Calculus and Linear Algebra

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1 Calculus

Theorem 1.1. *Taylor Expansion*

$$f(x) = T_n(x) + R_n(x) = \sum_{i=0}^{n} \frac{f^{(i)}(a)}{i!}(x-a)^i + \frac{f^{(n+1)}(\xi)}{(n+1)!}(x-a)^{n+1}, \quad \textit{for some} \quad \xi \in [a, x]$$

where we must have $\lim_{n\to\infty} R_n(x) = 0$.

We use $T_n(x) = \sum_{i=0}^{n} \frac{f^{(i)}(a)}{i!}(x-a)^i$ *as the approximate for* $f(x)$, *and* $R_n(x) = \frac{f^{(n+1)}(\xi)}{(n+1)!}(x-a)^{n+1}$ *as the error of approximation.*

The bound for the remainder $R_n(x)$ *is* $|R_n(x)| \le \frac{M}{(n+1)!}(x-a)^{n+1}$, $M = \max_{\xi\in[a,x]} |f^{(n+1)}(\xi)|$.

Lemma 1.2. ***(Useful Lemma for Differentiating Integrals)*** *Let* $p(x) = \int_x^C f(u)du$ *and* $q(x) = \int_C^x f(u)du$, *where* C *a constant, it is easy to verify the following.*

$$\frac{d}{dx}p(x) = -f(x), \quad \frac{d}{dx}q(x) = f(x)$$

1.1 Leibniz integral rule

Theorem 1.3. ***(Leibniz integral rule)*** *In calculus, the Leibniz integral rule for differentiation under the integral sign states that for an integral of the form*

$$\int_{a(x)}^{b(x)} f(x,t)dt$$

where $-\infty < a(x), b(x) < \infty$ *and the integrands are functions dependent on* x, *the derivative of this integral is expressible as*

$$\frac{d}{dx}\left(\int_{a(x)}^{b(x)} f(x,t)dt\right) = f(x, b(x)) \cdot \frac{d}{dx}b(x) - f(x, a(x)) \cdot \frac{d}{dx}a(x) + \int_{a(x)}^{b(x)} \frac{\partial}{\partial x} f(x,t)dt$$

where the partial derivative $\frac{\partial}{\partial x}$ *indicates that inside the integral, only the variation of* $f(x,t)$ *with* x *is considered in taking the derivative.*

Solution: This comes straightaway from Leibniz rule and Chain rule. Let

$$g(x, a(x), b(x)) = \int_{a(x)}^{b(x)} f(t,x)dt$$

Using the Chain rule of integration

$$\begin{aligned} \frac{d}{dx}g(x, a(x), b(x)) &= \frac{\partial g}{\partial x}\frac{dx}{dx} + \frac{\partial g}{\partial a}\frac{da}{dx} + \frac{\partial g}{\partial b}g\frac{db}{dx} \\ \textit{Lemma 1.2} \implies &= \int_{a(x)}^{b(x)} \frac{\partial}{\partial x} f(t,x)dt - f(a(x), x)\frac{d}{dx}a(x) + f(b(x), x)\frac{d}{dx}b(x) \end{aligned}$$

Remark 1.4.

1. When applying the Lemma 1.2 in the above proof, we treat $b(x)$ and $a(x)$ as constants when doing $\frac{\partial g}{\partial a}$ and $\frac{\partial g}{\partial b}$ respectively.
2. In the special case where the functions $a(x)$ and $b(x)$ are constants $a(x) = a$ and $b(x) = b$ with values that do not depend on x, this simplifies to:
$$\frac{d}{dx}\left(\int_a^b f(x,t)dt\right) = \int_a^b \frac{\partial}{\partial x} f(x,t)dt$$
3. If $a(x) = a$ is constant and $b(x) = x$, which is another common situation (for example, in the proof of Cauchy's repeated integration formula), the Leibniz integral rule becomes:
$$\frac{d}{dx}\left(\int_a^x f(x,t)dt\right) = f(x,x) + \int_a^x \frac{\partial}{\partial x} f(x,t)dt$$

△

Problem 1.5. We have the integral equation

$$\int_0^x \left(1 + x + e^{x-t}\right) y(t)\mathrm{d}t = g(x), \quad 0 \le x \le 1$$

By using Leibniz integral rule, we have that

$$g'(x) = (2+x)y(x) + \int_0^x \left(1 + e^{x-t}\right) y(t)\mathrm{d}t$$

Where y and g are chosen to satisfy the condition of Leibniz integral rule.

Solution: In the above example, $a(x) = 0, b(x) = x, f(t,x) = \left(1 + x + e^x e^{-t}\right) y(t)$, we will have the above equation simplifies to,

$$\begin{aligned} \frac{d}{dx}g\left(x, a(x), b(x)\right) &= \int_{a(x)}^{b(x)} \frac{\partial}{\partial x} f(t,x)dt - f\left(a(x), x\right)\frac{d}{dx}a(x) + f\left(b(x), x\right)\frac{d}{dx}b(x) \\ &= \int_0^x \frac{\partial}{\partial x}\left(1 + x + e^x e^{-t}\right) y(t)dt - \left(1 + x + e^x e^0\right) y(0)\frac{d}{dx}0 \\ &\quad + \left(1 + x + e^x e^{-x}\right) y(x)\frac{d}{dx}x \\ &= \int_0^x \left(1 + e^x e^{-t}\right) y(t)dt + (1 + x + 1)\, y(x) \\ &= (2+x)\, y(x) + \int_0^x \left(1 + e^{x-t}\right) y(t)dt. \end{aligned}$$

1.2 Gradient

1.3 Jacobian Matrix

Suppose $\mathbf{f}:\mathbf{R}^n \to \mathbf{R}^m$ 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

$$\mathbf{J} = \left[\begin{array}{ccc} \frac{\partial \mathbf{f}}{\partial x_1} & \cdots & \frac{\partial \mathbf{f}}{\partial x_n} \end{array}\right] = \left[\begin{array}{c} \nabla^{\mathrm{T}} f_1 \\ \vdots \\ \nabla^{\mathrm{T}} f_m \end{array}\right] = \left[\begin{array}{ccc} \frac{\partial f_1}{\partial x_1} & \cdots & \frac{\partial f_1}{\partial x_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial f_m}{\partial x_1} & \cdots & \frac{\partial f_m}{\partial x_n} \end{array}\right]$$

where $\nabla^{\mathrm{T}} f_i$ is the transpose (row vector) of the gradient of the i component. The Jacobian matrix, whose entries are functions of $\mathbf{x}$, is denoted in various ways; common notations include $D\mathbf{f}$, $\mathbf{J}_{\mathbf{f}}$, $\nabla \mathbf{f}$, and $\frac{\partial(f_1,\ldots,f_m)}{\partial(x_1,\ldots,x_n)}$. Some authors define the Jacobian as the transpose of the form given above.

