \end{aligned}$$

□

Proposition 6. If λ is an eigenvalue with multiplicity k , we can find k orthogonal eigenvectors for λ .

Multiplicity: the number of times an element is repeated in a multiset.

3.4 Diagonalization of Real Symmetric Matrices

A real symmetric matrix $A_{n \times n}$ can be written as

$$\begin{aligned} A &= \sum_{i=1}^n \lambda_i u_i u_i^T \\ &= U \Omega U^T \end{aligned}$$

u_i are orthonormal eigenvectors. λ_i are eigenvalues.

Where $U = [u_1, u_2, \dots, u_n]$, $\Omega = \text{diag}(\lambda_1, \dots, \lambda_n)$

Since u_i are orthonormal eigenvectors, $U^T U = I \Rightarrow U^T = U^{-1}$. U is an orthogonal matrix.

Proposition 7. For any $x \in \mathbb{R}^n$,

$$\lambda_{\min} \|x\|^2 \leq x^T A x \leq \lambda \|x\|^2$$

证明. Since u_i are orthonormal and linearly independent. $x = \sum_{i=1}^n \alpha_i u_i$ for some $\alpha_i \in \mathbb{R}, i = 1, \dots, n$

$$\begin{aligned} x^T A x &= \left(\sum_{i=1}^n \alpha_i u_i \right)^T A \left(\sum_{j=1}^n \alpha_j u_j \right) \\ &= \sum_{i=1}^n \sum_{j=1}^n \alpha_i \alpha_j u_i^T A u_j \\ &= \sum_{i=1}^n \sum_{j=1}^n \alpha_i \alpha_j u_i^T (A u_j) \\ &= \sum_{i=1}^n \alpha_i^2 \lambda_i \\ &\Rightarrow \lambda_{\min} \|x\|^2 \leq x^T A x \leq \lambda \|x\|^2 \end{aligned}$$

The first equation holds if x is the eigenvector for λ_{\min} . The second equation holds if x is the eigenvector for λ_{\max} . □

3.5 Trace

$$A_{n \times n}, \text{Tr}(A) = \sum_{i=1}^n A_{ii}$$

$$\det(A) = \prod_{i=1}^n \lambda_i, \text{Tr}(A) = \sum_{i=1}^n \lambda_i$$

Proposition 8 (Invariance Property). $A_{m \times n}, B_{n \times k}, C_{k \times m}, \text{Tr}(ABC) = \text{Tr}(CAB) = \text{Tr}(BCA)$.

3.6 Jacobian matrix

Suppose $\mathbf{f} : \mathbf{R}^n \rightarrow \mathbf{R}^m$ is a function such that each of its first-order partial derivatives exist on \mathbf{R}^n . This function takes a point $\mathbf{x} \in \mathbf{R}^n$ as input and produces the vector $\mathbf{f}(\mathbf{x}) \in \mathbf{R}^m$ as output. Then the Jacobian matrix of \mathbf{f} is defined to be an $m \times n$ matrix, denoted by \mathbf{J} , whose (i, j) th entry is $\mathbf{J}_{ij} = \frac{\partial f_i}{\partial x_j}$, or explicitly

$$\mathbf{J} = \begin{bmatrix} \frac{\partial \mathbf{f}}{\partial x_1} & \cdots & \frac{\partial \mathbf{f}}{\partial x_n} \end{bmatrix} = \begin{bmatrix} \nabla^T f_1 \\ \vdots \\ \nabla^T f_m \end{bmatrix} = \begin{bmatrix} \frac{\partial f_1}{\partial x_1} & \cdots & \frac{\partial f_1}{\partial x_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial f_m}{\partial x_1} & \cdots & \frac{\partial f_m}{\partial x_n} \end{bmatrix}$$

where $\nabla^T f_i$ is the transpose (row vector) of the gradient of the i component.

3.7 Hessian matrix

Suppose $f : \mathbb{R}^n \rightarrow \mathbb{R}$ is a function taking as input a vector $\mathbf{x} \in \mathbb{R}^n$ and outputting a scalar $f(\mathbf{x}) \in \mathbb{R}$. If all second partial derivatives of f exist and are continuous over the domain of the function, then the Hessian matrix \mathbf{H} of f is a square $n \times n$ matrix, usually defined and arranged as follows:

