

4. Matrix inverses

- left and right inverse
- linear independence
- nonsingular matrices
- matrices with linearly independent columns
- matrices with linearly independent rows

Left and right inverse

$AB \neq BA$ in general, so we have to distinguish two types of inverses

Left inverse: X is a *left inverse* of A if

$$XA = I$$

A is *left invertible* if it has at least one left inverse

Right inverse: X is a *right inverse* of A if

$$AX = I$$

A is *right invertible* if it has at least one right inverse

Examples

$$A = \begin{bmatrix} -3 & -4 \\ 4 & 6 \\ 1 & 1 \end{bmatrix}, \quad B = \begin{bmatrix} 1 & 0 & 1 \\ 0 & 1 & 1 \end{bmatrix}$$

- A is left invertible; the following matrices are left inverses:

$$\frac{1}{9} \begin{bmatrix} -11 & -10 & 16 \\ 7 & 8 & -11 \end{bmatrix}, \quad \begin{bmatrix} 0 & -1/2 & 3 \\ 0 & 1/2 & -2 \end{bmatrix}$$

- B is right invertible; the following matrices are right inverses:

$$\frac{1}{2} \begin{bmatrix} 1 & -1 \\ -1 & 1 \\ 1 & 1 \end{bmatrix}, \quad \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \end{bmatrix}, \quad \begin{bmatrix} 1 & -1 \\ 0 & 0 \\ 0 & 1 \end{bmatrix}$$

Some immediate properties

Dimensions

a left or right inverse of an $m \times n$ matrix must have size $n \times m$

Left and right inverse of (conjugate) transpose

- X is a left inverse of A if and only if X^T is a right inverse of A^T

$$A^T X^T = (XA)^T = I$$

- X is a left inverse of A if and only if X^H is a right inverse of A^H

$$A^H X^H = (XA)^H = I$$

Inverse

if A has a left **and** a right inverse, then they are equal and unique:

$$XA = I, \quad AY = I \quad \implies \quad X = X(AY) = (XA)Y = Y$$

- we call $X = Y$ the **inverse** of A (notation: A^{-1})
- A is *invertible* if its inverse exists

Example

$$A = \begin{bmatrix} -1 & 1 & -3 \\ 1 & -1 & 1 \\ 2 & 2 & 2 \end{bmatrix}, \quad A^{-1} = \frac{1}{4} \begin{bmatrix} 2 & 4 & 1 \\ 0 & -2 & 1 \\ -2 & -2 & 0 \end{bmatrix}$$

Linear equations

set of m linear equations in n variables

$$\begin{aligned}A_{11}x_1 + A_{12}x_2 + \cdots + A_{1n}x_n &= b_1 \\A_{21}x_1 + A_{22}x_2 + \cdots + A_{2n}x_n &= b_2 \\&\vdots \\A_{m1}x_1 + A_{m2}x_2 + \cdots + A_{mn}x_n &= b_m\end{aligned}$$

- in matrix form: $Ax = b$
- may have no solution, a unique solution, infinitely many solutions

Linear equations and matrix inverse

Left invertible matrix: if X is a left inverse of A , then

$$Ax = b \quad \implies \quad x = XAx = Xb$$

there is *at most one* solution (if there is a solution, it must be equal to Xb)

Right invertible matrix: if X is a right inverse of A , then

$$x = Xb \quad \implies \quad Ax = AXb = b$$

there is *at least one* solution (namely, $x = Xb$)

Invertible matrix: if A is invertible, then

$$Ax = b \quad \iff \quad x = A^{-1}b$$

there is a *unique* solution

Outline

- left and right inverse
- **linear independence**
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Linear combination

a linear combination of vectors a_1, \dots, a_n is a sum of scalar-vector products

$$x_1 a_1 + x_2 a_2 + \cdots + x_n a_n$$

- the scalars x_i are the *coefficients* of the linear combination
- can be written as a matrix-vector product

$$x_1 a_1 + x_2 a_2 + \cdots + x_n a_n = \begin{bmatrix} a_1 & a_2 & \cdots & a_n \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix}$$

- the *trivial* linear combination has coefficients $x_1 = \cdots = x_n = 0$

(same definition holds for real and complex vectors/scalars)

