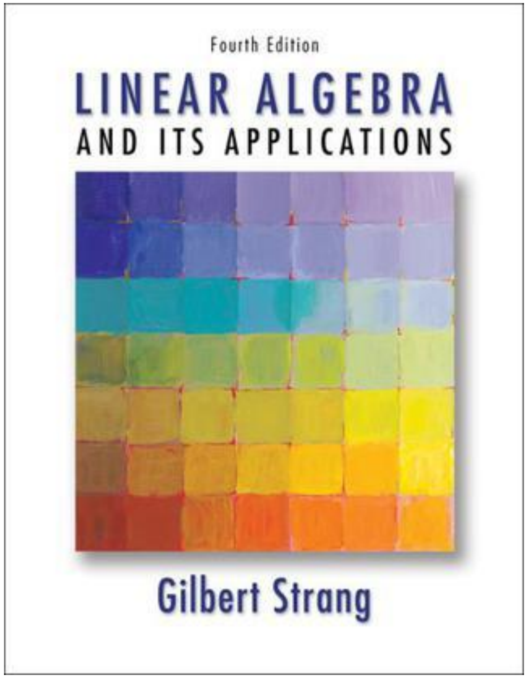
Linear Algebra



Instructor: Jing YAO

Linear Algebra and Its Applications

Gilbert Strang

1 Matrices and Gaussian Elimination

1.5

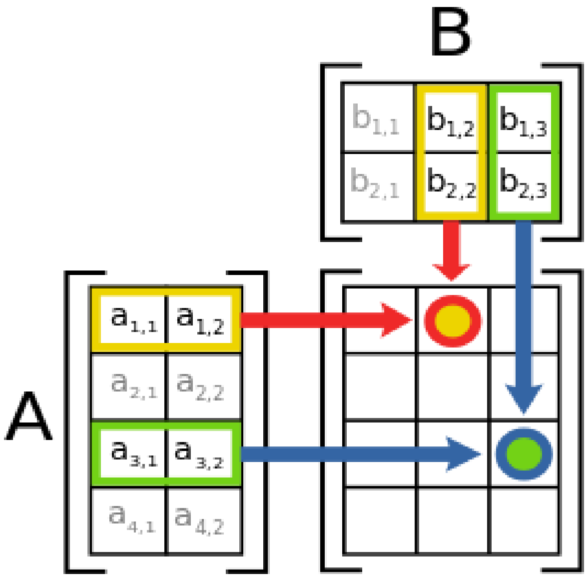
INVERSES AND TRANSPOSES

（矩阵的逆和转置）

Definitions

Properties

Algorithms



*** Textbook: Section1.6**

I. Transpose of a Matrix (转置矩阵)

1. Definition (定义)

Given an $m\times n$ matrix $\boldsymbol{A}$, the **transpose** of $\boldsymbol{A}$ is the $n\times m$ matrix, denoted by $\boldsymbol{A}^{\mathrm{T}}$, whose columns are formed from the corresponding rows of $\boldsymbol{A}$: the ith row of $\boldsymbol{A}$ becomes the ith column of $\boldsymbol{A}^{\mathrm{T}}$. (把 $m\times n$ 矩阵 $\boldsymbol{A}$ 的行换成同序数的列所得到的 $n\times m$ 矩阵称为矩阵 $\boldsymbol{A}$ 的**转置矩阵**，记作 $\boldsymbol{A}^{\mathrm{T}}$（或 $\boldsymbol{A}'$）.)

Let $\boldsymbol{A}=[a_{ij}]_{m\times n}$, $\boldsymbol{A}^{\mathrm{T}}=[b_{ij}]_{n\times m}$, then $a_{ij}=b_{ji}$.

For example,

$$\boldsymbol{A}=\begin{bmatrix}1 & 2 & 2\\ 4 & 5 & 8\end{bmatrix}, \qquad \boldsymbol{A}^{\mathrm{T}}=\begin{bmatrix}1 & 4\\ 2 & 5\\ 2 & 8\end{bmatrix};$$

$$\boldsymbol{B}=(18, 6), \qquad \boldsymbol{B}^{\mathrm{T}}=\begin{bmatrix}18\\ 6\end{bmatrix}.$$

2、Rules (转置矩阵的运算性质)

Let $\boldsymbol{A}$, $\boldsymbol{B}$, $\boldsymbol{A}_1, \ldots,$ and $\boldsymbol{A}_n$ denote matrices whose sizes are appropriate for the following sums and products.

