Mathematics for Machine Learning
— Linear Algebra: Eigenvalues, Eigenvectors, Eigenspaces, Cholesky Decomposition & Diagonalization

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Credits for the resource

- The slides are based on the textbooks:

  - *Marc Peter Deisenroth, A. Aldo Faisal, and Cheng Soon Ong: Mathematics for Machine Learning. Cambridge University Press. 2020.*
  - *Howard Anton, Chris Rorres, Anton Kaul: Elementary Linear Algebra. Wiley. 2019.*

- We could partially refer to the monograph:
  Francesco Orabona: A Modern Introduction to Online Learning. https://arxiv.org/abs/1912.13213

- Matrix decomposition or matrix factorization.

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- Three matrix decompositions will be introduced.

Outline

1. Eigenvalues & Eigenvectors

2. Cholesky Decomposition

3. Eigendecomposition & Diagonalization

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1. **Eigenvalues & Eigenvectors**

2. Cholesky Decomposition

3. Eigendecomposition & Diagonalization

Characteristic Polynomial

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For $\lambda \in \mathbb{R}$ and a square matrix $\boldsymbol{A} \in \mathbb{R}^{n \times n}$,

$$
\begin{aligned}
p_{\boldsymbol{A}}(\lambda) & := \det(\boldsymbol{A} - \lambda \boldsymbol{I}) \\
& = (-1)^n (\lambda - \lambda_1) \cdots (\lambda - \lambda_n) \\
& = c_0 + c_1 \lambda + \cdots + c_{n-1} \lambda^{n-1} + (-1)^n \lambda^n,
\end{aligned}
$$

for $c_0, \ldots, c_{n-1} \in \mathbb{R}$, is called the characteristic polynomial of $\boldsymbol{A}$.

Note that

- $c_0 = \det(\boldsymbol{A})$

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- $c_{n-1} = (-1)^{n-1} \text{tr}(\boldsymbol{A})$

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back

Example

Given $\boldsymbol{A} = \begin{bmatrix} 3 & 0 \\ 8 & -1 \end{bmatrix}$,

$$\det(\boldsymbol{A} - \lambda\boldsymbol{I}) = \begin{vmatrix} 3 - \lambda & 0 \\ 8 & -1 - \lambda \end{vmatrix} = (3 - \lambda)(-1 - \lambda).$$

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Given $\boldsymbol{B} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 4 & -17 & 8 \end{bmatrix}$,

$$\det(\boldsymbol{B} - \lambda \boldsymbol{I}) = \begin{vmatrix} -\lambda & 1 & 0 \\ 0 & -\lambda & 1 \\ 4 & -17 & 8 - \lambda \end{vmatrix} = -\lambda^3 + 8\lambda^2 - 17\lambda + 4.$$

Eigenvalue Equation

Eigenvalues & Eigenvectors

Let $\boldsymbol{A} \in \mathbb{R}^{n \times n}$ be a square matrix. Then

- $\lambda \in \mathbb{R}$ is an eigenvalue of $\boldsymbol{A}$ and
- $\mathbf{x} \in \mathbb{R}^n \setminus \{\mathbf{0}\}$ is the corresponding eigenvector of A

if $\boldsymbol{A}\mathbf{x} = \lambda\mathbf{x}$.

$$\boldsymbol{A}\mathbf{x} = \lambda\mathbf{x} \iff (\boldsymbol{A} - \lambda\boldsymbol{I})\mathbf{x} = \mathbf{0}$$

Equivalent statements:

- λ is an eigenvalue of $\boldsymbol{A} \in \mathbb{R}^{n \times n}$.

- There exists an $\mathbf{x} \in \mathbb{R}^n \setminus \{\mathbf{0}\}$ with $\boldsymbol{A}\mathbf{x} = \lambda\mathbf{x}$ (i.e., $(\boldsymbol{A} - \lambda\boldsymbol{I}_n)\mathbf{x} = \mathbf{0}$) that can be solved non-trivially (i.e., $\mathbf{x} \neq \mathbf{0}$).

- $\text{rank}(\boldsymbol{A} - \lambda\boldsymbol{I}_n) < n$.

- $\det(\boldsymbol{A} - \lambda\boldsymbol{I}_n) = 0$.

Remark

- Eigenvectors are NOT unique.