Example 1 Consider the function $\mathbf{f}:\mathbf{R}^2 \to \mathbf{R}^2$, with $(x,y) \mapsto (f_1(x,y), f_2(x,y))$, given by

$$\mathbf{f}\left(\left[\begin{array}{c} x \\ y \end{array}\right]\right) = \left[\begin{array}{c} f_1(x,y) \\ f_2(x,y) \end{array}\right] = \left[\begin{array}{c} x^2 y \\ 5x + \sin y \end{array}\right].$$

Then we have

$$f_1(x,y) = x^2 y$$

and

$$f_2(x,y) = 5x + \sin y$$

and the Jacobian matrix of $\mathbf{f}$ is

$$\mathbf{J}_{\mathbf{f}}(x,y) = \begin{bmatrix} \frac{\partial f_1}{\partial x} & \frac{\partial f_1}{\partial y} \\ \frac{\partial f_2}{\partial x} & \frac{\partial f_2}{\partial y} \end{bmatrix} = \left[\begin{array}{cc} 2xy & x^2 \\ 5 & \cos y \end{array}\right]$$

and the Jacobian determinant is

$$det\left(\mathbf{J}_{\mathbf{f}}(x,y)\right) = 2xy\cos y - 5x^2$$

Example 2: polar-Cartesian transformation [edit] The transformation from polar coordinates (r,φ) to Cartesian coordinates (x,y), is given by the function $\mathbf{F}:\mathbf{R}^+ \times [0,2\pi) \to \mathbf{R}^2$ with components:

$$\begin{aligned} x &= r\cos\varphi \\ y &= r\sin\varphi \\ \mathbf{J}_{\mathbf{F}}(r,\varphi) &= \begin{bmatrix} \frac{\partial x}{\partial r} & \frac{\partial x}{\partial \varphi} \\ \frac{\partial y}{\partial r} & \frac{\partial y}{\partial \varphi} \end{bmatrix} = \left[\begin{array}{cc} \cos\varphi & -r\sin\varphi \\ \sin\varphi & r\cos\varphi \end{array}\right] \end{aligned}$$

The Jacobian determinant is equal to r. This can be used to transform integrals between the two coordinate systems:

$$\iint_{\mathbf{F}(A)} f(x,y)dxdy = \iint_A f(r\cos\varphi, r\sin\varphi)rdrd\varphi.$$

Example 3: spherical-Cartesian transformation [edit] The transformation from spherical coordinates (ρ,φ,θ)[6] to Cartesian coordinates (x,y,z), is given by the function $\mathbf{F}:\mathbf{R}^+ \times [0,\pi) \times [0,2\pi) \to \mathbf{R}^3$ with components:

$$\begin{aligned} x &= \rho\sin\varphi\cos\theta; \\ y &= \rho\sin\varphi\sin\theta; \\ z &= \rho\cos\varphi. \end{aligned}$$

The Jacobian matrix for this coordinate change is

$$\mathbf{J}_{\mathbf{F}}(\rho,\varphi,\theta) = \begin{bmatrix} \frac{\partial x}{\partial \rho} & \frac{\partial x}{\partial \varphi} & \frac{\partial x}{\partial \theta} \\ \frac{\partial y}{\partial \rho} & \frac{\partial y}{\partial \varphi} & \frac{\partial y}{\partial \theta} \\ \frac{\partial z}{\partial \rho} & \frac{\partial z}{\partial \varphi} & \frac{\partial z}{\partial \theta} \end{bmatrix} = \left[\begin{array}{ccc} \sin\varphi\cos\theta & \rho\cos\varphi\cos\theta & -\rho\sin\varphi\sin\theta \\ \sin\varphi\sin\theta & \rho\cos\varphi\sin\theta & \rho\sin\varphi\cos\theta \\ \cos\varphi & -\rho\sin\varphi & 0 \end{array}\right]$$

The determinant is $\rho^2\sin\varphi$. Since $dV = dxdydz$ is the volume for a rectangular differential volume element (because the volume of a rectangular prism is the product of its sides), we can interpret $dV = \rho^2\sin\varphi d\rho d\varphi d\theta$ as the volume of the spherical differential volume element. Unlike rectangular differential volume element's volume, this differential volume element's volume is not a constant, and varies with coordinates (ρ and φ). It can be used to transform integrals between the two coordinate systems:

$$\iiint_{\mathbf{F}(U)} f(x,y,z)dxdydz = \iiint_U f(\rho\sin\varphi\cos\theta, \rho\sin\varphi\sin\theta, \rho\cos\varphi)\rho^2\sin\varphi d\rho d\varphi d\theta$$

Example 4: The Jacobian matrix of the function $\mathbf{F}:\mathbf{R}^3 \to \mathbf{R}^4$ with components

$$\begin{aligned} y_1 &= x_1 \\ y_2 &= 5x_3 \\ y_3 &= 4x_2^2 - 2x_3 \\ y_4 &= x_3\sin x_1 \end{aligned}$$

is

$$\mathbf{J}_{\mathbf{F}}(x_1,x_2,x_3) = \begin{bmatrix} \frac{\partial y_1}{\partial x_1} & \frac{\partial y_1}{\partial x_2} & \frac{\partial y_1}{\partial x_3} \\ \frac{\partial y_2}{\partial x_1} & \frac{\partial y_2}{\partial x_2} & \frac{\partial y_2}{\partial x_3} \\ \frac{\partial y_3}{\partial x_1} & \frac{\partial y_3}{\partial x_2} & \frac{\partial y_3}{\partial x_3} \\ \frac{\partial y_4}{\partial x_1} & \frac{\partial y_4}{\partial x_2} & \frac{\partial y_4}{\partial x_3} \end{bmatrix} = \left[\begin{array}{ccc} 1 & 0 & 0 \\ 0 & 0 & 5 \\ 0 & 8x_2 & -2 \\ x_3\cos x_1 & 0 & \sin x_1 \end{array}\right].$$

This example shows that the Jacobian matrix need not be a square matrix.

Example 5: The Jacobian determinant of the function $\mathbf{F}:\mathbf{R}^3 \to \mathbf{R}^3$ with components

$$\begin{aligned} y_1 &= 5x_2 \\ y_2 &= 4x_1^2 - 2\sin(x_2x_3) \\ y_3 &= x_2x_3 \end{aligned}$$

is

$$\begin{vmatrix} 0 & 5 & 0 \\ 8x_1 & -2x_3\cos(x_2x_3) & -2x_2\cos(x_2x_3) \\ 0 & x_3 & x_2 \end{vmatrix} = -8x_1 \begin{vmatrix} 5 & 0 \\ x_3 & x_2 \end{vmatrix} = -40x_1x_2.$$

From this we see that $\mathbf{F}$ reverses orientation near those points where x_1 and x_2 have the same sign; the function is locally invertible everywhere except near points where $x_1 = 0$ or $x_2 = 0$. Intuitively, if one starts with a tiny object around the point $(1, 2, 3)$ and apply $\mathbf{F}$ to that object, one will get a resulting object with approximately $40 \times 1 \times 2 = 80$ times the volume of the original one, with orientation reversed.

1.4 Hessian Matrix

1.5 Taylor Expansion

2 Linear Algebra

3 Basics

Proposition 3.1. *1. $\alpha\vec{v}+\beta\vec{u}$ - linear combination.*

2. $\alpha\vec{a}$ - line; $\alpha\vec{a}+\beta b-$ plane; $\alpha\vec{a}+\beta\vec{b}+8\vec{c}-$ space.

Proposition 3.2. *$\vec{a}=(a_1,a_2,a_3)$, $\vec{b}=(b_1,b_2,b_3)$.*

1. $\vec{a}\cdot\vec{b}=a_1b_1+a_2b_2+a_3b_3=\vec{b}\cdot\vec{a}=\vec{a}^\top b=\vec{b}^\top\vec{a}$
2. $\|\vec{a}\|=\sqrt{a_1^2+a_2^2+a_3^2}$
3. $\frac{\vec{a}\cdot\vec{b}}{\|a\|\|b\|}=\cos\theta$
4. $|\vec{a}\cdot\vec{b}|\le\|\vec{a}\|\|\vec{b}\|$ *(Cauchy-Schwartz)*
5. *if* $\vec{a}\cdot\vec{b}=0\Rightarrow\vec{a},\vec{b}$ *perpendicular* $\Rightarrow\|\vec{a}\|^2+\|\vec{b}\|^2=\|\vec{a}-\vec{b}\|^2$.
6. *unit vector:* $\|\vec{a}\|=1=\frac{\vec{b}}{\|\vec{b}\|}$
7. $\vec{a}^\top\vec{b}$ *- inner product;* $\vec{a}\vec{b}^\top$ *- outer product*
8. $e_i^\top A=Row_i(A)$.
9. *lower triangular matrix $\cdot$ lower triangular matrix = lower triangular matrix.*

Proposition 3.3.