$$\mathbf{H}_f = \begin{bmatrix} \frac{\partial^2 f}{\partial x_1^2} & \frac{\partial^2 f}{\partial x_1 \partial x_2} & \cdots & \frac{\partial^2 f}{\partial x_1 \partial x_n} \\ \frac{\partial^2 f}{\partial x_2 \partial x_1} & \frac{\partial^2 f}{\partial x_2^2} & \cdots & \frac{\partial^2 f}{\partial x_2 \partial x_n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial^2 f}{\partial x_n \partial x_1} & \frac{\partial^2 f}{\partial x_n \partial x_2} & \cdots & \frac{\partial^2 f}{\partial x_n^2} \end{bmatrix},$$

or, by stating an equation for the coefficients using indices i and j ,

$$(\mathbf{H}_f)_{i,j} = \frac{\partial^2 f}{\partial x_i \partial x_j}.$$

The Hessian matrix is a symmetric matrix, since the hypothesis of continuity of the second derivatives implies that the order of differentiation does not matter (Schwarz's theorem).

The determinant of the Hessian matrix is called the Hessian determinant.

3.8 Positive Definite Matrices

3.8.1 Definition

We say that a symmetric $n \times n$ matrix A is:

- (1). **positive semidefinite (PSD)** (written $A \succeq 0$) if $x^T A x \geq 0$ for all x .
- (2). **positive definite (PD)** (written $A \succ 0$) if $x^T A x > 0$ for all $x \neq 0$.
- (3). **negative semidefinite (NSD)** (written $A \preceq 0$) if $x^T A x \leq 0$ for all x .
- (4). **negative definite (ND)** (written $A \prec 0$) if $x^T A x < 0$ for all $x \neq 0$.
- (5). **indefinite** (not written in any particular way) if none of the above apply.

$x^T A x$ is a function of x called the quadratic form associated to A .

A is ND(NSD) $\Leftrightarrow -A$ is PD(PSD)

Note: $A^T A$ is **positive semidefinite**, since $x^T A^T A x = \|Ax\|^2 \geq 0$.

Note: We can extend definition to non-symmetric $n \times n$

$$x^T A x = x^T A^T x \Rightarrow x^T A x = x^T \left(\frac{A + A^T}{2} \right) x$$

3.8.2 Condition number (for PD matrix)

Condition number (for PD matrix):

$$\kappa(A) = \frac{\lambda_{max}}{\lambda_{min}} > 0$$

3.8.3 Diagonal matrix situation

$$D = \begin{bmatrix} d_1 & 0 & \dots & 0 \\ 0 & d_2 & \dots & 0 \\ \dots & \dots & \dots & \dots \\ 0 & 0 & \dots & d_n \end{bmatrix}$$

Lemma 1. If d_1, \dots, d_n are all nonnegative, then $D \succeq 0$;

If d_1, \dots, d_n are all positive, then $D \succ 0$;

If d_1, \dots, d_n are all nonpositive, then $D \preceq 0$;

If d_1, \dots, d_n are all negative, then $D \prec 0$;

3.8.4 Using eigenvalues

If A is an $n \times n$ symmetric matrix, then it can be factored as

$$A = Q^T \Lambda Q = Q^T \begin{bmatrix} \lambda_1 & 0 & \dots & 0 \\ 0 & \lambda_2 & \dots & 0 \\ \dots & \dots & \dots & \dots \\ 0 & 0 & \dots & \lambda_n \end{bmatrix} Q$$

where $\lambda_1, \dots, \lambda_n$ are the eigenvalues of A and the columns of Q are the corresponding eigenvectors.

We can get $x^T A x = x^T Q^T \Lambda Q x = (Qx)^T \Lambda (Qx)$

If we substitute $y = Qx$:

$$x^T A x = y^T \Lambda y = \lambda_1 y_1^2 + \lambda_2 y_2^2 + \dots + \lambda_n y_n^2$$

Theorem 3.

If $\lambda_1, \dots, \lambda_n$ are all nonnegative, then symmetric matrix $A \succeq 0$;

If $\lambda_1, \dots, \lambda_n$ are all positive, then $A \succ 0$;

If $\lambda_1, \dots, \lambda_n$ are all nonpositive, then $A \preceq 0$;

If $\lambda_1, \dots, \lambda_n$ are all negative, then $A \prec 0$;

if it has both positive and negative eigenvalues, then A is indefinite

3.8.5 Sylvester's Criterion

Consider a $n \times n$ matrix A :

$$A = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \dots & \dots & \dots & \dots \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{bmatrix}$$

Denote its $k \times k$ submatrix $A^{(k)}$:

$$A^{(k)} = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1k} \\ a_{21} & a_{22} & \dots & a_{2k} \\ \dots & \dots & \dots & \dots \\ a_{k1} & a_{k2} & \dots & a_{kk} \end{bmatrix}$$

Let $\Delta_k = \det(A^{(k)})$

$$\det(A - xI) = (\lambda_1 - x)(\lambda_2 - x)\dots(\lambda_n - x)$$

by setting $x = 0$ we get $\det(A) = \lambda_1\lambda_2\dots\lambda_n$. When $A \succ 0$, all the eigenvalues are positive, so $\det(A) > 0$ as well.