Remark

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- Suppose $\mathbf{x}$ is an eigenvector of $\boldsymbol{A}$ w.r.t. eigenvalue λ, then for any $c \in \mathbb{R} \setminus \mathbf{0}\}$
$$\boldsymbol{A}(c\mathbf{x}) = c\boldsymbol{A}\mathbf{x} = c\lambda\mathbf{x} = \lambda(c\mathbf{x}).$$

Theorems (or Definitions)

Theorem

$\lambda \in \mathbb{R}$ is an eigenvalue of $\boldsymbol{A} \in \mathbb{R}^{n \times n}$ if and only if λ is a root of the characteristic polynomial $p_{\boldsymbol{A}}(\lambda)$ of $\boldsymbol{A}$.

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Algebraic Multiplicity

Suppose that matrix $\boldsymbol{A} \in \mathbb{R}^{n \times n}$ has an eigenvalue λ_i. The algebraic multiplicity of λ_i is the number of times the root appears in the characteristic polynomial.

- Denoted by $\text{am}(\lambda_i)$

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Theorems (or Definitions)

Eigenspace

For $\boldsymbol{A} \in \mathbb{R}^{n \times n}$, the set of all eigenvectors of $\boldsymbol{A}$ associated with the eigenvalue λ spans the eigenspace of $\boldsymbol{A}$ (denoted by E_λ).

Geometric Multiplicity

$\dim(E_\lambda)$ is called the geometric multiplicity of λ.

- Denoted by $\text{gm}(\lambda)$.

Eigenspectrum (Spectrum)

The set of all eigenvalues of $\boldsymbol{A}$ is called the eigenspectrum (or spectrum) of $\boldsymbol{A}$.

Relation b/w am(λ) & gm(λ)

Geometric multiplicity $\leq$ Algebraic multiplicity

Given $\boldsymbol{A} \in \mathbb{R}^{n \times n}$ and assume that λ is a eigenvalue of $\boldsymbol{A}$, then

$$\text{gm}(\lambda) \leq \text{am}(\lambda).$$

- Assume that $\dim(E_\lambda) = k \leq n$ and let $\{\boldsymbol{v}_1, \ldots, \boldsymbol{v}_k\}$ is a basis of E_λ such that $\boldsymbol{v}_1, \ldots, \boldsymbol{v}_k$ are eigenvectors w.r.t. λ.

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- $\exists \boldsymbol{v}_{k+1}, \ldots, \boldsymbol{v}_n$ such that $\{\boldsymbol{v}_1, \ldots, \boldsymbol{v}_n\}$ is a basis of $\mathbb{R}^n$.

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- $\exists \mathbf{v}_{k+1}, \ldots, \mathbf{v}_n$ such that $\{\mathbf{v}_1, \ldots, \mathbf{v}_n\}$ is a basis of $\mathbb{R}^n$.

- Denote by $\boldsymbol{P} = [\boldsymbol{U} \ \boldsymbol{V}]$ for $\boldsymbol{U} = [\mathbf{v}_1 \cdots \mathbf{v}_k]$ and $\boldsymbol{V} = [\mathbf{v}_{k+1} \cdots \mathbf{v}_n]$ (note: $\boldsymbol{P}$ is invertible).

Relation b/w am(λ) & gm(λ) (contd.)

- $\because$ $\boldsymbol{P}$ is invertible $\Rightarrow$ Let $\boldsymbol{P}^{-1} = \begin{bmatrix} \boldsymbol{X} \\ \boldsymbol{Y} \end{bmatrix}$, where $\boldsymbol{X} \in \mathbb{R}^{k \times n}$ and
  $\boldsymbol{Y} \in \mathbb{R}^{(n-k) \times n}$.

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- Then,

$$\begin{bmatrix} \boldsymbol{I}_k & \boldsymbol{O} \\ \boldsymbol{O} & \boldsymbol{I}_{n-k} \end{bmatrix} = \boldsymbol{P}^{-1}\boldsymbol{P} = \begin{bmatrix} \boldsymbol{X} \\ \boldsymbol{Y} \end{bmatrix} [\boldsymbol{U} \ \ \boldsymbol{V}] = \begin{bmatrix} \boldsymbol{XU} & \boldsymbol{XV} \\ \boldsymbol{YU} & \boldsymbol{YV} \end{bmatrix}$$

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- Then,

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- Note that $\boldsymbol{A}\boldsymbol{U} = \boldsymbol{A}[\mathbf{v}_1 \cdots \mathbf{v}_k] = [\boldsymbol{A}\mathbf{v}_1 \cdots \boldsymbol{A}\mathbf{v}_k] = [\lambda\mathbf{v}_1 \cdots \lambda\mathbf{v}_k] = \lambda\boldsymbol{U}$.