Linear dependence

a collection of vectors a_1, a_2, \dots, a_n is *linearly dependent* if

$$x_1 a_1 + x_2 a_2 + \dots + x_n a_n = 0$$

for some scalars x_1, \dots, x_n , not all zero

- vector 0 can be written as a nontrivial linear combination of a_1, \dots, a_n
- equivalently, at least one vector a_i is a linear combination of the rest:

$$a_i = -\frac{x_1}{x_i} a_1 - \dots - \frac{x_{i-1}}{x_i} a_{i-1} - \frac{x_{i+1}}{x_i} a_{i+1} - \dots - \frac{x_n}{x_i} a_n$$

if $x_i \neq 0$

Example

the vectors

$$a_1 = \begin{bmatrix} 0.2 \\ -7 \\ 8.6 \end{bmatrix}, \quad a_2 = \begin{bmatrix} -0.1 \\ 2 \\ -1 \end{bmatrix}, \quad a_3 = \begin{bmatrix} 0 \\ -1 \\ 2.2 \end{bmatrix}$$

are linearly dependent

- 0 can be expressed as a nontrivial linear combination of a_1, a_2, a_3 :

$$0 = a_1 + 2a_2 - 3a_3$$

- a_1 can be expressed as a linear combination of a_2, a_3 :

$$a_1 = -2a_2 + 3a_3$$

(and similarly a_2 and a_3)

Linear independence

vectors a_1, \dots, a_n are *linearly independent* if they are not linearly dependent

- the zero vector cannot be written as a nontrivial linear combination:

$$x_1 a_1 + x_2 a_2 + \cdots + x_n a_n = 0 \quad \implies \quad x_1 = x_2 = \cdots = x_n = 0$$

- none of the vectors a_i is a linear combination of the other vectors

Matrix with linearly independent columns

$$A = \begin{bmatrix} a_1 & a_2 & \cdots & a_n \end{bmatrix}$$

has linearly independent columns if $Ax = 0$ only for $x = 0$

Example

the vectors

$$a_1 = \begin{bmatrix} 1 \\ -2 \\ 0 \end{bmatrix}, \quad a_2 = \begin{bmatrix} -1 \\ 0 \\ 1 \end{bmatrix}, \quad a_3 = \begin{bmatrix} 0 \\ 1 \\ 1 \end{bmatrix}$$

are linearly independent:

$$x_1 a_1 + x_2 a_2 + x_3 a_3 = \begin{bmatrix} x_1 - x_2 \\ -2x_1 + x_3 \\ x_2 + x_3 \end{bmatrix} = 0$$

only if $x_1 = x_2 = x_3 = 0$

Dimension inequality

if n vectors a_1, a_2, \dots, a_n of length m are linearly independent, then

$$n \leq m$$

(proof is in textbook)

- if an $m \times n$ matrix has linearly independent columns then $m \geq n$
- if an $m \times n$ matrix has linearly independent rows then $m \leq n$

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- **nonsingular matrices**
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Nonsingular matrix

for a **square** matrix A the following four properties are equivalent

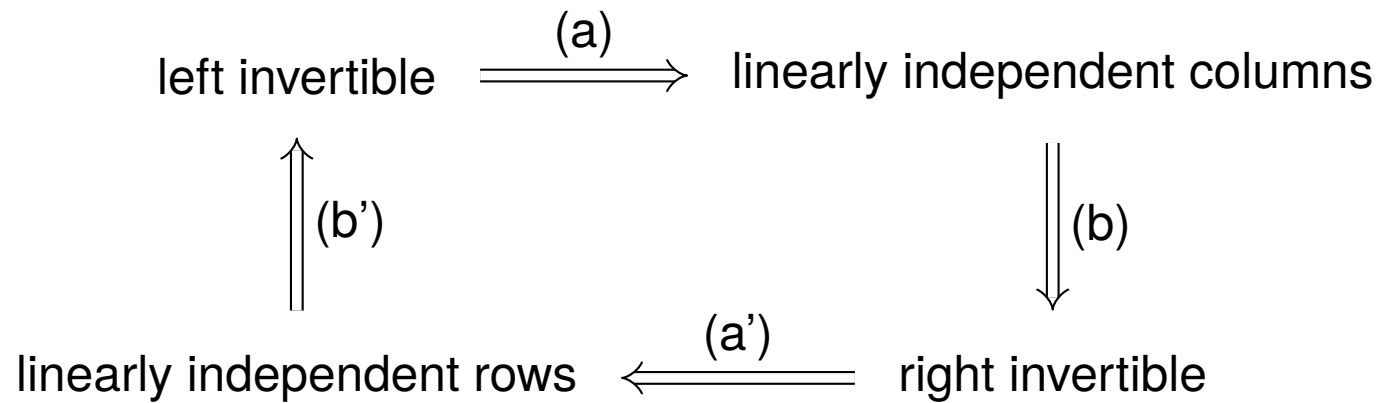
1. A is left invertible
2. the columns of A are linearly independent
3. A is right invertible
4. the rows of A are linearly independent