$A \succ 0 \Rightarrow \mathbf{u}^T A \mathbf{u} > 0$ for all \mathbf{u} :

Set $\mathbf{u} = [0, 0, \dots, 0, u_{k+1}, u_{k+2}, \dots, u_n]$

Then we can simplify the quadratic form for A to the quadratic form for $A^{(k)}$. Therefore, we expect $A^{(k)} \succ 0 \Rightarrow \Delta_k > 0$ for all k .

Theorem 4.

$A \succ 0$ iff $\Delta_i > 0 \forall i = 1, \dots, n$

$A \prec 0$ iff $(-1)^i \Delta_i > 0 \forall i = 1, \dots, n$

A is indefinite if the first Δ_k (nozero) that breaks each pattern respectively is the wrong sign.

Proposition 9.

1. Symmetric matrix A is PD

\Leftrightarrow All eigenvalues of A are > 0

$\Leftrightarrow \Delta_i > 0 \forall i = 1, \dots, n$

2. Symmetric matrix A is PSD

\Leftrightarrow All eigenvalues of A are ≥ 0

$\Leftrightarrow \Delta_i \geq 0 \forall i = 1, \dots, n$

3. For ND and NSD, test $-A$ instead of A

3.9 Matrix Norm (Induced Norm) and Spectral Radius

$\|A\| = \max_{\|x\|=1} \|Ax\|$. 即找到最大的绝对值之和的“列”。

Spectral Radius: for $n \times n$ matrix A ,

$$S(A) = \max_{i=1, \dots, n} |\lambda_i|$$

Proposition 10. $S(A) \leq \|A\|$

证明.

$$\|A\| = \max_{\|x\|=1} \|Ax\| \geq \|Au\| = |\lambda| \|u\| = |\lambda|$$

□

Proposition 11. For symmetric $A_{n \times n}$, $S(A) = \|A\|$

证明.

$\forall x \in \mathbb{R}^n$, decompose it by u_i . Since u_i are orthonormal and linearly independent. $x = \sum_{i=1}^n \alpha_i u_i$ for some $\alpha_i \in \mathbb{R}, i = 1, \dots, n$. $\|x\|^2 = \sum_{i=1}^n |\alpha_i|^2$

$$\begin{aligned} \|Ax\|^2 &= \left\| \sum_{i=1}^n \alpha_i A u_i \right\|^2 = \left\| \sum_{i=1}^n \alpha_i \lambda_i u_i \right\|^2 = \sum_{i=1}^n |\alpha_i|^2 |\lambda_i|^2 \\ &\leq \sum_{i=1}^n |\alpha_i|^2 S(A)^2 = S(A)^2 \|x\|^2 \Rightarrow \|A\| \leq S(A) \end{aligned}$$

Since we proved $S(A) \leq \|A\|$ before, $S(A) = \|A\|$.

□

4 Euclidean geometry basics

4.1 Norm

4.1.1 Vector's Norm

Vector $x \in \mathbb{R}^n$ -n-dim Euclidean space

$$x = (x_1, \dots, x_n) \equiv \begin{bmatrix} x_1 & x_2 & \dots & x_n \end{bmatrix}^\top = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix}$$

Norm of x , $\|x\|$ satisfies properties:

- (a) $\|x\| \geq 0$
- (b) $\|x\| = 0 \Leftrightarrow x = 0$
- (c) $\|cx\| = |c| \|x\|$, for $c \in \mathbb{R}$
- (d) $\|x + y\| \leq \|x\| + \|y\| \leftarrow$ Triangle Ineq.