1. *Linearly independence:* $\alpha\vec{a}+\beta\vec{b}+\gamma\vec{c}=\vec{0}$ *only if* $\alpha=\beta=\gamma=0$
2. *linearly dependence:* $\exists(\alpha,\beta,\gamma)\neq(0,0,0)$ *s.t.* $\alpha\vec{a}+\beta\vec{b}+\gamma\vec{c}=\vec{0}$.
3. $\begin{bmatrix} | & | & | \\ \vec{a} & \vec{b} & \vec{c} \\ | & | & | \end{bmatrix}\begin{bmatrix}\alpha\\ \beta\\ \gamma\end{bmatrix}=\vec{0}\Longrightarrow\begin{cases}\textit{linearly independence}\Longrightarrow A-invertible.\\ \textit{linearly dependence } A \textit{ - singular (not invertible)}\end{cases}$

Matix Multiplication

- $AB=A\begin{bmatrix}\vec{b}_1 & \vec{b}_2 & \vec{b}_3\end{bmatrix}=\begin{bmatrix}\vec{Ab_1} & \vec{Ab_2} & \vec{Ab_3}\end{bmatrix}$.
- $Row_i(AB)=A\cdot Row_i(B)$.
- $Row_i(AB)=Row_i(A)\cdot B$.

4 Vector norms

A norm $\|\cdot\|:\mathbb{R}^n\to\mathbb{R}$ is a function satisfying the properties:

- $\|x\|=0$ if and only if $x=0$ (definiteness)
- $\|cx\|=|c|\|x\|$ for all $c\in\mathbb{R}$ (homogeneity)
- $\|x+y\|\le\|x\|+\|y\|$ (triangle inequality)

Common examples of norms:

- $\|x\|_1=|x_1|+\cdots+|x_n|$ (the 1-norm)
- $\|x\|_2=\sqrt{x_1^2+\cdots+x_n^2}$ (the 2-norm / Euclidean norm) -> default norm
- $\|x\|_\infty=\max_{1\le i\le n}|x_i|$ (max-norm)

5 Linear Equations, Elimination, Permutation

Linear Equations Given $A\in\mathbb{R}^{m\times n}$ and $b\in\mathbb{R}^m$, linear equations take the form

$$Ax=b$$

where we must solve for $x\in\mathbb{R}^n$.

Understandings of $Ax=b$

- $A\vec{x}$: matrix A acts on $\vec{x}$.
- General Thinking: The column picture of $A\vec{x}=\vec{b}$.
  A combination of n columns of A produces the vector $\vec{b}$.
- Geometric Thinking: The row picture of $A\vec{x}=\vec{b}$ coefficient matrix
  Matrix A can be view as a coefficient matrix, then m equations from m rows give m planes ($P_i:\text{row}_i\cdot\vec{x}-b_i=0$) meeting at $\vec{x}$.

Four possibilities for solutions

- $r=m=n\Longrightarrow R=\begin{bmatrix}I\end{bmatrix}$, $Ax=b$ has exactly one solution.
- $r=m, r<n\Longrightarrow R=\begin{bmatrix}I & F\end{bmatrix}$, $Ax=b$ has ∞ solution.
- $r<m, r=n\Longrightarrow R=\begin{bmatrix}I\\ \mathbf{0}\end{bmatrix}$, $Ax=b$ has 0 or 1 solution.
- $r<m, r<n\Longrightarrow R=\begin{bmatrix}I & F\\ \mathbf{0} & \mathbf{0}\end{bmatrix}$, $Ax=b$ has 0 or ∞ solution.

Idea of Elimination

The core idea is to convert A to an upper Triangular matrix A' (Elimination), then solve for $\vec{x}$ from x_n to x_1 (Back substitution). E.g.

$$\underbrace{\begin{bmatrix}* & * & * & *\\ & * & * & *\\ & & * & *\\ & & & *\end{bmatrix}}_{A}\underbrace{\begin{bmatrix}x_1\\x_2\\x_3\\x_4\end{bmatrix}}_{x}=\underbrace{\begin{bmatrix}b_1\\b_2\\b_3\\b_4\end{bmatrix}}_{b}$$

Elimination matrix $E_{ij}=\begin{bmatrix}1 & & & \\ & 1 & & \\ -l & & \ddots & \\ & & & 1\end{bmatrix}$ where $e_{ij}=-l$ is use to reduce the (i,j) entry of A, a_{ij}, to zero.

$$E_{ij}A=\begin{bmatrix}\vdots\\ Row_i-l\cdot Row_1\\ \vdots\end{bmatrix},\quad E_{ij}^{-1}=\begin{bmatrix}1 & & & \\ & 1 & & \\ l & & \ddots & \\ & & & 1\end{bmatrix}$$

Permutation Matrix

$$P_{23}=\begin{bmatrix}1&0&0\\0&0&1\\0&1&0\end{bmatrix}=\begin{bmatrix}-\vec{e_1}^\top-\\-\vec{e_3}^\top-\\-\vec{e_2}^\top-\end{bmatrix}$$

$P_{23}A$ exchanges Row 2 & Row 3 of matrix A.

- Permutation matrix is orthogonal matrix, i.e., $P^\top=P^{-1}, PP^\top=I$.
- Sometimes we need to exchange some rows of A so it can be reduced to a valid rref R. In this case, we need permutation matrix P.
  E.g. $\begin{bmatrix}0 & 2\\ 3 & -2\end{bmatrix}$ can be fixed though has 0 as the first pivot $\Rightarrow\begin{bmatrix}3 & -2\\ 0 & 2\end{bmatrix}\to$ a row exchange produces an upper triangular matrix.
- For the ease of Elimination & Permutation for both sides of $A\vec{x}=\vec{b}$ we create an augmented matrix $L=\begin{bmatrix}A & \vec{b}\end{bmatrix}$ and let elimination and permutation matrices act on L.
  $$(E_{ij}P_{ij}\cdots)\cdot\begin{bmatrix}A & \vec{b}\end{bmatrix}$$

Pivots

- Pivots are on the diagonal of the triangle after elimination. We need n pivots to solve for n unknowns.

6 CR Decomposition

7 LU Decomposition

8 Inverse & Transpose

Proposition 8.1. ***(Basic properties of the matrix inverse and transpose):***

A^{-1} *is unique if it exists.*	$(A^{-1})^{-1}=A$	$(A^{-1})^\top=(A^\top)^{-1}$
$(AB)^{-1}=B^{-1}A^{-1}$	$(A^\top)^\top=A$	$(AB)^\top=B^\top A^\top$

left-inverse = right inverse = two-sided inverse

Suppose $BA=I$ & $AC=I\Rightarrow B=B(AC)=(BA)C=C$.