a square matrix with these properties is called **nonsingular**

Nonsingular = invertible

- if properties 1 and 3 hold, then A is invertible (page 4-5)
- if A is invertible, properties 1 and 3 hold (by definition of invertibility)

Proof



- we show that (a) holds in general
- we show that (b) holds for square matrices
- (a') and (b') follow from (a) and (b) applied to A^T

Part a: suppose A is left invertible

- if B is a left inverse of A (satisfies $BA = I$), then

$$\begin{aligned} Ax = 0 &\implies BAx = 0 \\ &\implies x = 0 \end{aligned}$$

- this means that the columns of A are linearly independent: if

$$A = \begin{bmatrix} a_1 & a_2 & \cdots & a_n \end{bmatrix}$$

then

$$x_1 a_1 + x_2 a_2 + \cdots + x_n a_n = 0$$

holds only for the trivial linear combination $x_1 = x_2 = \cdots = x_n = 0$

Part b: suppose A is square with linearly independent columns a_1, \dots, a_n

- for every n -vector b the vectors a_1, \dots, a_n, b are linearly dependent
(from dimension inequality on page 4-13)
- hence for every b there exists a nontrivial linear combination

$$x_1 a_1 + x_2 a_2 + \cdots + x_n a_n + x_{n+1} b = 0$$

we must have $x_{n+1} \neq 0$ because a_1, \dots, a_n are linearly independent

- hence every b can be written as a linear combination of a_1, \dots, a_n
- in particular, there exist n -vectors c_1, \dots, c_n such that

$$Ac_1 = e_1, \quad Ac_2 = e_2, \quad \dots, \quad Ac_n = e_n,$$

- the matrix $C = \begin{bmatrix} c_1 & c_2 & \cdots & c_n \end{bmatrix}$ is a right inverse of A :

$$A \begin{bmatrix} c_1 & c_2 & \cdots & c_n \end{bmatrix} = \begin{bmatrix} e_1 & e_2 & \cdots & e_n \end{bmatrix} = I$$

Examples

$$A = \begin{bmatrix} 1 & -1 & 1 \\ -1 & 1 & 1 \\ 1 & 1 & -1 \end{bmatrix}, \quad B = \begin{bmatrix} 1 & -1 & 1 & -1 \\ -1 & 1 & -1 & 1 \\ 1 & 1 & -1 & -1 \\ -1 & -1 & 1 & 1 \end{bmatrix}$$

- A is nonsingular because its columns are linearly independent:

$$x_1 - x_2 + x_3 = 0, \quad -x_1 + x_2 + x_3 = 0, \quad x_1 + x_2 - x_3 = 0$$

is only possible if $x_1 = x_2 = x_3 = 0$

- B is singular because its columns are linearly dependent:

$$Bx = 0 \quad \text{for } x = (1, 1, 1, 1)$$

Example: Vandermonde matrix

$$A = \begin{bmatrix} 1 & t_1 & t_1^2 & \cdots & t_1^{n-1} \\ 1 & t_2 & t_2^2 & \cdots & t_2^{n-1} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & t_n & t_n^2 & \cdots & t_n^{n-1} \end{bmatrix} \quad \text{with } t_i \neq t_j \text{ for } i \neq j$$

we show that A is nonsingular by showing that $Ax = 0$ only if $x = 0$

- $Ax = 0$ means $p(t_1) = p(t_2) = \cdots = p(t_n) = 0$ where

$$p(t) = x_1 + x_2t + x_3t^2 + \cdots + x_nt^{n-1}$$

$p(t)$ is a polynomial of degree $n - 1$ or less

- if $x \neq 0$, then $p(t)$ can not have more than $n - 1$ distinct real roots
- therefore $p(t_1) = \cdots = p(t_n) = 0$ is only possible if $x = 0$