Euclidean Norm (default $\rho = 2$): $\|x\| = \sqrt{x^\top x} = \sqrt{\sum_{i=1}^n x_i^2}$

Other norms:

1. l_1 -norm : $\|x\|_1 = \sum_{i=1}^n |x_i|$
2. l_ρ -norm : $\|x\|_\rho = \sqrt[\rho]{\sum_{i=1}^n |x_i|^\rho}$
3. Supremum norm or l_∞ -norm : $\|x\|_\infty = \max_i |x_i|$

4.1.2 Matrix's Norm

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

$$\|Ax\| \leq \|A\|\|x\|, \|AB\| \leq \|A\|\|B\|$$

Default is $\rho = 1$: $\|A\| = \max_{\|x\|=1} \|Ax\|$. 即找到最大的绝对值和的“列”。

$\|A\|_F = \sqrt{\sum_{i,j} a_{ij}^2}$ (Frobenius norm); Frobenius norm property: $\|A\|_F^2 = \langle A, A \rangle = \text{trace}(A^T A)$

$\|A\|_1 = \max_j \sum_{i=1}^n |A_{ij}|$ 即找到最大的绝对值和的“列”。

$\|A\|_\infty = \max_j \sum_{i=1}^n |A_{ij}|$ 即找到最大的绝对值和的“行”。

$\|A\|_2 = \sqrt{\lambda_{\max}(A^T A)} = \sigma_{\max}(A)$. $\|A\|_2 = \max_k \sigma_k$ is the singular value (square root of $A^T A$) of A (spectral norm, Euclidean norm)

$$\|A\| = \max \left(\frac{\|Ax\|}{\|x\|} \right) \Rightarrow \|A\| \geq \frac{\|Ax\|}{\|x\|}, \|Ax\| \leq \|A\|\|x\|$$

4.1.3 Difference between Spectral Radius and Spectral Norm

Spectral Radius: $S(A) = \max_{i=1, \dots, n} |\lambda_i|$; Spectral Norm: $\|A\|_2 = \max_k \sigma_k$

For real symmetric matrices, $\|A\|_2 = S(A)$.

For general matrices, $\|A\|_2 \geq S(A)$.

4.2 Euclidean distance, inner product

Euclidean distance on \mathbb{R}^n :

$$|x - y| = \sqrt{(x_1 - y_1)^2 + \dots + (x_n - y_n)^2}$$

Euclidean inner product:

$$x \cdot y = x_1 y_1 + \dots + x_n y_n = x^T y$$

Also written as $\langle x, y \rangle$

Useful fact:

$$\langle x, y \rangle = \cos(\theta) \|x\|_2 \|y\|_2$$

θ is the angle between x and y .

Two important results for Euclidean norm:

1) Pythagorean Theorem: If $x^\top y = 0$,

$$\|x + y\|^2 = \|x\|^2 + \|y\|^2$$

2) Cauchy - Schwarz Inequality:

$$\begin{aligned} \langle x, y \rangle &= |x^\top y| \leq \|x\|_2 \|y\|_2 \\ " = " &\text{ iff } x = \alpha y \text{ for some } \alpha \in \mathbb{R} \end{aligned}$$

4.3 Isometry

An **isometry** of \mathbb{R}^n is a bijection $\Phi : \mathbb{R}^n \rightarrow \mathbb{R}^n$ that preserves distance, which means,

$$|\Phi(x) - \Phi(y)| = |x - y|, \quad \forall x, y \in \mathbb{R}^n$$

We use $Isom(\mathbb{R}^n)$ denotes the set of all isometries of \mathbb{R}^n ,

$$Isom(\mathbb{R}^n) = \{\Phi : \mathbb{R}^n \rightarrow \mathbb{R}^n \mid |\Phi(x) - \Phi(y)| = |x - y|, \quad \forall x, y \in \mathbb{R}^n\}$$

Proposition 12. $\Phi, \Psi \in Isom(\mathbb{R}^n)$, then $\Phi \circ \Psi, \Phi^{-1} \in Isom(\mathbb{R}^n)$

证明.

Since Φ, Ψ are bijections, so is $\Phi \circ \Psi$. Moreover,

$$|\Phi \circ \Psi(x) - \Phi \circ \Psi(y)| = |\Phi(\Psi(x)) - \Phi(\Psi(y))| = |\Psi(x) - \Psi(y)| = |x - y|$$

Since $id \in Isom(\mathbb{R}^n)$,

$$|x - y| = |id(x) - id(y)| = |\Phi \circ \Phi^{-1}(x) - \Phi \circ \Phi^{-1}(y)| = |\Phi^{-1}(x) - \Phi^{-1}(y)|$$

□

4.4 Linear isometries i.e. orthogonal group

There is a matrix $A \in GL(n, \mathbb{R})$ i.e. a *invertible linear transformations* $T_A : \mathbb{R}^n \rightarrow \mathbb{R}^n$ is given by $T_A(v) = Av$.

$$T_A(v) \cdot T_A(w) = (Av) \cdot (Aw) = (Av)^t (Aw) = v^t A^t Aw$$

$$A^t A = I \Leftrightarrow T_A(v) \cdot T_A(w) = v \cdot w \Leftrightarrow T_A \in Isom(\mathbb{R}^n)$$