Gauss - Jordan Elimination for computing A^{-1} *By using* $A^{-1}[A\mid I]=\begin{bmatrix}I\mid A^{-1}\end{bmatrix}$ *where* $[A\mid I]$ *is the augmented matrix.* $\Rightarrow$ *convert* $[A\mid I]\to[I\mid A]$ *using elimination matrix.*

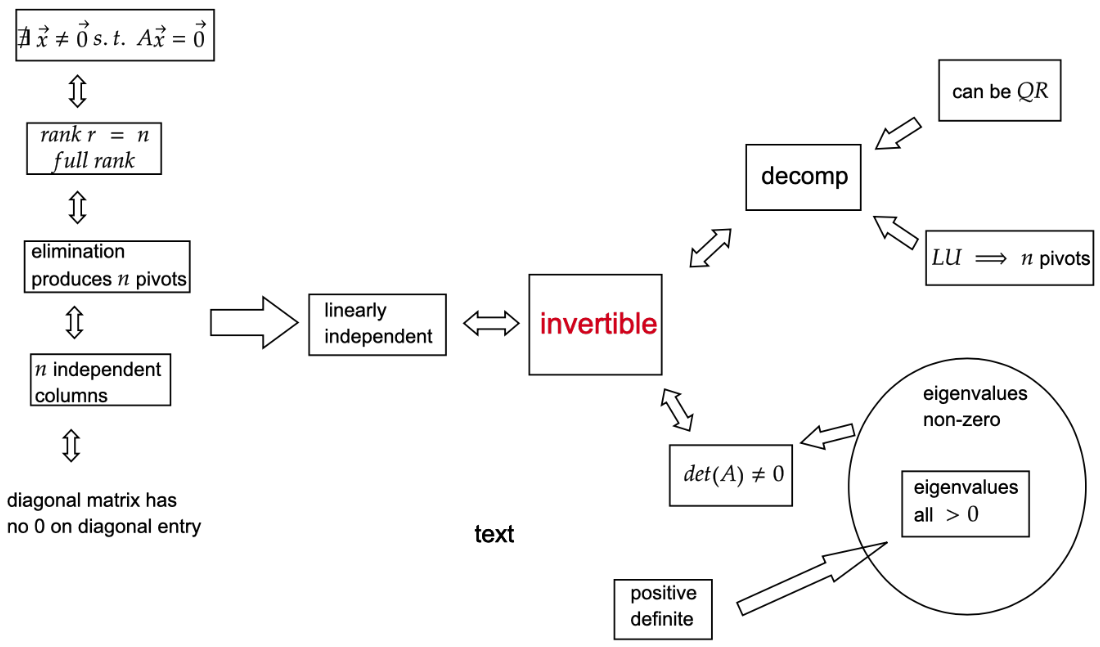

Figure 1: inverse all in one

9 The rank of a matrix

Note: When considering rank, think about the rref (the row reduced echelon form) of a matrix.

$\text{rank}(A) =$ maximum number of linearly independent columns $=$ maximum number of linearly independent rows $=$ number of pivots

If $A \in \mathbb{R}^{m\times n}$ and $B \in \mathbb{R}^{n\times p}$ then

- $\text{rank}(A) \le \min(m, n)$
- $\text{rank}(AB) \le \min(\text{rank}(A), \text{rank}(B)) \le \min(m, n, p)$
- if $\text{rank}(A) = n$ then $\text{rank}(AB) = \text{rank}(B)$
- if $\text{rank}(B) = n$ then $\text{rank}(AB) = \text{rank}(A)$

So multiplying by an invertible matrix does not alter the rank.

General properties of the matrix rank:

- $\text{rank}(A + B) \le \text{rank}(A) + \text{rank}(B)$
- $\text{rank}(A) = \text{rank}\left(A^\top\right) = \text{rank}\left(A^\top A\right) = \text{rank}\left(AA^\top\right)$
- $A \in \mathbb{R}^{n\times n}$ is invertible if and only if $\text{rank}(A) = n$.
- rank-1 matrix $A = cuv^\top$ where $u \in \mathbb{R}^m$, $v \in \mathbb{R}^n$ and $A \in \mathbb{R}^{m\times n}$.
- rank-2 matrix $A = au_1v_1^\top + bu_2v_2^\top$ where $u_i \in \mathbb{R}^m$, $v_i \in \mathbb{R}^n$ and $A \in \mathbb{R}^{m\times n}$.
- rank-k matrix $A = \sum_{i=1}^k a_iu_iv_i^\top$ where $u_i \in \mathbb{R}^m$, $v_i \in \mathbb{R}^n$ and $A \in \mathbb{R}^{m\times n}$.

10 Four Spaces

Vector Space:

Subspace: A is a subspace, $\subseteq$, of S if $\forall u, v \in S, a, b$-constant, we have $au + bv \in S$.

Basis: Vector spaces are linearly independent & span the space. (e.g. The columns of every invertible matrix give a basis for $\mathbb{R}^n$.) The dimension of the space is the number of basis in the set of basis.

Four Space: Given $A \in \mathbb{R}^{m\times n}$, we have the definitions:

- Range/Column/Image space: $R(A) = C(A) = Im(A) = \{Ax \mid x \in \mathbb{R}^n\} \subseteq \mathbb{R}^m$.
- Row space: $C(A^\top) \subseteq \mathbb{R}^n$.
- Null/Kernel space: $N(A) = Ker(A) = \{x \in \mathbb{R}^n \mid Ax = 0\} \subseteq \mathbb{R}^n$.
- Left-Null space: $N(A^\top) = Ker(A^\top) = \left\{x \in \mathbb{R}^m \mid A^\top x = 0\right\} \subseteq \mathbb{R}^m$.

Properties:

- The column space of $A \iff$ the row space of $A^\top$.
- $0 \in N(A) = Ker(A)$.
- Rank-Nullity Theorem: $\text{rank}(A) + \dim(N(A)) = n$
- $\dim(Im(A)) = \dim(Im(A^\top)) = rank(A) = r$
- $\dim(N(A)) = n - r, \dim(N(A^\top)) = m - r$.

Space Orthogonality: The orthogonal complement of a subspace V, $V^\perp$, contains every vector that is perpendicular to V.

- $C(A^\top) = N(A)^\perp$, i.e. The row space is perpendicular to the null space. (Think $Ax = 0$.)
- $C(A) = N(A^\top)^\perp$, i.e. The column space is perpendicular to the null space of $A^\top$ (left-null space).(Think $A^\top x = 0$.)
- Suppose $A \in \mathbb{R}^{m\times n}$, $\forall x \in \mathbb{R}^n$, it can be represented as $x = x_r + x_n$ where $x_r \in C(A^\top)$ and $x_n \in N(A)$.

rref of A: Suppose $R = rref(A)$, then

- $C(A^\top) = C(R^\top)$, i.e. same row space.
- $C(A) \neq C(R)$, the lase few entries of $C(R)$ could only be zero.
- $\dim(C(A)) = \dim(C(R))$, $(Ax = 0 \implies Rx = 0)$.
- $N(A) = N(R)$.

Link to equation $Ax = b$

The following statements are equivalent:

- There exists a solution to the equation $Ax = b$.
- $b \in R(A)$.
- $\text{rank}(A) = \text{rank}\left(\begin{bmatrix} A & b \end{bmatrix}\right)$

The following statements are equivalent:

- Solutions to the equation $Ax = b$ are unique.
- $N(A) = \{0\}$.
- $\text{rank}(A) = n$.

11 Determinant

Proposition 11.1. ***(Basic 3)***

1. *swapping two columns:* $\left|\begin{bmatrix}\cdots & \boldsymbol{a}_i & \cdots & \boldsymbol{a}_j & \cdots\end{bmatrix}\right| = -\left|\begin{bmatrix}\cdots & \boldsymbol{a}_j & \cdots & \boldsymbol{a}_i & \cdots\end{bmatrix}\right|$
2. $\left|\begin{bmatrix}\cdots & \alpha\boldsymbol{u} + \beta\boldsymbol{v} & \cdots\end{bmatrix}\right| = \alpha\left|\begin{bmatrix}\cdots & \boldsymbol{u} & \cdots\end{bmatrix}\right| + \beta\left|\begin{bmatrix}\cdots & \boldsymbol{v} & \cdots\end{bmatrix}\right|$
3. *duplicates:* $\left|\begin{bmatrix}\cdots & \boldsymbol{a}_i & \cdots & \boldsymbol{a}_i & \cdots\end{bmatrix}\right| = 0$

Proposition 11.2. *If A is singular $\iff \{\boldsymbol{a}_1 \cdots \boldsymbol{a}_n\}$ linearly dependent $\iff |A| = 0$.*

Hint: singular -> one of the columns / rows linearly depends on the rest -> use Basic 2 and 3.

Proposition 11.3.