(1) $(\boldsymbol{A}^{\mathrm{T}})^{\mathrm{T}} = \boldsymbol{A};$

(2) $(\boldsymbol{A}+\boldsymbol{B})^{\mathrm{T}} = \boldsymbol{A}^{\mathrm{T}} + \boldsymbol{B}^{\mathrm{T}};$

$$(\boldsymbol{A}_1 + \boldsymbol{A}_2 + \cdots + \boldsymbol{A}_n)^{\mathrm{T}} = \boldsymbol{A}_1^{\mathrm{T}} + \boldsymbol{A}_2^{\mathrm{T}} + \cdots + \boldsymbol{A}_n^{\mathrm{T}};$$

(3) $(k\boldsymbol{A})^{\mathrm{T}} = k\boldsymbol{A}^{\mathrm{T}};$

(4) $(\boldsymbol{A}\boldsymbol{B})^{\mathrm{T}} = \boldsymbol{B}^{\mathrm{T}}\boldsymbol{A}^{\mathrm{T}};$

The transpose of a product of matrices equals the product of their transposes in the *reverse* order.

$$(\boldsymbol{A}_1\boldsymbol{A}_2 \cdots \boldsymbol{A}_n)^{\mathrm{T}} = \boldsymbol{A}_n^{\mathrm{T}} \cdots \boldsymbol{A}_2^{\mathrm{T}}\boldsymbol{A}_1^{\mathrm{T}}.$$

$$\boldsymbol{AB} = \begin{bmatrix} 1 & 2 \\ 3 & 4 \end{bmatrix} \begin{bmatrix} 0 & 1 \\ 2 & 3 \end{bmatrix} = \begin{bmatrix} 4 & 7 \\ 8 & 15 \end{bmatrix}, \qquad \boldsymbol{B}^{\mathrm{T}}\boldsymbol{A}^{\mathrm{T}} = \begin{bmatrix} 0 & 2 \\ 1 & 3 \end{bmatrix} \begin{bmatrix} 1 & 3 \\ 2 & 4 \end{bmatrix} = \begin{bmatrix} 4 & 8 \\ 7 & 15 \end{bmatrix}.$$

$(\boldsymbol{AB})^{\mathrm{T}} = \boldsymbol{B}^{\mathrm{T}}\boldsymbol{A}^{\mathrm{T}}.$

"Proof".

(j, i)-entry of $(\boldsymbol{AB})^{\mathrm{T}} = (\boldsymbol{AB})_{ij} =$ (row i of $\boldsymbol{A}$) times (column j of $\boldsymbol{B}$)

$$= [a_{i1} \quad a_{i2} \quad \cdots \quad a_{in}] \begin{bmatrix} b_{1j} \\ b_{2j} \\ \vdots \\ b_{nj} \end{bmatrix} = a_{i1}b_{1j} + a_{i2}b_{2j} + \cdots + a_{in}b_{nj}$$

(j, i)-entry of $\boldsymbol{B}^{\mathrm{T}}\boldsymbol{A}^{\mathrm{T}} = \left(\text{row } j \text{ of } \boldsymbol{B}^{\mathrm{T}}\right)$ times $\left(\text{column } i \text{ of } \boldsymbol{A}^{\mathrm{T}}\right)$

$$= [b_{1j} \quad b_{2j} \quad \cdots \quad b_{nj}] \begin{bmatrix} a_{i1} \\ a_{i2} \\ \vdots \\ a_{in} \end{bmatrix} = b_{1j}a_{i1} + b_{2j}a_{i2} + \cdots + b_{nj}a_{in}$$

对称矩阵(symmetric matrix)与反对称矩阵(skew-symmetric / antisymmetric / antimetric matrix)

定义(Definition) 设 $\boldsymbol{A}$ 为n阶方阵, 如果满足 $\boldsymbol{A}^{\mathrm{T}}=\boldsymbol{A}$, 即

$$a_{ij}=a_{ji}\quad (i,j=1,2,\ \dots,n),$$

那么 $\boldsymbol{A}$ 称为 对称矩阵.

$$\boldsymbol{A}=\begin{bmatrix} 12 & 6 & 1 \\ 6 & 8 & 0 \\ 1 & 0 & 6 \end{bmatrix}. \quad \boldsymbol{A}=\begin{bmatrix} 0 & 3 & 1 \\ -3 & 0 & -9 \\ -1 & 9 & 0 \end{bmatrix}.$$

如果满足 $\boldsymbol{A}^{\mathrm{T}}=-\boldsymbol{A}$, 则称 $\boldsymbol{A}$ 为反对称矩阵, 即满足

$$a_{ij}=-a_{ji}\quad (i,j=1,2,\dots,n).$$

反对称矩阵中$a_{ii}=0$.

Example 1 Suppose $\boldsymbol{A}$, $\boldsymbol{B}$ are n by n matrices, try to verify that $\boldsymbol{AB}^{\mathrm{T}}+\boldsymbol{BA}^{\mathrm{T}}$ is symmetric.

Proof Since

$$
\begin{aligned}
(\boldsymbol{AB}^{\mathrm{T}}+\boldsymbol{BA}^{\mathrm{T}})^{\mathrm{T}} &= (\boldsymbol{AB}^{\mathrm{T}})^{\mathrm{T}}+(\boldsymbol{BA}^{\mathrm{T}})^{\mathrm{T}} \\
&= (\boldsymbol{B}^{\mathrm{T}})^{\mathrm{T}}\boldsymbol{A}^{\mathrm{T}}+(\boldsymbol{A}^{\mathrm{T}})^{\mathrm{T}}\boldsymbol{B}^{\mathrm{T}} \\
&= \boldsymbol{BA}^{\mathrm{T}}+\boldsymbol{AB}^{\mathrm{T}} = \boldsymbol{AB}^{\mathrm{T}}+\boldsymbol{BA}^{\mathrm{T}},
\end{aligned}
$$

therefore $\boldsymbol{AB}^{\mathrm{T}}+\boldsymbol{BA}^{\mathrm{T}}$ is symmetric.