We define the all isometries in *invertible linear transformations* $\mathbb{R}^n \rightarrow \mathbb{R}^n$ as **orthogonal group**

$$O(n) = \{A \in GL(n, \mathbb{R}) \mid A^t A = I\} \subset GL(n, \mathbb{R})$$

4.5 Special orthogonal group

$O(n)$ are the matrices representing linear isometries of \mathbb{R}^n . $1 = \det(I) = \det(A^t A) = \det(A^t) \det(A) = \det(A)^2 \Rightarrow \det(A) = 1$ or $\det(A) = -1$. We use **special orthogonal group** represents A with $\det(A) = 1$,

$$SO(n) = \{A \in O(n) \mid \det(A) = 1\}$$

4.6 translation

Define a *translation* by $v \in \mathbb{R}^n$,

$$\tau_v : \mathbb{R}^n \rightarrow \mathbb{R}^n, \tau_v(x) = x + v$$

Note 1 (Exercise 2.5.3). $\forall v \in \mathbb{R}^n, \tau_v$ is an isometry.

証明. $|\tau_v(x) - \tau_v(y)| = |(x + v) - (y + v)| = |x - y|$ □

4.7 All isometries can be represented by a composition of a *translation* and an *orthogonal transformation*

Since the composition of isometries is an isometry, $\forall A \in O(n)$ and $v \in \mathbb{R}^n$, the composition

$$\Phi_{A,v}(x) = \tau_v(T_A(x)) = Ax + v$$

is an isometry. **which could account for all isometries.**

Theorem 5. $Isom(\mathbb{R}^n) = \{\Phi_{A,v} | A \in O(n), v \in \mathbb{R}^n\}$

5 Algebra Computation

5.1 Hessian Matrix

Definition 1. The Hessian of f at point x is an $n \times n$ symmetric matrix denoted by $\nabla^2 f(x)$ with $[\nabla^2 f(x)]_{ij} = \frac{\partial^2 f(x)}{\partial x_i \partial x_j}$

5.2 Taylor expansion

$$f(y) - f(x) = \nabla f(x)^T (y - x) + \frac{1}{2} (x - y)^T \nabla^2 f(x) (x - y) + o(\|x - y\|^2)$$

5.3 Random Vectors

Mean:

$$\mu = \mathbb{E}(\mathbf{Z}) = \begin{pmatrix} \mathbb{E}(Z_1) \\ \mathbb{E}(Z_2) \\ \dots \\ \mathbb{E}(Z_m) \end{pmatrix}$$

Variance-Covariance matrix Σ :

$$\Sigma_{m \times m} = Cov(\mathbf{Z}) = \mathbb{E}((\mathbf{Z} - \mu)(\mathbf{Z} - \mu)^T) = \begin{bmatrix} Var(Z_1) & \dots & Cov(Z_1, Z_m) \\ \dots & \dots & \dots \\ Cov(Z_m, Z_1) & \dots & Var(Z_m) \end{bmatrix}$$

Affine Transformation

(1)

$$\mathbf{W} = \mathbf{a}_{n \times 1} + \mathbf{B}_{n \times m} \mathbf{Z}_{m \times 1}$$

$$\mathbb{E}(\mathbf{W}) = \mathbf{a} + \mathbf{B}\mu, \text{Cov}(\mathbf{W}) = \mathbf{B}\Sigma\mathbf{B}^T$$

(2)

$$\mathbf{W} = \mathbf{v}^T \mathbf{Z} = v_1 Z_1 + \dots + v_m Z_m$$

$$\mathbb{E}(\mathbf{W}) = \mathbf{v}^T \mu = \sum_{i=1}^m v_i \mu_i$$

$$\text{Var}(\mathbf{W}) = \mathbf{v}^T \Sigma \mathbf{v} = \sum_{i=1}^m v_i^2 \text{Var}(Z_i) + 2 \sum_{i < j} v_i v_j \text{Cov}(Z_i, Z_j)$$

$$\text{i.e. } \mathbb{E}(\mathbf{AZ}) = \mathbf{A}\mathbb{E}(Z); \text{Var}(\mathbf{AZ}) = \mathbf{A}\text{Var}(\mathbf{Z})\mathbf{A}^T$$