1. $|I| = 1$, $|P^{permu}| = 1/-1$ *(use Basic 1)*, $|P^{ortho}| = 1/-1$.
2. $|A| = |A^\top|$
3. $|AB| = |A| \cdot |B|$
4. $|A^{-1}| = \frac{1}{|A|}$
5. *Orthogonal matrix* $|Q| = \pm|1|$ *because* $Q^\top Q = I$ *gives* $|Q|^2 = 1$.

6. *Triangular matrix* $|U| = u_{11}u_{22}\cdots u_{nn}$
7. $|A| = |LU| = |L|\cdot|U| =$ *product of the pivots* u_{ii}
8. $\left|\begin{bmatrix} A & 0 \\ 0 & B \end{bmatrix}\right| = |A|\cdot|B|$, $\left|\begin{bmatrix} A & C \\ 0 & B \end{bmatrix}\right| = |A|\cdot|B|$.

Proposition 11.4. ***(Cramer's Rule)*** *Cramer's Rule to Solve* $Ax = b$ *Start from*

$$\begin{bmatrix} \boldsymbol{A} \end{bmatrix} \begin{bmatrix} \boldsymbol{x_1} & 0 & 0 \\ \boldsymbol{x_2} & 1 & 0 \\ \boldsymbol{x_3} & 0 & 1 \end{bmatrix} = \begin{bmatrix} \boldsymbol{b_1} & a_{12} & a_{13} \\ \boldsymbol{b_2} & a_{22} & a_{23} \\ \boldsymbol{b_3} & a_{32} & a_{33} \end{bmatrix} = \boldsymbol{B_1}$$

Use $(det\boldsymbol{A})(\boldsymbol{x}_1) = (det\boldsymbol{B}_1)$ *to find* $\boldsymbol{x}_1$ *Same idea* $[A]\begin{bmatrix} 1 & x_1 & 0 \\ 0 & x_2 & 0 \\ 0 & x_3 & 1 \end{bmatrix} = \begin{bmatrix} a_1 & b & a_3 \end{bmatrix} = B_2$ $\quad x_1 = \dfrac{detB_1}{detA}$, $x_2 = \dfrac{detB_2}{detA}$ *Cramer's Rule is usually not efficient! Too many determinants*

$$\begin{bmatrix} 3 & 2 \\ 5 & 4 \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} 12 \\ 22 \end{bmatrix} \quad \boldsymbol{B}_1 = \begin{bmatrix} 12 & 2 \\ 22 & 4 \end{bmatrix} \quad \boldsymbol{B}_2 = \begin{bmatrix} 3 & 12 \\ 5 & 22 \end{bmatrix} \quad x_1 = \frac{detB_1}{detA} = \frac{4}{2} \quad x_2 = \frac{2}{2}$$

12 Least squares

Suppose $A \in \mathbb{R}^{n\times p}$. When the linear equations $Ax = b$ are overdetermined ($n > p$) and there is no solution, we minimize the 2-norm of the residual:

$$\underset{x}{\text{minimize}}\|Ax - b\|_2 \Longrightarrow A^\top A\hat{x} = A^\top b \quad \to \text{Normal Equation}$$

The normal equations have a unique solution iff $rank(A) = p$ (full column rank / the columns of A are linearly independent). Why? Because $A^\top A \in \mathbb{R}^{p\times p}$ and $Im(A^\top A) = Im(A) \Longrightarrow rank(A^\top A) = rank(A) = p \Longrightarrow A^\top A$ is full rank.

Then,

$$\hat{x} = \left(A^\top A\right)^{-1} A^\top b = A^\dagger b$$

where $A^\dagger = (A^\top A)^{-1}A^\top$ is the Moore-Penrose inverse (or pseudo-inverse).

13 Orthogonal matrices

A square matrix U is orthogonal if $U^\top U = I$.

Some properties of orthogonal U and V :

- **Orthogonal Columns and Rows**: $u_i \cdot u_j = 0$, $\|u_i\| = \|u_j\| = 1$.
- **Orthogonal Basis**: The columns (or rows) of an orthogonal matrix form an orthogonal basis for the vector space.
- **Orthogonal transformations preserve angles & length**: $(Ux)^\top(Uz) = x^\top z$ and $\|Ux\|_2 = \|x\|_2$.
- Certain matrix norms are also invariant: $\left\|UAV^\top\right\|_2 = \|A\|_2$ and $\left\|UAV^\top\right\|_F = \|A\|_F$
- If U is square, $U^\top U = UU^\top = I$ and $U^{-1} = U^\top$.
- UV is orthogonal.

Every subspace has an orthonormal basis: For any $A \in \mathbb{R}^{m\times n}$, there exists an orthogonal $U \in \mathbb{R}^{m\times r}$ such that $R(A) = R(U)$ and $r = \text{rank}(A)$. One way to find U is using Gram-Schmidt.

14 Projections

If $P \in \mathbb{R}^{n\times n}$ satisfies $P^2 = P$, $P^\top = P$ it's called a projection matrix.

In general, $P : \mathbb{R}^n \to S$, where $S \subseteq \mathbb{R}^n$ is a subspace.

If P is a projection matrix, so is $(I - P)$. We can uniquely decompose:

$$x = u + v = Px + (I - P)x \quad \text{where } u \in S, v \in S^\perp$$

Pythagorean theorem: $\|x\|_2^2 = \|u\|_2^2 + \|v\|_2^2$

If $A \in \mathbb{R}^{m\times n}$ has linearly independent columns, then the projection onto $R(A)$ is given by $P = A\left(A^\top A\right)^{-1} A^\top$.

$$e \perp R(A) \Longrightarrow (b - Ax)^\top A = 0 \Longrightarrow x = \left(A^\top A\right)^{-1} A^\top b \Longrightarrow p = Ax = A\left(A^\top A\right)^{-1} A^\top b$$

Least-squares: decompose b using the projection above:

$$\begin{aligned} b &= A\left(A^\top A\right)^{-1} A^\top b + \left(I - A\left(A^\top A\right)^{-1} A^\top\right) b \\ &= A\hat{x} + (b - A\hat{x}) \end{aligned}$$

where $\hat{x} = \left(A^\top A\right)^{-1} A^\top b$ is the LS estimate. Therefore the optimal residual is orthogonal to $A\hat{x}$.

15 QR Decomposition

16 Eigenvalues and Eigenvectors

Intuition: The whole idea is to avoid the complexity presented by matrix A. It's generally more convenient to deal with λx instead of Ax.

Basics: Suppose $A \in \mathbb{R}^{n\times n}$ is a square matrix.

- $A^k x = \lambda^k x$.
- $A^{-1}x = \lambda^{-1}x$.
- $(A + cI)x = (\lambda + c)x$.
- If α is an eigenvalue of A and β is an eigenvalue of B, then $\alpha\beta$ is NOT an eigenvalue of AB; and $\alpha + \beta$ is NOT an eigenvalue of $A + B$.
- $Ax = \lambda x \Longrightarrow (A - \lambda I)x$ to have non-zero solutions for $x \Longrightarrow (A - \lambda I)$ is singular $\Longrightarrow det(A - \lambda I) = 0$.
- The mapping between eigenvalue and eigenvector is 1-to-1.

  But why are there cases where one eigenvalue maps to two eigenvector?

  This is because there could be two eigenvalues having the same value.
- If $A \in \mathbb{R}^{n\times n}$, then A has at most n different eigenvalues.
- If $A \in \mathbb{R}^{n\times n}$ has $d \le n$ distinct eigenvalues $\lambda_1, \ldots, \lambda_d$, then we have at least d independent eigenvectors. (E.g. Identity matrix I has only 1 distinct eigenvalue, but it has $e_1, e_2, \ldots, e_n$, in total, n independent eigenvectors.)
- Eigenvectors $x_1, \ldots, x_j$ correspond to distinct eigenvalues are linearly independent.
- One eigenvector (unit) of A cannot correspond to two or more different eigenvalues.