Similary, if $\boldsymbol{A}$ is an $m\times n$ matrix, then it is easy to show that $\boldsymbol{AA}^{\mathrm{T}}$, $\boldsymbol{A}^{\mathrm{T}}\boldsymbol{A}$ are both symmetric matrices.

e.g., $\boldsymbol{A}=[1\ \ 2]$. What are $\boldsymbol{AA}^{\mathrm{T}}$ and $\boldsymbol{A}^{\mathrm{T}}\boldsymbol{A}$?

Inverse

引例 ***Coding & Decoding; Encrypting & Decrypting***

A	B	C	D	E	F	G	H	I	J	K	L	M		
1	2	3	4	5	6	7	8	9	10	11	12	13		
N	O	P	Q	R	S	T	U	V	W	X	Y	Z		Space
14	15	16	17	18	19	20	21	22	23	24	25	26		0

考虑加解密方案：明文信息经编码后分成三个一组（空格也是一种明文信息，不足3个时可加空格）. 对明文 $(p_1, p_2, p_3)^T$, 相应的密文为：

$$\begin{bmatrix} c_1 \\ c_2 \\ c_3 \end{bmatrix} = \boldsymbol{A}\begin{bmatrix} p_1 \\ p_2 \\ p_3 \end{bmatrix} + \boldsymbol{b}, \quad \text{其中 } \boldsymbol{A} = \begin{bmatrix} 0 & 0 & -2 \\ -1 & -4 & -3 \\ -1 & -3 & -4 \end{bmatrix}, \boldsymbol{b} = \begin{bmatrix} 20 \\ 30 \\ 40 \end{bmatrix}.$$

已知明文DIG,求密文； 已知密文$(-8,-103,-86)^T$,求明文.

II. Inverse of a Matrix (矩阵的逆)-- Definition

- An $n \times n$ matrix $\boldsymbol{A}$ is said to be **invertible** (可逆的) if there is an $n \times n$ matrix $\boldsymbol{C}$ such that

$$\boldsymbol{CA} = \boldsymbol{I} \quad \underline{\text{and}} \quad \boldsymbol{AC} = \boldsymbol{I},$$

where $\boldsymbol{I} = \boldsymbol{I}_n$, the $n \times n$ identity matrix.

- In this case, $\boldsymbol{C}$ is an **inverse** of $\boldsymbol{A}$ ($\boldsymbol{A}$的逆).
- In fact, $\boldsymbol{C}$ is <u>uniquely</u> determined by $\boldsymbol{A}$, because if $\boldsymbol{B}$ were another inverse of $\boldsymbol{A}$, then

$$\boldsymbol{B} = \boldsymbol{BI} = \boldsymbol{B}(\boldsymbol{AC}) = (\boldsymbol{BA})\boldsymbol{C} = \boldsymbol{IC} = \boldsymbol{C}.$$

- This unique inverse is denoted by $\boldsymbol{A}^{-1}$ ('$\boldsymbol{A}$ inverse'), so that

$$\boldsymbol{A}^{-1}\boldsymbol{A} = \boldsymbol{I} \quad \text{and} \quad \boldsymbol{A}\boldsymbol{A}^{-1} = \boldsymbol{I}.$$

For example, $\boldsymbol{A}=\begin{bmatrix}1 & -1\\ 1 & 1\end{bmatrix}$, $\boldsymbol{M}=\begin{bmatrix}1/2 & 1/2\\ -1/2 & 1/2\end{bmatrix}$,

Since $\boldsymbol{AM}=\boldsymbol{MA}=\boldsymbol{I}$, $\boldsymbol{M}$ is the inverse of $\boldsymbol{A}$.

- A matrix that is *not* invertible is also called a singular matrix (奇异矩阵), and an invertible matrix is called a nonsingular matrix (非奇异矩阵).

Not all matrices have inverses. (并非所有矩阵都可逆)
An inverse is impossible when $\boldsymbol{Ax}$ is zero and $\boldsymbol{x}$ is nonzero.

Application:

If $\boldsymbol{A}$ is invertible, the *one and only solution* to $\boldsymbol{Ax}=\boldsymbol{0}$ is $\boldsymbol{x}=\boldsymbol{0}$.

当 $\boldsymbol{A}$ 可逆(即: 非奇异)时, $\boldsymbol{Ax}=\boldsymbol{0}$ **只有零解** $\boldsymbol{x}=\boldsymbol{0}$.

- **Theorem 1** Let $\boldsymbol{A} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}$. If $a_{11}a_{22} - a_{12}a_{21} \neq 0$, then

  $\boldsymbol{A}$ is invertible and

$$\boldsymbol{A}^{-1} = \frac{1}{a_{11}a_{22} - a_{12}a_{21}} \begin{bmatrix} a_{22} & -a_{12} \\ -a_{21} & a_{11} \end{bmatrix}.$$

  If $a_{11}a_{22} - a_{12}a_{21} = 0$, then $\boldsymbol{A}$ is not invertible.