(3)

$$\text{Cov}(\mathbf{AX}, \mathbf{BY}) = \mathbb{E}[(\mathbf{AX} - \mathbf{A}\mathbb{E}(X))(\mathbf{BY} - \mathbf{B}\mathbb{E}(Y))^T] = \mathbf{A}\mathbb{E}[(\mathbf{X} - \mathbb{E}(X))(\mathbf{Y} - \mathbb{E}(Y))^T]\mathbf{B}^T = \mathbf{A}\text{Cov}(\mathbf{X}, \mathbf{Y})\mathbf{B}^T$$

5.4 Matrix Multiplication

$$(1). A(BC) = (AB)C.$$

$$(2). A(B + C) = AB + AC.$$

$$(3). \text{No commutative: } AB \neq BA.$$

5.5 矩阵求导

<https://zhuanlan.zhihu.com/p/24709748>

<https://blog.csdn.net/daaikuaichuan/article/details/80620518>

Vector by vector:

Identities: vector-by-vector $\frac{\partial \mathbf{y}}{\partial \mathbf{x}}$			
Condition	Expression	Numerator layout, i.e. by \mathbf{y} and \mathbf{x}^T	Denominator layout, i.e. by \mathbf{y}^T and \mathbf{x}
\mathbf{a} is not a function of \mathbf{x}	$\frac{\partial \mathbf{a}}{\partial \mathbf{x}} =$	$\mathbf{0}$	
	$\frac{\partial \mathbf{x}}{\partial \mathbf{x}} =$	\mathbf{I}	
\mathbf{A} is not a function of \mathbf{x}	$\frac{\partial \mathbf{A} \mathbf{x}}{\partial \mathbf{x}} =$	\mathbf{A}	\mathbf{A}^T
\mathbf{A} is not a function of \mathbf{x}	$\frac{\partial \mathbf{x}^T \mathbf{A}}{\partial \mathbf{x}} =$	\mathbf{A}^T	\mathbf{A}
\mathbf{a} is not a function of \mathbf{x} , $\mathbf{u} = \mathbf{u}(\mathbf{x})$	$\frac{\partial \mathbf{a} \mathbf{u}}{\partial \mathbf{x}} =$	$\mathbf{a} \frac{\partial \mathbf{u}}{\partial \mathbf{x}}$	
$\mathbf{v} = \mathbf{v}(\mathbf{x})$, $\mathbf{u} = \mathbf{u}(\mathbf{x})$	$\frac{\partial \mathbf{u} \mathbf{v}}{\partial \mathbf{x}} =$	$\frac{\partial \mathbf{u}}{\partial \mathbf{x}} \mathbf{v} + \mathbf{u} \frac{\partial \mathbf{v}}{\partial \mathbf{x}}$	$\frac{\partial \mathbf{u}}{\partial \mathbf{x}} \mathbf{v}^T + \frac{\partial \mathbf{v}}{\partial \mathbf{x}} \mathbf{u}^T$
\mathbf{A} is not a function of \mathbf{x} , $\mathbf{u} = \mathbf{u}(\mathbf{x})$	$\frac{\partial \mathbf{A} \mathbf{u}}{\partial \mathbf{x}} =$	$\mathbf{A} \frac{\partial \mathbf{u}}{\partial \mathbf{x}}$	$\frac{\partial \mathbf{u}}{\partial \mathbf{x}} \mathbf{A}^T$
$\mathbf{u} = \mathbf{u}(\mathbf{x})$, $\mathbf{v} = \mathbf{v}(\mathbf{x})$	$\frac{\partial (\mathbf{u} + \mathbf{v})}{\partial \mathbf{x}} =$	$\frac{\partial \mathbf{u}}{\partial \mathbf{x}} + \frac{\partial \mathbf{v}}{\partial \mathbf{x}}$	
$\mathbf{u} = \mathbf{u}(\mathbf{x})$	$\frac{\partial \mathbf{g}(\mathbf{u})}{\partial \mathbf{x}} =$	$\frac{\partial \mathbf{g}(\mathbf{u})}{\partial \mathbf{u}} \frac{\partial \mathbf{u}}{\partial \mathbf{x}}$	$\frac{\partial \mathbf{u}}{\partial \mathbf{x}} \frac{\partial \mathbf{g}(\mathbf{u})}{\partial \mathbf{u}}$
$\mathbf{u} = \mathbf{u}(\mathbf{x})$	$\frac{\partial \mathbf{f}(\mathbf{g}(\mathbf{u}))}{\partial \mathbf{x}} =$	$\frac{\partial \mathbf{f}(\mathbf{g})}{\partial \mathbf{g}} \frac{\partial \mathbf{g}(\mathbf{u})}{\partial \mathbf{u}} \frac{\partial \mathbf{u}}{\partial \mathbf{x}}$	$\frac{\partial \mathbf{u}}{\partial \mathbf{x}} \frac{\partial \mathbf{g}(\mathbf{u})}{\partial \mathbf{u}} \frac{\partial \mathbf{f}(\mathbf{g})}{\partial \mathbf{g}}$

