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:

\[ \frac{1}{2} \begin{bmatrix} 1 & -1 \\ -1 & 1 \\ 1 & 1 \end{bmatrix}, \quad \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \quad \begin{bmatrix} 1 & -1 \\ 0 & 0 \\ 0 & 1 \end{bmatrix} \]
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:

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

- in this case, 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

\[ A_{11}x_1 + A_{12}x_2 + \cdots + A_{1n}x_n = b_1 \]
\[ A_{21}x_1 + A_{22}x_2 + \cdots + A_{2n}x_n = b_2 \]
\[ \vdots \]
\[ A_{m1}x_1 + A_{m2}x_2 + \cdots + A_{mn}x_n = b_m \]

- 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

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

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

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

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

**Invertible matrix:** if $A$ is invertible, then

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

there is a *unique* solution
Outline

• left and right inverse

• **linear independence**

• nonsingular matrices

• matrices with linearly independent columns

• matrices with linearly independent rows
Linear combination

A linear combination of vectors $a_1, \ldots, a_n$ 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 $a_1, a_2, \ldots, a_n$ is linearly dependent if

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

for some scalars $x_1, \ldots, x_n$, not all zero.

• The vector 0 can be written as a nontrivial linear combination of $a_1, \ldots, a_n$.

• Equivalently, at least one vector $a_i$ is a linear combination of the other vectors:

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

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 \( a_2, a_3 \):

\[ a_1 = -2a_1 + 3a_3 \]

(and similarly \( a_2 \) and \( a_3 \))
Linear independence

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

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

  $$x_1a_1 + x_2a_2 + \cdots + x_na_n = 0 \implies x_1 = x_2 = \cdots = x_n = 0$$

- 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

$$Ax = 0 \implies x = 0$$
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:

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

holds only if \( x_1 = x_2 = x_3 = 0 \)
Dimension inequality

if $n$ vectors $a_1, a_2, \ldots, a_n$ 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 $m \leq n$
Outline

• left and right inverse

• linear independence

• **nonsingular matrices**

• matrices with linearly independent columns

• matrices with linearly independent rows
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

left-invertible $\rightarrow$ (a) linearly independent columns

(b')

linearly independent rows $\leftarrow$ (a') right-invertible

- 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

\[ Ax = 0 \implies BAx = 0 \implies x = 0 \]

- 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 $a_1, \ldots, a_n$

- for every $n$-vector $b$ the vectors $a_1, \ldots, a_n, b$ are linearly dependent
  (from dimension inequality on page 4.13)

- hence for every $b$ there exists a nontrivial linear combination
  
  \[ x_1a_1 + x_2a_2 + \cdots + x_na_n + x_{n+1}b = 0 \]

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

- hence every $b$ can be written as a linear combination of $a_1, \ldots, a_n$

- in particular, there exist $n$-vectors $c_1, \ldots, c_n$ such that
  
  \[ Ac_1 = e_1, \quad Ac_2 = e_2, \quad \ldots, \quad Ac_n = e_n, \]

- 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:

  \[ Bx = 0 \quad \text{for} \quad x = (1, 1, 1, 1) \]
Example: Vandermonde matrix

$$A = \begin{bmatrix} 1 & t_1 & t_1^2 & \cdots & t_1^{n-1} \\ 1 & t_2 & t_2^2 & \cdots & t_2^{n-1} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & t_n & t_n^2 & \cdots & t_n^{n-1} \end{bmatrix}$$

with $t_i \neq t_j$ 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

$$p(t) = x_1 + x_2 t + x_3 t^2 + \cdots + x_n t^{n-1}$$

$p(t)$ 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:

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

- for complex matrices

\[
A^H A = \begin{bmatrix}
    a_1^H a_1 & a_1^H a_2 & \cdots & a_1^H a_n \\
    a_2^H a_1 & a_2^H a_2 & \cdots & a_2^H a_n \\
    \vdots & \vdots & \ddots & \vdots \\
    a_n^H a_1 & a_n^H a_2 & \cdots & a_n^H a_n
\end{bmatrix}
\]
Nonsingular Gram matrix

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

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

  \[ A^T A x = 0 \implies x^T A^T A x = (Ax)^T (Ax) = \|Ax\|^2 = 0 \]
  \[ \implies Ax = 0 \]
  \[ \implies x = 0 \]

  therefore $A^T A$ is nonsingular

- suppose the columns of $A \in \mathbb{R}^{m \times n}$ 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 $A \in \mathbb{C}^{m \times n}$, replace $A^T$ with $A^H$ and $x^T$ with $x^H$)
Pseudo-inverse

- suppose $A \in \mathbb{R}^{m \times n}$ 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 for a real matrix $A$

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
• for complex matrices, replace $A^T A$ in property 3 by $A^H A$
Outline

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Pseudo-inverse

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

- $1 \implies 2$ and $2 \iff 3$: by transposing result on page 4.24
- $2 \implies 1$: we have seen that the pseudo-inverse is a right inverse
- a matrix with these properties must be wide or square
- for complex matrices, replace $AA^T$ in property 3 by $AA^H$