- The quantity $a_{11}a_{22} - a_{12}a_{21}$ is called the **determinant (行列式)** of $\boldsymbol{A}$, and we write $\det \boldsymbol{A} = a_{11}a_{22} - a_{12}a_{21}$.

- This theorem says that a 2×2 matrix $\boldsymbol{A}$ is invertible if and only if $\det \boldsymbol{A} \neq 0$.

Proof: **（by definition, or 待定系数法）**

Let $\boldsymbol{M} = \begin{bmatrix} x_1 & x_2 \\ x_3 & x_4 \end{bmatrix}$, which satisfies that $\boldsymbol{AM} = \boldsymbol{I}$,

$$\begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} x_1 & x_2 \\ x_3 & x_4 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \Rightarrow \begin{bmatrix} a_{11}x_1 + a_{12}x_3 & a_{11}x_2 + a_{12}x_4 \\ a_{21}x_1 + a_{22}x_3 & a_{21}x_2 + a_{22}x_4 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}.$$

$$\Rightarrow \begin{cases} a_{11}x_1 + a_{12}x_3 = 1, \\ a_{21}x_1 + a_{22}x_3 = 0, \\ a_{11}x_2 + a_{12}x_4 = 0, \\ a_{21}x_2 + a_{22}x_4 = 1, \end{cases} \Rightarrow \begin{cases} x_1 = \dfrac{a_{22}}{a_{11}a_{22} - a_{12}a_{21}}, \\ x_2 = \dfrac{-a_{12}}{a_{11}a_{22} - a_{12}a_{21}}, \\ x_3 = \dfrac{-a_{21}}{a_{11}a_{22} - a_{12}a_{21}}, \\ x_4 = \dfrac{a_{11}}{a_{11}a_{22} - a_{12}a_{21}}. \end{cases} \Rightarrow \quad \boldsymbol{M} = \frac{1}{a_{11}a_{22} - a_{12}a_{21}} \begin{bmatrix} a_{22} & -a_{12} \\ -a_{21} & a_{11} \end{bmatrix}.$$

$$(a_{11}a_{22} - a_{12}a_{21} \neq 0)$$

We can also check that $\boldsymbol{AM} = \boldsymbol{MA} = \boldsymbol{I}$. Therefore

$$\boldsymbol{A}^{-1} = \frac{1}{a_{11}a_{22} - a_{12}a_{21}} \begin{bmatrix} a_{22} & -a_{12} \\ -a_{21} & a_{11} \end{bmatrix}.$$

求二阶可逆矩阵**A**的逆的"**两调一除**"方法:

先将矩阵 $\boldsymbol{A}$ 的主对角元素互换位置, 再将次对角元素反号, 最后用 $\det \boldsymbol{A}$ 去除 $\boldsymbol{A}$ 的每一个元素.

For example,

$$\boldsymbol{A} = \begin{bmatrix} 2 & 3 \\ -1 & 0 \end{bmatrix}, \quad \boldsymbol{A}^{-1} = \frac{1}{3}\begin{bmatrix} 0 & -3 \\ 1 & 2 \end{bmatrix} = \begin{bmatrix} 0 & -1 \\ \frac{1}{3} & \frac{2}{3} \end{bmatrix}.$$

Example 2 A diagonal matrix has an inverse provided no diagonal entries are zero. (主对角元都是非零数的对角阵是可逆的.)

$$\begin{bmatrix} a_1 & & & \\ & a_2 & & \\ & & \ddots & \\ & & & a_n \end{bmatrix}^{-1} = \begin{bmatrix} a_1^{-1} & & & \\ & a_2^{-1} & & \\ & & \ddots & \\ & & & a_n^{-1} \end{bmatrix}$$

Note:

If $ab \neq 0$, then $\begin{bmatrix} 0 & a \\ b & 0 \end{bmatrix} \begin{bmatrix} 0 & b^{-1} \\ a^{-1} & 0 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}.$

Note: $\boldsymbol{A}+\boldsymbol{B}$ is not necessarily invertible for invertible matrices $\boldsymbol{A}$, $\boldsymbol{B}$.

And we can easily give an example that shows

$(\boldsymbol{A}+\boldsymbol{B})^{-1} \neq \boldsymbol{A}^{-1} + \boldsymbol{B}^{-1}$, even if $\boldsymbol{A}+\boldsymbol{B}$ is invertible.

For example, $\boldsymbol{A} = \mathrm{diag}(2,-1)$, $\boldsymbol{B} = \boldsymbol{I}_2$, $\boldsymbol{C} = \mathrm{diag}(1,2)$.