Relation b/w am(λ) & gm(λ) (contd.)

$$P^{-1}AP = \left[\begin{array}{c} X \\ Y \end{array}\right] A[U \; V] = \left[\begin{array}{cc} XAU & XAV \\ YAU & YAV \end{array}\right]$$

Relation b/w am(λ) & gm(λ) (contd.)

$$
\begin{aligned}
\boldsymbol{P}^{-1}\boldsymbol{AP} &= \left[\begin{array}{c} \boldsymbol{X} \\ \boldsymbol{Y} \end{array}\right] \boldsymbol{A}[\boldsymbol{U}\ \ \boldsymbol{V}] = \left[\begin{array}{cc} \boldsymbol{XAU} & \boldsymbol{XAV} \\ \boldsymbol{YAU} & \boldsymbol{YAV} \end{array}\right] \\
&= \left[\begin{array}{cc} \lambda\boldsymbol{XU} & \boldsymbol{XAV} \\ \lambda\boldsymbol{YU} & \boldsymbol{YAV} \end{array}\right] = \left[\begin{array}{cc} \lambda\boldsymbol{I}_k & \boldsymbol{XAV} \\ \boldsymbol{O} & \boldsymbol{YAV} \end{array}\right]
\end{aligned}
$$

Relation b/w am(λ) & gm(λ) (contd.)

$$
\begin{aligned}
\boldsymbol{P}^{-1}\boldsymbol{A}\boldsymbol{P} &= \left[\begin{array}{c} \boldsymbol{X} \\ \boldsymbol{Y} \end{array}\right] \boldsymbol{A}[\boldsymbol{U}\ \boldsymbol{V}] = \left[\begin{array}{cc} \boldsymbol{X}\boldsymbol{A}\boldsymbol{U} & \boldsymbol{X}\boldsymbol{A}\boldsymbol{V} \\ \boldsymbol{Y}\boldsymbol{A}\boldsymbol{U} & \boldsymbol{Y}\boldsymbol{A}\boldsymbol{V} \end{array}\right] \\
&= \left[\begin{array}{cc} \lambda\boldsymbol{X}\boldsymbol{U} & \boldsymbol{X}\boldsymbol{A}\boldsymbol{V} \\ \lambda\boldsymbol{Y}\boldsymbol{U} & \boldsymbol{Y}\boldsymbol{A}\boldsymbol{V} \end{array}\right] = \left[\begin{array}{cc} \lambda\boldsymbol{I}_k & \boldsymbol{X}\boldsymbol{A}\boldsymbol{V} \\ \boldsymbol{O} & \boldsymbol{Y}\boldsymbol{A}\boldsymbol{V} \end{array}\right]
\end{aligned}
$$

$$
\det(\boldsymbol{P}^{-1}\boldsymbol{A}\boldsymbol{P} - z\boldsymbol{I}) = \det\left[\begin{array}{cc} \lambda\boldsymbol{I}_k - z\boldsymbol{I}_k & \boldsymbol{X}\boldsymbol{A}\boldsymbol{V} \\ \boldsymbol{O} & \boldsymbol{Y}\boldsymbol{A}\boldsymbol{V} - z\boldsymbol{I}_{n-k} \end{array}\right]
$$

Relation b/w am(λ) & gm(λ) (contd.)

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\begin{aligned}
P^{-1}AP &= \begin{bmatrix} X \\ Y \end{bmatrix} A[U \ V] = \begin{bmatrix} XAU & XAV \\ YAU & YAV \end{bmatrix} \\
&= \begin{bmatrix} \lambda XU & XAV \\ \lambda YU & YAV \end{bmatrix} = \begin{bmatrix} \lambda I_k & XAV \\ O & YAV \end{bmatrix}
\end{aligned}
$$

$$
\begin{aligned}
\det(P^{-1}AP - zI) &= \det \begin{bmatrix} \lambda I_k - zI_k & XAV \\ O & YAV - zI_{n-k} \end{bmatrix} \\
&= (\lambda - z)^k \det(YAV - zI_{n-k}).
\end{aligned}
$$

- Note: $\det(A - zI) = \det(P^{-1}AP - zI)$.