图 1: Denominator layout means $x \in \mathbb{R}^{n \times 1}$

$$\begin{aligned}
\frac{\partial u}{\partial x^T} &= \left(\frac{\partial u^T}{\partial x}\right)^T \\
\frac{\partial u^T v}{\partial x} &= \frac{\partial u^T}{\partial x} v + \frac{\partial v^T}{\partial x} u \\
\frac{\partial uv^T}{\partial x} &= \frac{\partial u}{\partial x} v^T + u \frac{\partial v^T}{\partial x} \\
\frac{\partial x^T x}{\partial x} &= 2x \\
\frac{\partial x^T A x}{\partial x} &= (A + A^T)x
\end{aligned}$$

where $x, u, v \in \mathbb{R}^{n \times 1}$

Note:

$$\frac{d\|Aw - b\|^2}{dw} = \frac{d(Aw - b)^T(Aw - b)}{dw} = \frac{d(Aw - b)^T}{dw}(Aw - b) + \frac{d(Aw - b)^T}{dw}(Aw - b) = 2A(Aw - b)$$

Matrix by vector:

$$\frac{\partial AB}{\partial x} = \frac{\partial A}{\partial x} B + A \frac{\partial B}{\partial x}$$

Matrix by matrix:

$$\begin{aligned}
\frac{\partial u^T X v}{\partial X} &= uv^T \\
\frac{\partial u^T X^T X u}{\partial X} &= 2Xuu^T \\
\frac{\partial [(Xu - v)^T(Xu - v)]}{\partial X} &= 2(Xu - v)u^T
\end{aligned}$$

Trace (迹):

$$\begin{aligned}
tr(a) &= a \\
tr(AB) &= tr(BA) \\
tr(ABC) &= tr(CAB) = tr(BCA) \\
\frac{\partial tr(AB)}{\partial A} &= B^T \\
tr(A) &= tr(A^T) \\
\frac{\partial tr(ABA^T C)}{\partial A} &= CAB + C^T AB^T
\end{aligned}$$

5.6 Linear Regression: Least Square

$$\text{Minimize}_w \mathcal{R}(w) = \|Xw - y\|^2$$

5.6.1 Normal Equations

$$\begin{aligned}
\nabla_w \|Xw - y\|^2 &= 2X^T(Xw - y) = 0 \\
&\Rightarrow X^T Xw = X^T y
\end{aligned}$$

These are called the **normal equations**.

Proposition 13. \hat{w} satisfies $\mathcal{R}(\hat{w}) = \min_w \mathcal{R}(w)$ if and only if \hat{w} satisfies the normal equations. (i.e. prove it is the global minimum)

证明. Consider w with $X^\top Xw = X^\top y$, and any w' ; then

$$\begin{aligned}\|Xw' - y\|^2 &= \|Xw' - Xw + Xw - y\|^2 \\ &= \|Xw' - Xw\|^2 + 2(Xw' - Xw)^\top (Xw - y) + \|Xw - y\|^2\end{aligned}$$

Since

$$(Xw' - Xw)^\top (Xw - y) = (w' - w)^\top (X^\top Xw - X^\top y) = 0$$

then

$$\|Xw' - y\|^2 = \|Xw' - Xw\|^2 + \|Xw - y\|^2 \geq \|Xw - y\|^2$$

□

5.7 LU Decomposition (Restricted to Square)

Triangular matrix saves time when computing $Ax = b$.

Let A be a square matrix. An LU factorization refers to the factorization of A , with proper row and/or column orderings or permutations, into two factors – a lower triangular matrix L and an upper triangular matrix U :

$A = LU$. In the lower triangular matrix all elements above the diagonal are zero, in the upper triangular matrix, all the elements below the diagonal are zero. For example, for a 3×3 matrix A , its LU decomposition looks like this:

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} = \begin{bmatrix} \ell_{11} & 0 & 0 \\ \ell_{21} & \ell_{22} & 0 \\ \ell_{31} & \ell_{32} & \ell_{33} \end{bmatrix} \begin{bmatrix} u_{11} & u_{12} & u_{13} \\ 0 & u_{22} & u_{23} \\ 0 & 0 & u_{33} \end{bmatrix}.$$

$$A = PLU$$

P is a permutation matrix (used to swap row, only one 1 in every row). P is orthogonal, so $P^{-1} = P^T$.