$\boldsymbol{A}+\boldsymbol{B} = \mathrm{diag}(3,0)$: not invertible

$\boldsymbol{A}+\boldsymbol{C} = \mathrm{diag}(3,1)$: invertible

$$(\boldsymbol{A}+\boldsymbol{C})^{-1} = \mathrm{diag}(1/3, 1) \neq \boldsymbol{A}^{-1} + \boldsymbol{C}^{-1} = \mathrm{diag}(3/2, -1/2).$$

Example 3 Let a square matrix $\boldsymbol{B}$ be idempotent (幂等, i.e., $\boldsymbol{B}^2=\boldsymbol{B}$), and $\boldsymbol{A}=\boldsymbol{I}+\boldsymbol{B}$. Show that $\boldsymbol{A}$ is invertible, and $\boldsymbol{A}^{-1}=(3\boldsymbol{I}-\boldsymbol{A})/2$.

Proof By $\boldsymbol{B}=\boldsymbol{A}-\boldsymbol{I}$, $\boldsymbol{B}^2=(\boldsymbol{A}-\boldsymbol{I})^2=\boldsymbol{A}^2-2\boldsymbol{A}+\boldsymbol{I}$,

and $\boldsymbol{B}^2=\boldsymbol{B}$, we can get

$$\boldsymbol{A}^2-2\boldsymbol{A}+\boldsymbol{I}=\boldsymbol{A}-\boldsymbol{I},$$

$$\boldsymbol{A}^2-3\boldsymbol{A}=\boldsymbol{A}(\boldsymbol{A}-3\boldsymbol{I})=-2\boldsymbol{I},$$

i.e., $$\boldsymbol{A}[(3\boldsymbol{I}-\boldsymbol{A})/2]=\boldsymbol{I}.$$

Similarly, $$[(3\boldsymbol{I}-\boldsymbol{A})/2]\boldsymbol{A}=\boldsymbol{I}.$$

Therefore, $\boldsymbol{A}$ is invertible, and $\boldsymbol{A}^{-1}=(3\boldsymbol{I}-\boldsymbol{A})/2$.

III. Inverse -- Properties

- **Theorem 2** If $\boldsymbol{A}$ is an invertible $n\times n$ matrix, then for each $\boldsymbol{b}$ in $\mathbb{R}^n$, the equation $\boldsymbol{A}\,\boldsymbol{x} = \boldsymbol{b}$ has the unique (*one and only one*) solution $\boldsymbol{x} = \boldsymbol{A}^{-1}\boldsymbol{b}$.

- **Proof:** Take any $\boldsymbol{b}$ in $\mathbb{R}^n$.

A solution exists because if $\boldsymbol{A}^{-1}\boldsymbol{b}$ is substituted for $\boldsymbol{x}$, then $\boldsymbol{A}\boldsymbol{x} = \boldsymbol{A}(\boldsymbol{A}^{-1}\boldsymbol{b}) = (\boldsymbol{A}\boldsymbol{A}^{-1})\boldsymbol{b} = \boldsymbol{I}\,\boldsymbol{b} = \boldsymbol{b}$.

So $\boldsymbol{A}^{-1}\boldsymbol{b}$ is a solution.

To prove that the solution is unique, show that if $\boldsymbol{u}$ is any solution, then $\boldsymbol{u}$ must be $\boldsymbol{A}^{-1}\boldsymbol{b}$.

If $\boldsymbol{A}\,\boldsymbol{u} = \boldsymbol{b}$, we can multiply both sides by $\boldsymbol{A}^{-1}$ and obtain $\boldsymbol{A}^{-1}\boldsymbol{A}\,\boldsymbol{u} = \boldsymbol{A}^{-1}\boldsymbol{b}$, $\boldsymbol{I}\,\boldsymbol{u} = \boldsymbol{A}^{-1}\boldsymbol{b}$, and $\boldsymbol{u} = \boldsymbol{A}^{-1}\boldsymbol{b}$.

- **Theorem 3**

a. If $\boldsymbol{A}$ is an invertible matrix, then $\boldsymbol{A}^{-1}$ is invertible and $(\boldsymbol{A}^{-1})^{-1}=\boldsymbol{A}$. (若 $\boldsymbol{A}$ 可逆，则 $\boldsymbol{A}^{-1}$ 亦可逆)

b. If $\boldsymbol{A}$ and $\boldsymbol{B}$ are $n\times n$ invertible matrices, then so is $\boldsymbol{AB}$ (若 $\boldsymbol{A}$，$\boldsymbol{B}$ 为同阶可逆方阵，则 $\boldsymbol{AB}$ 也可逆),

and the inverse of $\boldsymbol{AB}$ is the product of the inverses of $\boldsymbol{A}$ and $\boldsymbol{B}$ in the *reverse* order. That is,

$$(\boldsymbol{AB})^{-1}=\boldsymbol{B}^{-1}\boldsymbol{A}^{-1}.$$

$$\boxed{(\boldsymbol{A}^{k})^{-1}=(\boldsymbol{A}^{-1})^{k}=\boldsymbol{A}^{-k}}$$

c. If $\boldsymbol{A}$ is an invertible matrix, then so is $\boldsymbol{A}^{\mathrm{T}}$ (若 $\boldsymbol{A}$ 可逆, 则 $\boldsymbol{A}^{\mathrm{T}}$ 亦可逆), and the inverse of $\boldsymbol{A}^{\mathrm{T}}$ is the transpose of $\boldsymbol{A}^{-1}$. That is,

$$(\boldsymbol{A}^{\mathrm{T}})^{-1}=(\boldsymbol{A}^{-1})^{\mathrm{T}}.$$

- **Proof:** To verify statement (a), find a matrix $\boldsymbol{C}$ such that

$$\boldsymbol{A}^{-1}\boldsymbol{C} = \boldsymbol{I} \quad \text{and} \quad \boldsymbol{C}\boldsymbol{A}^{-1} = \boldsymbol{I}\ .$$

These equations are satisfied with $\boldsymbol{A}$ in place of $\boldsymbol{C}$.