  Otherwise, $A\vec{x} = \lambda_1\vec{x}$, $A\vec{x} = \lambda_2\vec{x}$, $\lambda_1 \neq \lambda_2 \Rightarrow 0 = (\lambda_1 - \lambda_2)\vec{x} \Rightarrow \vec{x} = 0$; and that's a contradiction!
- Elementary matrices E, P, row-exchange/permutation matrices DOES NOT preserve eigenvalues.

Characteristic Polynomial:

$A - \lambda I$: characteristic polunomial of A; $|A - \lambda I|$ is the characteristic equation of A.

- Vieta's Formula: $\sum_{i=1}^n \lambda_i = trace(A) = \sum_{i=1}^n a_{ii}$ and $\prod_{i=1}^n \lambda_i = |A|$.
- Eigenvalues of a triangular matrix lie along its diagonal. (Because $det(A) = \prod_{i=1}^n a_{ii}$ if $A \in \mathbb{R}^{n\times n}$ is triangular. $\Longrightarrow det(A - \lambda I) = \prod_{i=1}^n (a_{ii} - \lambda)$.)

17 Diagonalizing a Matrix

Suppose $A \in \mathbb{R}^{n\times n}$ has n linearly independent eigenvectors $x_1, x_2, \ldots, x_n$. Set $X = \begin{bmatrix} | & & | \\ x_1 & \cdots & x_n \\ | & & | \end{bmatrix}$ and $\Lambda = \begin{bmatrix} \lambda_1 & & \\ & \ddots & \\ & & \lambda_n \end{bmatrix}$, then we have $AX = X\Lambda$. Since X is formed by n linearly independent vectors, X is invertible. Hence

$$A = X\Lambda X^{-1}$$

Properties:

- Any matrix with no repeated eigenvalues, i.e. n eigenvalues, can be diagonalized.

  If $\lambda_1, \ldots, \lambda_n$ are all different $\Longrightarrow$ we have $\geq n$ independent eigenvectors. Since $dim(A) = n$, we have exactly n eigenvectors. Hence, X is invertible.
- $A^k = (X\Lambda X^{-1})^k = X\Lambda^k X^{-1}$.
- If all eigenvalues of A has $|\lambda| < 1$, then $\lim_{k\to\infty} \Lambda^k = 0$. Since matrix $A^k = XA^kX^{-1}$, $\lim_{k\to\infty} A^k = 0$ matrix.
- If $A = S\Lambda S^{-1}$, then $A^{-1} = S\Lambda^{-1}S^{-1}$ (same eigenvectors, inverse eigenvalues).
- If A has 0 as its eigenvalue, then $Ax = 0x \Longrightarrow Ax = 0$ has non-zero eigenvectors, $\Longrightarrow A$ is singular.

GM, AM

- Geometric Multiplicity = GM = dim of Null space of $(A - \lambda I)$: counts the independent eigenvectors for λ.
- Algebraic Mutciplicity =AM $\to$ look at roots of $\det(A - \lambda I)$: counts the repetition of λ among the eigenvalues.

E.g. If A has $\lambda = 4, 4, 4 \Rightarrow AM = 3, GM = 1, 2,$ or 3.

If for A, $GM \leq AM$. That means we have an eigenvalue repeated AM times but have only GM lines of eigenvectors correspond to it $\Rightarrow$ lack of independent eigenvectors for $\mathbb{R}^{n\times n}$ eigenvector matrix X. $\Rightarrow A$ is not diagonalizable.

Similar Matrices:

If $B \in \mathbb{R}^{n\times n}$ - invertible, $C \in \mathbb{R}^{n\times n}$ - constant matrix, then $A = BCB^{-1}$ are similar matrices (one for each choice of invertible matrix B).

- All matrices $A = BCB^{-1}$ are "similar". They all share the eigenvalues of C.

  Proof:

  $$(A - \lambda I) = BCB^{-1} - \lambda I = BCB^{-1} - B\lambda IB^{-1} = B(C - \lambda I)B^{-1}$$

  Then, we have

  $$\det(C - \lambda I) = \det(A - \lambda I)$$

  Hence, they share the same set of eigenvalues as C's.

18 Symmetric Matrix

$S = S^\top \in \mathbb{R}^{n\times n}$.

Properties:

- S has only real eigenvalues.
- **(Important!)** S always has n independent, mutually orthogonal eigenvectors (a set of orthonormal basis).

Spectral Theorem Every real symmetric matrix has factorization $S = Q\Lambda Q^\top$, with n (countingmultiplicities) real eigenvalues in Λ and orthonormal eigenvectors as columns of Q:

$$S = Q\Lambda Q^{-1} = Q\Lambda Q^\top = \lambda_1 q_1 q_1^\top + \cdots + \lambda_n q_n q_n^\top$$

where q_i's are orthonormal eigenvectors of S.

Symmetric Matrix Decompositions

- **LU:**

  $$A = LDU = LDL^\top = LD^{1/2}(LD^{1/2})^\top$$

  where the 4th term is the *square-root-free* Cholesky Decomposition of A which is only valid if A is positive definite, since you want eigenvalues to be all positive so that you could take the square root.

  Note: It is reminiscent of the eigen-decomposition of real symmetric matrices, $A = Q\Lambda Q^\top$, but is quite different in practice because Λ and D are not similar matrices.
- **SVD:**

  $$S = Q\Lambda Q^{-1} = Q\Lambda Q^\top = U\Sigma V^\top$$

Proposition 18.1. *For any matrix $A \in \mathbb{R}^{m\times n}$, the matrix $A^\top A \in \mathbb{R}^{n\times n}$ is always square, symmetric, and positive semi-definite($\forall x \neq 0, x^\top A^\top Ax = \|Ax\|^2 \geq 0$). If in addition A has linearly independent columns, then A^TA is positive definite.*

Skew-symmetric Matrix $A^\top = -A$.

- Eigenvalues are purely imaginary.
- A always has n independent, mutually orthogonal eigenvectors (a set of orthonormal basis).

Quadratic Form $q = x^\top Qx$, where Q is a symmetic matrix.

E.g. Consider the case of quadratic forms in three variables x, y, z. The matrix Q has the form

$$Q = \begin{bmatrix} a & b & c \\ d & e & f \\ g & h & k \end{bmatrix}$$

The above formula gives

$$q = ax^2 + ey^2 + kz^2 + (b + d)xy + (c + g)xz + (f + h)yz.$$

So, two different matrices define the same quadratic form if and only if they have the same elements on the diagonal and the same values for the sums $b+d, c+g$ and $f + h$. In particular, the quadratic form q is defined by a unique symmetric matrix

$$Q = \begin{bmatrix} a & \frac{b+d}{2} & \frac{c+g}{2} \\ \frac{b+d}{2} & e & \frac{f+h}{2} \\ \frac{c+g}{2} & \frac{f+h}{2} & k \end{bmatrix}$$

19 Positive-Definite Matrix

A positive definite if

1. A is symmetric.
2. Eigenvalues of A are all positive.
3. All the upper-left determinants are positive
4. $x^TAx > 0$ unless $x = 0$.

- If A and B are positive definite then so is $A + B$.