Solve $Ax = b$:

$$Ax = b$$

$$PLUx = b$$

Let $y = Ux$, then solve $PLy = b$

$$Ly = P^T b$$

Complexity: $O(n^3)$

5.8 SVD: Singular Value Decomposition

For a $n \times m$ matrix A with rank r ,

$$\begin{aligned}
 A_{n \times m} &= U_{n \times n} \Sigma_{n \times m} V_{m \times m}^T \\
 &= \sum_{i=1}^r s_i u_i v_i^T \\
 &= \begin{bmatrix} | & | & \cdots & | \\ u_1 & u_2 & \cdots & u_n \\ | & | & \cdots & | \end{bmatrix} \begin{bmatrix} s_1 & & & \\ & s_2 & & \\ & & \ddots & \\ & & & s_r \\ & & & & 0 \\ & & & & & \ddots \\ & & & & & & 0 \end{bmatrix} \begin{bmatrix} | & | & \cdots & | \\ v_1 & v_2 & \cdots & v_m \\ | & | & \cdots & | \end{bmatrix}^T
 \end{aligned}$$

U, V are orthogonal matrices. $u_i \in \mathbb{R}^{n \times 1}$ are left singular vectors, $v_i \in \mathbb{R}^{m \times 1}$ are right singular vectors. $s_i, i = 1, \dots, r$ are singular values (absolute values of eigenvalues of a normal matrix).

Complexity: $O(mn^2 + n^3)$

5.8.1 Pseudoinverse

We can't compute the inverse matrix of a singular matrix. We can use pseudoinverse matrix.

$$A_{m \times n}^+ = \sum_{i=1}^r \frac{1}{s_i} v_i u_i^T = V \Sigma^+ U^T$$

Where

$$\Sigma^+ = \begin{bmatrix} \frac{1}{s_1} & & & \\ & \frac{1}{s_2} & & \\ & & \ddots & \\ & & & \frac{1}{s_r} \\ & & & & 0 \\ & & & & & \ddots \\ & & & & & & 0 \end{bmatrix}$$

The SVD may not be unique, but the pseudoinverse of A , A^+ is unique.

$$\begin{aligned}
 AA^+ &= \sum_{i=1}^r u_i u_i^T = \begin{bmatrix} I_{r \times r} & O_{r \times n-r} \\ O_{n-r \times r} & O_{n-r \times n-r} \end{bmatrix}_{n \times n} \\
 A^+A &= \sum_{i=1}^r v_i v_i^T = \begin{bmatrix} I_{r \times r} & O_{r \times m-r} \\ O_{m-r \times r} & O_{m-r \times m-r} \end{bmatrix}_{m \times m}
 \end{aligned}$$

If A^{-1} exists, $A^{-1} = A^+$.

5.8.2 Analysis about $A^T A$ and AA^T

$$\begin{aligned} A^T A &= (U \Sigma V^T)^T (U \Sigma V^T) \\ &= V \Sigma^T U^T U \Sigma V^T \\ &= V \Sigma^T \Sigma V^T \\ &= V \Sigma^2 V^T \\ &\Rightarrow V = A^T U \Sigma^+ \end{aligned}$$

Columns of V are the eigenvectors of $A^T A$.

The diagonal entries of Σ^2 , $s_1^2, s_2^2, \dots, s_r^2$ are the eigenvalues of $A^T A$.

Similarly:

$$\begin{aligned} AA^T &= U \Sigma^2 U^T \\ &\Rightarrow U = AV \Sigma^+ \end{aligned}$$

Columns of U are the eigenvectors of AA^T .

Fact: $A^T A$ is positive semidefinite.

5.8.3 Solve Normal Equations

Solve $X^T X w = X^T y$,

$$\begin{aligned} \hat{w}_{ols} &= X^+ y \\ X^T X \hat{w}_{ols} &= X^T X X^+ y = (X^T (X X^+)) y = X^T y \end{aligned}$$

5.8.4 Low-Rank Approximation

For a $n \times m$ matrix A with rank r , $A = \sum_{i=1}^r s_i u_i v_i^T$.

Rank- k approximation for A is

$$A_k = \sum_{i=1}^k s_i u_i v_i^T$$

Where $s_1 \geq s_2 \geq \dots \geq 0$

参考文献

- [1] MATH 417: Christopher J Leininger Introduction to Abstract Algebra (Draft) 2017.
- [2] MATH 484
- [3] ECE 490
- [4] STAT 425
- [5] CS/MATH 357