Hence $\boldsymbol{A}^{-1}$ is invertible, and $\boldsymbol{A}$ is its inverse.

- Next, to prove statement (b), compute:

$$(\boldsymbol{AB})(\boldsymbol{B}^{-1}\boldsymbol{A}^{-1}) = \boldsymbol{A}(\boldsymbol{BB}^{-1})\boldsymbol{A}^{-1} = \boldsymbol{A}\,\boldsymbol{I}\,\boldsymbol{A}^{-1} = \boldsymbol{A}\,\boldsymbol{A}^{-1} = \boldsymbol{I}\ .$$

A similar calculation shows that $(\boldsymbol{B}^{-1}\boldsymbol{A}^{-1})\,(\boldsymbol{AB}) = \boldsymbol{I}\ .$

- For statement (c), use Theorem of transpose matrix, read from right to left,

$$(\boldsymbol{A}^{-1})^{\mathrm{T}}\boldsymbol{A}^{\mathrm{T}} = (\boldsymbol{AA}^{-1})^{\mathrm{T}} = \boldsymbol{I}^{\mathrm{T}} = \boldsymbol{I}.$$

Similarly, $\boldsymbol{A}^{\mathrm{T}}(\boldsymbol{A}^{-1})^{\mathrm{T}} = \boldsymbol{I}^{\mathrm{T}} = \boldsymbol{I}.$

The inverses of elementary matrices (初等矩阵的逆矩阵)

Recall: (1)初等对换矩阵:

将单位矩阵的第 i, j 行(或列)对换

$$
\boldsymbol{P}_{ij} = \begin{array}{c} \left[\begin{array}{ccccccccc}
1 & & & & & & & & \\
& \ddots & & & & & & & \\
& & 1 & & & & & & \\
& & & 0 & \cdots & 1 & & & \\
& & & \vdots & 1 & \vdots & & & \\
& & & & \ddots & & & & \\
& & & & 1 & & & & \\
& & & 1 & \cdots & 0 & & & \\
& & & & & & 1 & & \\
& & & & & & & \ddots & \\
& & & & & & & & 1
\end{array}\right]
\begin{array}{l} \\ \\ \\ \leftarrow \text{第 } i \text{ 行} \\ \\ \\ \\ \leftarrow \text{第 } j \text{ 行} \\ \\ \\ \\ \end{array} \\
\text{第 } i \text{ 列} \qquad \text{第 } j \text{ 列}
\end{array}
$$

(2)初等倍乘矩阵:

将单位矩阵第 i 行(或列)乘 $k \neq 0$

$$
\boldsymbol{D}_i(k) = \begin{array}{cc}
\begin{bmatrix}
1 & & & & & \\
& \ddots & & & & \\
& & 1 & & & \\
& & & k & & \\
& & & & 1 & \\
& & & & & \ddots & \\
& & & & & & 1
\end{bmatrix} & \begin{array}{c} \\ \\ \\ \leftarrow 第\, i\, 行 \\ \\ \\ \\ \end{array} \\
\text{第 } i \text{ 列} &
\end{array}
$$

(3)初等倍加矩阵：

将单位矩阵第 i 行乘 k 加到第 j 行，

或将第 j 列乘 k 加到第 i 列

$$E_{ij}(k)=\begin{bmatrix} 1 &&&&&& \\ &\ddots&&&&& \\ &&1&&&& \\ &&\vdots&\ddots&&& \\ &&k&\cdots&1&& \\ &&&&&\ddots& \\ &&&&&&1 \end{bmatrix}\begin{array}{l} \\ \\ \leftarrow 第\ i\ 行 \\ \\ \leftarrow 第\ j\ 行 \\ \\ \\ \end{array}$$

第 i 列　　第 j 列

The inverses of elementary matrices (初等矩阵的逆矩阵)

变换 $r_i \leftrightarrow r_j$ 的逆变换是其本身，则

$$P_{ij}^{-1} = P_{ij};$$

变换 $kr_i\ (k \neq 0)$的逆变换是 $\frac{1}{k} r_i$，则

$$D_i^{-1}(k) = D_i\left(\frac{1}{k}\right);$$

变换 $r_j + kr_i$ 的逆变换是 $r_j + (-k)r_i$，则

$$E_{ij}^{-1}(k) = E_{ij}(-k).$$

初等矩阵的逆矩阵仍为同类型的初等矩阵.

Each elementary matrix $\boldsymbol{E}$ is invertible. The inverse of $\boldsymbol{E}$ is the elementary matrix of the same type that transforms $\boldsymbol{E}$ back into $\boldsymbol{I}$.