Remark

$$
\begin{aligned}
\boldsymbol{P}^{-1}\boldsymbol{A}\boldsymbol{P} - z\boldsymbol{I} &= \boldsymbol{P}^{-1}\boldsymbol{A}\boldsymbol{P} - z\boldsymbol{P}^{-1}\boldsymbol{P} \\
&= \boldsymbol{P}^{-1}\boldsymbol{A}\boldsymbol{P} - \boldsymbol{P}^{-1}(z\boldsymbol{I})\boldsymbol{P} \\
&= \boldsymbol{P}^{-1}(\boldsymbol{A} - z\boldsymbol{I})\boldsymbol{P}.
\end{aligned}
$$

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Therefore,

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\det(\boldsymbol{A} - z\boldsymbol{I}) = \det(\boldsymbol{P}^{-1}\boldsymbol{A}\boldsymbol{P} - z\boldsymbol{I}).
$$

The Case of the Identity Matrix

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For $I_n \in \mathbb{R}^{n \times n}$,

- what is $p_I(\lambda)$?
- What are its eigenvalues and the associated eigenvectors?
- What are the eigenspaces?

Useful Properties (1/4)

- $\boldsymbol{A}$ and $\boldsymbol{A}^\top$ possess the same eigenvalues

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- The eigenspace E_λ is $\text{null}(A - \lambda I)$.

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\begin{aligned}
A\mathbf{x} = \lambda\mathbf{x} \quad &\Leftrightarrow \quad A\mathbf{x} - \lambda\mathbf{x} = \mathbf{0} \\
&\Leftrightarrow \quad (A - \lambda I)\mathbf{x} = \mathbf{0} \\
&\Leftrightarrow \quad \mathbf{x} \in \ker(A - \lambda I).
\end{aligned}
$$

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- Symmetric, positive definite matrices always have positive, real eigenvalues.

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- Symmetric, positive definite matrices always have positive, real eigenvalues.
  - $\mathbf{x}^\top \boldsymbol{A}\mathbf{x} = \mathbf{x}^\top \lambda\mathbf{x} = \lambda\|\mathbf{x}\|^2 > 0$.

Useful Properties (2/4)

Theorem (4.13)

The eigenvectors $\mathbf{x}_1, \ldots, \mathbf{x}_n$ of a matrix $\boldsymbol{A} \in \mathbb{R}^{n \times n}$ with n distinct eigenvalues $\lambda_1, \ldots, \lambda_n$ are linearly independent.

Theorem (4.14)

Given a matrix $\boldsymbol{A} \in \mathbb{R}^{m \times n}$, we can always obtain a symmetric, positive semidefinite matrix $\boldsymbol{S} \in \mathbb{R}^{n \times n}$ by defining

$$\boldsymbol{S} := \boldsymbol{A}^\top \boldsymbol{A}.$$

If rank($\boldsymbol{A}$) $= n$, then $S := \boldsymbol{A}^\top \boldsymbol{A}$ is symmetric, positive definite.

Useful Properties (3/4)

Theorem

If $\boldsymbol{A}$ is symmetric, then eigenvectors to different eigenvalues are orthogonal.

Proof.

- Assume that $\boldsymbol{A}\mathbf{v} = \lambda\mathbf{v}$ and $\boldsymbol{A}\mathbf{w} = \mu\mathbf{w}$ for two eigenvectors $\mathbf{v}, \mathbf{w} \in V$ corresponding to eigenvalues λ and μ such that $\lambda \neq \mu$.

- $$\begin{aligned} \lambda\langle\mathbf{v},\mathbf{w}\rangle &= \langle\lambda\mathbf{v},\mathbf{w}\rangle = \langle\boldsymbol{A}\mathbf{v},\mathbf{w}\rangle = (\boldsymbol{A}\mathbf{v})^{\top}\mathbf{w} = \mathbf{v}^{\top}\boldsymbol{A}^{\top}\mathbf{w} = \langle\mathbf{v},\boldsymbol{A}^{\top}\mathbf{w}\rangle \\ &= \langle\mathbf{v},\boldsymbol{A}\mathbf{w}\rangle = \langle\mathbf{v},\mu\mathbf{w}\rangle = \mu\langle\mathbf{v},\mathbf{w}\rangle. \end{aligned}$$

  The equalities hold only if $\langle\mathbf{v},\mathbf{w}\rangle = 0$.