Inverse of transpose and product

Transpose and conjugate transpose

if A is nonsingular, then A^T and A^H are nonsingular and

$$(A^T)^{-1} = (A^{-1})^T, \quad (A^H)^{-1} = (A^{-1})^H,$$

we write these as A^{-T} and A^{-H}

Product

if A and B are nonsingular and of equal size, then AB is nonsingular with

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

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Gram matrix

the *Gram matrix* associated with a matrix

$$A = \begin{bmatrix} a_1 & a_2 & \cdots & a_n \end{bmatrix}$$

is the matrix of column inner products

- for real matrices:

$$A^T A = \begin{bmatrix} a_1^T a_1 & a_1^T a_2 & \cdots & a_1^T a_n \\ a_2^T a_1 & a_2^T a_2 & \cdots & a_2^T a_n \\ \vdots & \vdots & & \vdots \\ a_n^T a_1 & a_n^T a_2 & \cdots & a_n^T a_n \end{bmatrix}$$

- for complex matrices

$$A^H A = \begin{bmatrix} a_1^H a_1 & a_1^H a_2 & \cdots & a_1^H a_n \\ a_2^H a_1 & a_2^H a_2 & \cdots & a_2^H a_n \\ \vdots & \vdots & & \vdots \\ a_n^H a_1 & a_n^H a_2 & \cdots & a_n^H a_n \end{bmatrix}$$

Nonsingular Gram matrix

the Gram matrix is nonsingular if only if A has linearly independent columns

- suppose $A \in \mathbf{R}^{m \times n}$ has linearly independent columns:

$$\begin{aligned} A^T A x = 0 &\implies x^T A^T A x = (Ax)^T (Ax) = \|Ax\|^2 = 0 \\ &\implies Ax = 0 \\ &\implies x = 0 \end{aligned}$$

therefore $A^T A$ is nonsingular

- suppose the columns of $A \in \mathbf{R}^{m \times n}$ are linearly dependent

$$\exists x \neq 0, Ax = 0 \implies \exists x \neq 0, A^T A x = 0$$

therefore $A^T A$ is singular

(for $A \in \mathbf{C}^{m \times n}$, replace A^T with A^H and x^T with x^H)

Pseudo-inverse

- suppose $A \in \mathbf{R}^{m \times n}$ has linearly independent columns
- this implies that A is tall or square ($m \geq n$); see page 4-13

the *pseudo-inverse* of A is defined as

$$A^\dagger = (A^T A)^{-1} A^T$$

- this matrix exists, because the Gram matrix $A^T A$ is nonsingular
- A^\dagger is a left inverse of A :

$$A^\dagger A = (A^T A)^{-1} (A^T A) = I$$

(for complex A with linearly independent columns, $A^\dagger = (A^H A)^{-1} A^H$)

Summary

the following three properties are equivalent

1. A is left invertible
2. the columns of A are linearly independent
3. $A^T A$ is nonsingular

- $1 \Rightarrow 2$ was already proved on page 4-16
- $2 \Rightarrow 1$: we have seen that the pseudo-inverse is a left inverse
- $2 \Leftrightarrow 3$: proved on page 4-22
- a matrix with these properties must be tall or square

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Pseudo-inverse

- suppose $A \in \mathbf{R}^{m \times n}$ has linearly independent rows
- this implies that A is wide or square ($m \leq n$); see page 4-13

the *pseudo-inverse* of A is defined as

$$A^\dagger = A^T(AA^T)^{-1}$$

- A^T has linearly independent columns
- hence its Gram matrix AA^T is nonsingular, so A^\dagger exists
- A^\dagger is a right inverse of A :

$$AA^\dagger = (AA^T)(AA^T)^{-1} = I$$

(for complex A with linearly independent rows, $A^\dagger = A^H(AA^H)^{-1}$)

Summary

the following three properties are equivalent

1. A is right invertible
 2. the rows of A are linearly independent
 3. AA^T is nonsingular
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- $1 \Rightarrow 2$ and $2 \Leftrightarrow 3$: by transposing result on page 4-24
 - $2 \Rightarrow 1$: we have seen that the pseudo-inverse is a right inverse
 - a matrix with these properties must be wide or square