IV. Algorithm (初等变换法求逆矩阵)

定理4 可逆矩阵可以经过若干次初等变换化为单位矩阵.

析 任何矩阵$\boldsymbol{A}$, 都可经初等行变换将其化为行简化阶梯形矩阵.

任何方阵$\boldsymbol{A}$, 都可经初等行变换将其化为上三角形矩阵.

任何可逆矩阵$\boldsymbol{A}$, 都可经初等行变换将其化为单位矩阵$\boldsymbol{I}$.

即 $\boldsymbol{P}_s \ldots \boldsymbol{P}_2 \boldsymbol{P}_1 \boldsymbol{A} = \boldsymbol{I}$. ($\boldsymbol{P}_1, \ldots, \boldsymbol{P}_s$均为初等矩阵)

Hint: Suppose that $\boldsymbol{A}$ is invertible.

Then, since the equation $\boldsymbol{A}\boldsymbol{x} = \boldsymbol{b}$ has a solution for each $\boldsymbol{b}$ (Theorem 2), $\boldsymbol{A}$ has a pivot position in every row.

Because $\boldsymbol{A}$ is square, the n pivot positions must be on the diagonal, which implies that the reduced echelon form of $\boldsymbol{A}$ is $\boldsymbol{I}_n$.

Then, since each step of the row reduction of $\boldsymbol{A}$ corresponds to left-multiplication by an elementary matrix, there exist elementary matrices $\boldsymbol{P}_1, \ldots, \boldsymbol{P}_s$ such that $\boldsymbol{P}_s \ldots \boldsymbol{P}_2 \boldsymbol{P}_1 \boldsymbol{A} = \boldsymbol{I}$.

由$\underline{P_s \dots P_2 P_1} A=I$ 得 $A = P_1^{-1} P_2^{-1} \cdots P_s^{-1} I$ 和

$A^{-1}=P_s \dots P_2 P_1 = \underline{P_s \dots P_2 P_1} I$

初等矩阵的逆矩阵仍然是初等矩阵

(A^{-1} results from applying P_1, ..., P_s successively to I.)

This is the same sequence that reduced A to I.

结论： (1) 可逆矩阵可以表示为若干初等矩阵的乘积；

(2) 对 A 作若干初等变换, 将 A 化为单位矩阵 I 时,

同样的这些初等变换将单位矩阵 I 化为 A^{-1}.

$$P_s \cdots P_2 P_1 [A \quad I] = [I \quad A^{-1}]$$

Row reduce the matrix $[A \quad I]$. If A is row equivalent to I, then $[A \quad I]$ is row equivalent to $[I \quad A^{-1}]$.
Otherwise, A does not have an inverse.

用初等行变换求 A 的逆矩阵
(the ***Gauss-Jordan method*** for calculating A^{-1})

即对 $n\times 2n$ 矩阵 $[A\ \ I_n]$ 实施一系列初等行变换，把矩阵 A 变成 I_n 时，原来的 I_n 就变成了 A^{-1}.

$$[A, I_n] \xrightarrow{\text{ERO}} [I_n, A^{-1}]$$

- **Theorem 5** An $n\times n$ matrix A is invertible if and only if A is row equivalent to I_n, and in this case, any sequence of elementary row operations that reduces A to I_n also transforms I_n into A^{-1}.

Example 4 Write the matrix $\boldsymbol{A}$ as the product of elementary matrices, where

$$\boldsymbol{A}=\begin{bmatrix}1&0&0\\2&0&-1\\0&-1&0\end{bmatrix}.$$

Solution The matrix $\boldsymbol{A}$ can be obtained from the 3 by 3 identity matrix $\boldsymbol{I}$ by 4 elementary operations

$$r_2\leftrightarrow r_3,\quad c_1+2c_3,\quad (-1)r_3,\quad (-1)c_3$$

therefore $\boldsymbol{A}=\boldsymbol{P}_3\boldsymbol{P}_1\boldsymbol{I}\boldsymbol{P}_2\boldsymbol{P}_4=\boldsymbol{P}_3\boldsymbol{P}_1\boldsymbol{P}_2\boldsymbol{P}_4,$

where

$$\boldsymbol{P}_1=\begin{pmatrix}1&0&0\\0&0&1\\0&1&0\end{pmatrix},\quad \boldsymbol{P}_2=\begin{pmatrix}1&0&0\\0&1&0\\2&0&1\end{pmatrix},\quad \boldsymbol{P}_3=\begin{pmatrix}1&0&0\\0&1&0\\0&0&-1\end{pmatrix},\quad \boldsymbol{P}_4=\begin{pmatrix}1&0&0\\0&1&0\\0&0&-1\end{pmatrix}.$$

Example 5 Use ERO to find the inverse of $\boldsymbol{A}=\begin{bmatrix}0 & 2 & -1\\ 1 & 1 & 2\\ -1 & -1 & -1\end{bmatrix}$.