Example:

$$A = \begin{bmatrix} 4 & 12 & -16 \\ 12 & 37 & -43 \\ -16 & -43 & 98 \end{bmatrix} = Q\Lambda Q^\top = \begin{bmatrix} -0.16 & 0.21 & 0.96 \\ -0.45 & 0.84 & -0.26 \\ 0.87 & 0.48 & 0.04 \end{bmatrix} \begin{bmatrix} 123.47 & 0 & 0 \\ 0 & 15.50 & 0 \\ 0 & 0 & 0.018 \end{bmatrix} \begin{bmatrix} -0.16 & 0.21 & 0.96 \\ -0.45 & 0.84 & -0.26 \\ 0.87 & 0.48 & 0.04 \end{bmatrix} = U\Sigma V^\top$$

$$= LL^\top = \begin{bmatrix} 2 & 0 & 0 \\ 6 & 1 & 0 \\ -8 & 5 & 3 \end{bmatrix} \begin{bmatrix} 2 & 6 & -8 \\ 0 & 1 & 5 \\ 0 & 0 & 3 \end{bmatrix} = LDL^\top \begin{bmatrix} 1 & 0 & 0 \\ 3 & 1 & 0 \\ -4 & 5 & 1 \end{bmatrix} \begin{bmatrix} 4 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 9 \end{bmatrix} \begin{bmatrix} 1 & 3 & -4 \\ 0 & 1 & 5 \\ 0 & 0 & 1 \end{bmatrix}$$

20 Cholesky Decomposition

21 The Singular Value Decomposition

Every $A \in \mathbb{R}^{m\times n}$ can be factored as

$$\underset{(m\times n)}{A} = \underset{(m\times r)}{U_1}\,\underset{(r\times r)}{\Sigma_1}\,\underset{(n\times r)^\top}{V_1}{}^\top \quad \text{(economy SVD)}$$

U_1 is orthogonal, its columns are the left singular vectors V_1 is orthogonal, its columns are the right singular vectors Σ_1 is diagonal. $\sigma_1 \geq \cdots \geq \sigma_r > 0$ are the singular values

Complete the orthogonal matrices so they become square:

$$\underset{(m\times n)}{A} = \underset{(m\times m)}{\begin{bmatrix} U_1 & U_1 \end{bmatrix}} \underset{(m\times n)}{\begin{bmatrix} \Sigma_1 & 0 \\ 0 & 0 \end{bmatrix}} \underset{(n\times n)}{\begin{bmatrix} V_1^\top \\ V_2^\top \end{bmatrix}} = U\Sigma V^\top \quad \text{(full SVD)}$$

The SVD is not unique, but every SVD of A has the same Σ_1.

22 Properties of the SVD

Singular vectors u_i, v_i and singular values σ_i satisfy

$$Av_i = \sigma_i u_i \quad \text{and} \quad A^\top u_i = \sigma_i v_i$$

Suppose $A = U\Sigma V^\top$ (full SVD) as in previous slide.

- rank: $\operatorname{rank}(A) = r$
- transpose: $A^\top = V\Sigma U^\top$
- pseudoinverse: $A^\dagger = V_1\Sigma_1^{-1}U_1^\top$

Fundamental subspaces:

- $R(U_1) = R(A)$ and $R(U_2) = R(A)^\perp$ (range of A)
- $R(V_1) = N(A)^\perp$ and $R(V_2) = N(A)$ (nullspace of A)

Matrix norms:

- $\|A\|_2 = \sigma_1$ and $\|A\|_F = \sqrt{\sigma_1^2 + \cdots + \sigma_r^2}$

23 Triangular Matrix

- The eigenvalues of a triangular matrix are the entries on its main diagonal.

24 Some nice problems

Proposition 24.1. *Diagonally dominant matrices are invertible. Diagonally dominant:* $|a_{ii}| > \sum_{j\neq i} |a_{ij}|$

Solution: If $\exists \vec{x} \neq \overrightarrow{0}$ s.t. $A\vec{x} = \overrightarrow{0}, A \in \mathbb{R}^{n\times n}$. then $\sum_{j=1}^n a_{ij}x_j = 0 \quad \forall i \in [1,n], i \in Z^+$ W LOG suppose $|\vec{x}_i| \geq |\vec{x}_k| \quad \forall k \neq i \quad k \in [1,n], k \in Z^+$.

$\Rightarrow |a_{ii}|x_i| = |\sum_{j\neq i} a_{ij}x_j \Big| \leqslant \sum_{j\neq i} \Big| a_{ij}||x_j|$ That's a contradiction since we have.

$$|a_{ii}|\,|x_i| > \left(\sum_{j\neq i} |a_{ij}|\right)|x_i| > \sum_{j\neq i} |a_{ij}|\,|x_j|$$

Proposition 24.2. *Prove that matrix* $A = au_1v_1^\top + bu_2v_2^\top$ *where* $u_i \in \mathbb{R}^m$, $v_i \in \mathbb{R}^n$ *and* $A \in \mathbb{R}^{m\times n}$ *is a rank-2 matrix.*

Solution: We have

$$A = u_1v_1^\top + u_2v_2^\top = \begin{bmatrix} | & | \\ u_1 & u_2 \\ | & | \end{bmatrix} \begin{bmatrix} a & 0 \\ 0 & b \end{bmatrix} \begin{bmatrix} - & v_1^\top & - \\ - & v_2^\top & - \end{bmatrix} = UV \Longrightarrow rankA =$$

Proposition 24.3. *Suppose* $A \in \mathbb{R}^{m\times n}$, $\forall x \in \mathbb{R}^n$, *it can be represented as* $x = x_r + x_n$ *where* $x_r \in C(A^\top)$ *and* $x_n \in N(A)$.

Solution:

Proposition 24.4. *Eigenvectors* $x_1, \ldots, x_j$ *that correspond to distinct eigenvalues are linearly independent.*

Solution: Assume dependent $c_i\vec{x}_i + c_j\vec{x}_j = 0 \Longrightarrow \lambda_i c_i\vec{x}_i + \lambda_i c_j\vec{x}_j = 0$. We have

$$\Rightarrow A(c_i\vec{x}_i + c_j\vec{x}_j) = \lambda_i c_i\vec{x}_i + \lambda_j c_j\overrightarrow{x_j} = \lambda_i c_i\vec{x}_i + \lambda_i c_j\vec{x}_j + (\lambda_j - \lambda_i)c_j\vec{x}_j = 0 \Longrightarrow (\lambda_j - \lambda_i)c_j\vec{x}_j = 0 \Longrightarrow c_j = 0 \Longrightarrow c_i = 0.$$

This proof can be extended to $c_1\vec{x}_i + c_2\vec{x}_i + \cdots + c_j\vec{x}_j = 0$

Proposition 24.5. A, B *share the same* n *independent eigenvectors if and only if* $AB = BA$.

Solution:

"$\Longrightarrow$"

Suppose A, B share same n independent eigenvectors. $\vec{v}_1, \cdots, \vec{V}_n$, then A, B have eigen-decompositions $A = S\Lambda_a S^{-1}, B = S\Lambda_b S^{-1}$.

$$\Rightarrow AB = S\Lambda_a S^{-1}S\Lambda_b S^{-1} = S\Lambda_a\Lambda_b S^{-1} = S\Lambda_b\Lambda_a S^{-1} = BA$$

"$\Longleftarrow$"

Suppose $AB = BA$, and $\vec{v}_1, \ldots, \vec{v}_n$ are n unit-length, independent eigenvectors of A, then

$$AB\overrightarrow{v_i} = BA\overrightarrow{v_i} = B\alpha_i\overrightarrow{v_i} = \alpha_i B\overrightarrow{v_i} \Rightarrow B\vec{v}_i \text{ is eigenvector of } A$$

Since the eigenvectors of A are independent, we have $B\overrightarrow{v_i} = \beta\overrightarrow{v_i} \Rightarrow \vec{v}_i$ is an eigenvector of B.