Solution

$$[\boldsymbol{A},\boldsymbol{I}]=\left[\begin{array}{ccc:ccc}0 & 2 & -1 & 1 & 0 & 0\\ 1 & 1 & 2 & 0 & 1 & 0\\ -1 & -1 & -1 & 0 & 0 & 1\end{array}\right]\xrightarrow{r1\leftrightarrow r2}\left[\begin{array}{ccc:ccc}1 & 1 & 2 & 0 & 1 & 0\\ 0 & 2 & -1 & 1 & 0 & 0\\ -1 & -1 & -1 & 0 & 0 & 1\end{array}\right]$$

$$\xrightarrow{r3+r1}\left[\begin{array}{ccc:ccc}1 & 1 & 2 & 0 & 1 & 0\\ 0 & 2 & -1 & 1 & 0 & 0\\ 0 & 0 & 1 & 0 & 1 & 1\end{array}\right]\xrightarrow[r2+r3]{r1+r3\times(-2)}\left[\begin{array}{ccc:ccc}1 & 1 & 0 & 0 & -1 & -2\\ 0 & 2 & 0 & 1 & 1 & 1\\ 0 & 0 & 1 & 0 & 1 & 1\end{array}\right]$$

$$\xrightarrow[r1+r2\times(-1)]{r2\times\frac{1}{2}}\left[\begin{array}{ccc:ccc}1 & 0 & 0 & -\frac{1}{2} & -\frac{3}{2} & -\frac{5}{2}\\ 0 & 1 & 0 & \frac{1}{2} & \frac{1}{2} & \frac{1}{2}\\ 0 & 0 & 1 & 0 & 1 & 1\end{array}\right]\qquad \boldsymbol{A}^{-1}=\begin{bmatrix}-\frac{1}{2} & -\frac{3}{2} & -\frac{5}{2}\\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2}\\ 0 & 1 & 1\end{bmatrix}.$$

Remark: 1. *Can we use* ***elementary column operations*** *on* ***A*** *to find its inverse?*

也可以对 $\begin{bmatrix} A \\ I \end{bmatrix}$ 施行初等列变换，当 A 变成单位矩阵时，I 被化为了 A^{-1}.

Remark: 2. *Can we use elementary operations to solve system of linear equations?*

初等行变换求逆矩阵的方法，还可用于求矩阵 $A^{-1}b$.

$$A^{-1}[A \quad b] = [I \quad A^{-1}b]$$

$$\begin{matrix} [A & b] \\ \downarrow & \downarrow \\ I & A^{-1}b \end{matrix} \quad \text{初等行变换}$$

Example 6 Find the matrix $\boldsymbol{X}$, such that $\boldsymbol{AX} = \boldsymbol{B}$, where

$$\boldsymbol{A} = \begin{bmatrix} 1 & 2 & 3 \\ 2 & 2 & 1 \\ 3 & 4 & 3 \end{bmatrix}, \quad \boldsymbol{B} = \begin{bmatrix} 2 & 5 \\ 3 & 1 \\ 4 & 3 \end{bmatrix}.$$

Solution If $\boldsymbol{A}$ is invertible, then $\boldsymbol{X} = \boldsymbol{A}^{-1}\boldsymbol{B}$.

$$[\boldsymbol{A} \;\; \boldsymbol{B}] = \left[\begin{array}{ccc|cc} 1 & 2 & 3 & 2 & 5 \\ 2 & 2 & 1 & 3 & 1 \\ 3 & 4 & 3 & 4 & 3 \end{array}\right] \to \begin{bmatrix} 1 & 2 & 3 & 2 & 5 \\ 0 & -2 & -5 & -1 & -9 \\ 0 & -2 & -6 & -2 & -12 \end{bmatrix}$$

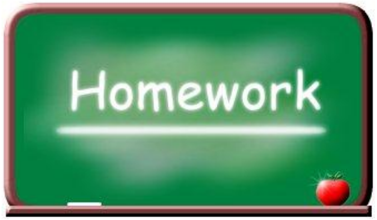
$$\rightarrow \begin{bmatrix} 1 & 2 & 3 & 2 & 5 \\ 0 & -2 & -5 & -1 & -9 \\ 0 & -2 & -6 & -2 & -12 \end{bmatrix} \rightarrow \begin{bmatrix} 1 & 0 & -2 & 1 & -4 \\ 0 & -2 & -5 & -1 & -9 \\ 0 & 0 & -1 & -1 & -3 \end{bmatrix}$$

$$\rightarrow \begin{bmatrix} 1 & 0 & 0 & 3 & 2 \\ 0 & -2 & 0 & 4 & 6 \\ 0 & 0 & -1 & -1 & -3 \end{bmatrix} \rightarrow \left[\begin{array}{ccc|cc} 1 & 0 & 0 & 3 & 2 \\ 0 & 1 & 0 & -2 & -3 \\ 0 & 0 & 1 & 1 & 3 \end{array}\right],$$

$$\boldsymbol{X} = \boldsymbol{A}^{-1}\boldsymbol{B} = \begin{bmatrix} 3 & 2 \\ -2 & -3 \\ 1 & 3 \end{bmatrix}.$$

What if -- we want to solve *XA*=*B* for *X* ?

Homework



- See Blackboard announcement
- ***Hardcover* textbook + Supplementary problems**

Deadline (DDL):

- Next tutorial class