Proposition 24.6. *How can you estimate the eigenvalues of any* A *? (Gershgorin)*

Solution: **Intuition:** Every eigenvalue of A must be "near" at least one of the entries a_{ii} on the main diagonal; i.e. every λ is in the circle around one or more diagonal entries a_{ii}:

$$|a_{ii} - \lambda| \leq R_i = \sum_{j \neq i} |a_{ij}|$$

If λ is eigenvalue $\Rightarrow (A - \lambda I)$ is singular $\Rightarrow \det(A - \lambda I) = 0 \Rightarrow (A - \lambda I)$ is not invertible. $\Rightarrow (A - \lambda I)$ is not diagonally dominant.

$$\Rightarrow \exists i \text{ sit } |a_{ii} - \lambda| \leq R_i$$

Proposition 24.7. ***(Spectral Theorem)*** *Every real symmetric matrix has factorization $S = Q\Lambda Q^\top$, with real eigenvalues in Λ and orthonormal eigenvectors as columns of Q:*

$$S = Q\Lambda Q^{-1} = Q\Lambda Q^\top$$

Solution:

1. All eigenvalues are real. Suppose $S\vec{x} = \lambda\vec{x}$ where $\lambda = a + bi, b \neq 0$. Take conjugate, we get

$$S\bar{\vec{x}} = \bar{\lambda}\bar{\vec{x}} \Rightarrow \bar{\vec{x}}^\top S^\top = \bar{\lambda}\bar{\vec{x}}^\top \Rightarrow \bar{\vec{x}}^\top S^\top \vec{x} = \bar{\lambda}\bar{\vec{x}}^\top \vec{x}$$

   Since $S\vec{x} = \lambda\vec{x}$, we have $\bar{\vec{x}}^\top S^\top \vec{x} = \lambda\bar{\vec{x}}^\top \vec{x}$, then

$$\Rightarrow 0 = (\lambda - \bar{\lambda})\bar{\vec{x}}^\top \vec{x} \Rightarrow \lambda = \bar{\lambda} \Rightarrow b = 0 \quad \text{contradiction!}$$

   Hence, $\lambda \in \mathbb{R}$.

2. Eigenvectors of a real symmetric matrix (when they correspond to different λ's) are always perpendicular.
   Suppose $S\vec{x}_1 = \lambda_1\vec{x}_1; S\vec{x}_2 = \lambda_2\vec{x}_2; \lambda_1 \neq \lambda_2$, then

$$\lambda_1\vec{x}_2^\top\vec{x}_1 = \vec{x}_2^\top S\vec{x}_1 \xlongequal{constant} \left(\vec{x}_2^\top S\vec{x}_1\right)^\top = \vec{x}_1^\top S^\top \vec{x}_2 \xlongequal{symmetric} \vec{x}_1^\top S\vec{x}_2 = \lambda_2\vec{x}_1^\top\vec{x}_2$$

   Since $\vec{x}_2^\top\vec{x}_1 \xlongequal{constant} \vec{x}_1^\top\vec{x}_2$, we have

$$(\lambda_2 - \lambda_1)\vec{x}_2^\top\vec{x}_1 \Rightarrow \vec{x}_2^\top\vec{x}_1 = 0 \rightarrow \text{ orthogonal.}$$

Theorem 24.8. ***(Shur's Theorem)*** *If $\boldsymbol{A}$ is a square real matrix with real eigenvalues, then there is an orthogonal matrix $\boldsymbol{Q}$ and an upper triangular matrix $\boldsymbol{T}$ such that $\boldsymbol{A} = \boldsymbol{QTQ}^{\mathrm{T}}$.*

Solution: Note that $\boldsymbol{A} = \boldsymbol{QTQ}^{\mathrm{T}} \Leftrightarrow \boldsymbol{AQ} = \boldsymbol{QT}$. Let $\boldsymbol{q}_1$ be an eigenvector of norm 1, with eigenvalue λ_1. Let $\boldsymbol{q}_2, \ldots, \boldsymbol{q}_n$ be any orthonormal vectors orthogonal to $\boldsymbol{q}_1$. Let $\boldsymbol{Q}_1 = [\boldsymbol{q}_1, \ldots, \boldsymbol{q}_n]$. Then $\boldsymbol{Q}_1^{\mathrm{T}}\boldsymbol{Q}_1 = \boldsymbol{I}$, and

$$\boldsymbol{Q}_1^{\mathrm{T}}\boldsymbol{A}\boldsymbol{Q}_1 = \begin{pmatrix} \lambda_1 & \ldots \\ \underline{0} & \boldsymbol{A}_2 \end{pmatrix}$$

Now I claim that $\boldsymbol{A}_2$ has eigenvalues $\lambda_2, \ldots, \lambda_n$. This is true because

$$\begin{aligned}
\det(\boldsymbol{A} - \lambda\boldsymbol{I}) &= \det \boldsymbol{Q}_1^{\mathrm{T}} \det(\boldsymbol{A} - \lambda\boldsymbol{I}) \det \boldsymbol{Q}_1 = \det\left(\boldsymbol{Q}_1^{\mathrm{T}}(\boldsymbol{A} - \lambda\boldsymbol{I})\boldsymbol{Q}_1\right) \\
&= \det\left(\boldsymbol{Q}_1^{\mathrm{T}}\boldsymbol{A}\boldsymbol{Q}_1 - \lambda\boldsymbol{Q}_1^{\mathrm{T}}\boldsymbol{Q}_1\right) = \det\begin{pmatrix} (\lambda_1 - \lambda) & \ldots \\ \mathbf{0} & (\boldsymbol{A}_2 - \lambda\boldsymbol{I}) \end{pmatrix} \\
&= (\lambda_1 - \lambda)\det\left(\boldsymbol{A}_2 - \lambda\boldsymbol{I}\right).
\end{aligned}$$

So $\boldsymbol{A}_2$ has real eigenvalues, namely $\lambda_2, \ldots, \lambda_n$. Now we proceed by induction. Suppose we have proved the theorem for $n = k$. Then we use this fact to prove the theorem is true for $n = k + 1$. Note that the theorem is trivial if $n = 1$.

So for $n = k + 1$, we proceed as above and then apply the known theorem to $\boldsymbol{A}_2$, which is $k \times k$. We find that $\boldsymbol{A}_2 = \boldsymbol{Q}_2\boldsymbol{T}_2\boldsymbol{Q}_2^{\mathrm{T}}$. Now this is the hard part. Let $\boldsymbol{Q}_1$ and $\boldsymbol{A}_2$ be as above, and let

$$\boldsymbol{Q} = \boldsymbol{Q}_1\begin{pmatrix} 1 & \mathbf{0} \\ \mathbf{0} & \boldsymbol{Q}_2 \end{pmatrix}$$

Then

$$\begin{aligned}
\boldsymbol{AQ} &= \boldsymbol{A}\boldsymbol{Q}_1\begin{pmatrix} 1 & \mathbf{0} \\ \mathbf{0} & \boldsymbol{Q}_2 \end{pmatrix} = \boldsymbol{Q}_1\begin{pmatrix} \lambda_1 & \ldots \\ \mathbf{0} & \boldsymbol{A}_2 \end{pmatrix}\begin{pmatrix} 1 & \mathbf{0} \\ \mathbf{0} & \boldsymbol{Q}_2 \end{pmatrix} \\
&= \boldsymbol{Q}_1\begin{pmatrix} \lambda_1 & \ldots \\ \mathbf{0} & \boldsymbol{A}_2\boldsymbol{Q}_2 \end{pmatrix} = \boldsymbol{Q}_1\begin{pmatrix} \lambda_1 & \ldots \\ \mathbf{0} & \boldsymbol{Q}_2\boldsymbol{T}_2 \end{pmatrix} \\
&= \boldsymbol{Q}_1\begin{pmatrix} 1 & \mathbf{0} \\ \mathbf{0} & \boldsymbol{Q}_2 \end{pmatrix}\begin{pmatrix} \lambda_1 & \ldots \\ \mathbf{0} & \boldsymbol{T}_2 \end{pmatrix} = \boldsymbol{QT}
\end{aligned}$$

where $\boldsymbol{T}$ is upper triangular. So $\boldsymbol{AQ} = \boldsymbol{QT}$, or $\boldsymbol{A} = \boldsymbol{QTQ}^{\mathrm{T}}$.