$\square$

Useful Properties (4/4)

Theorem (4.15; Spectral Theorem)

If $\boldsymbol{A} \in \mathbb{R}^{n \times n}$ is symmetric, then there exists an orthonormal basis, consisting of eigenvectors of $\boldsymbol{A}$, of the corresponding vector space V, and each eigenvalue is real.

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Example

Consider

$$\boldsymbol{A} = \begin{bmatrix} 3 & 2 & 2 \\ 2 & 3 & 2 \\ 2 & 2 & 3 \end{bmatrix}$$

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$$\boldsymbol{A} = \begin{bmatrix} 3 & 2 & 2 \\ 2 & 3 & 2 \\ 2 & 2 & 3 \end{bmatrix}$$

Compute $p_{\boldsymbol{A}}(\lambda) = -(\lambda - 1)^2(\lambda - 7)$

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Example

Consider

$$\boldsymbol{A} = \begin{bmatrix} 3 & 2 & 2 \\ 2 & 3 & 2 \\ 2 & 2 & 3 \end{bmatrix}$$

Compute $p_{\boldsymbol{A}}(\lambda) = -(\lambda - 1)^2(\lambda - 7) \;\;\Rightarrow\;\; \lambda_1 = 1$ (repeated), $\lambda_2 = 7$.

- $E_1 = \text{span}(\mathbf{x}_1, \mathbf{x}_2)$, where $\mathbf{x}_1 = \begin{bmatrix} -1 \\ 1 \\ 0 \end{bmatrix}, \mathbf{x}_2 = \begin{bmatrix} -1 \\ 0 \\ 1 \end{bmatrix}$,

  $E_7 = \text{span}(\mathbf{x}_3)$, where $\mathbf{x}_3 = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix}$.

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- **Note:** Any linear combination of $\mathbf{x}_1$ and $\mathbf{x}_2$ is also an eigenvector of $\mathbf{A}$ w.r.t. λ_1.

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- **Note:** Any linear combination of $\mathbf{x}_1$ and $\mathbf{x}_2$ is also an eigenvector of $\mathbf{A}$ w.r.t. λ_1.

$$\mathbf{A}(\alpha\mathbf{x}_1 + \beta\mathbf{x}_2) = \mathbf{A}\mathbf{x}_1\alpha + \mathbf{A}\mathbf{x}_2\beta = \lambda(\alpha\mathbf{x}_1 + \beta\mathbf{x}_2).$$

- Use Gram-Schmidt algorithm to construct an orthogonal basis for $\text{span}(\mathbf{x}_1, \mathbf{x}_2)$!

Take $\mathbf{u}_1 = \mathbf{x}_1 = \begin{bmatrix} -1 \\ 1 \\ 0 \end{bmatrix}$,

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$\mathbf{u}_2 = \mathbf{x}_2 - \dfrac{\mathbf{u}_1 \mathbf{u}_1^\top}{\|\mathbf{u}_1\|^2} \mathbf{x}_2 \;\; =$

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$$
\begin{aligned}
\mathbf{u}_2 = \mathbf{x}_2 - \frac{\mathbf{u}_1 \mathbf{u}_1^\top}{\|\mathbf{u}_1\|^2} \mathbf{x}_2 &= \begin{bmatrix} -1 \\ 0 \\ 1 \end{bmatrix} - \frac{1}{2} \begin{bmatrix} 1 & -1 & 0 \\ -1 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} -1 \\ 0 \\ 1 \end{bmatrix} \\
&= -\frac{1}{2} \begin{bmatrix} 1 \\ 1 \\ -2 \end{bmatrix}.
\end{aligned}
$$

A Practical Example

- Google uses the eigenvector corresponding to the maximal eigenvalue of a matrix A to determine the rank of a page for search.
  - The PageRank algorithm was developed at Stanford University by Larry Page and Sergey Brin in 1996.

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- Websites are represented as a huge directed graph (pages: vertices; links: edges).
- Compute the weight (importance) $x_i \geq 0$ for a website a_i and get $\mathbf{x}$.
  - The number of pages pointing to a_i.
- A transition matrix $\boldsymbol{A}$ (prob.): modeling the navigation behavior of a user.
- **Goal: $\mathbf{x}$, $\boldsymbol{A}\mathbf{x}$, $\boldsymbol{A}^2\mathbf{x}$, ..., $\mathbf{x}^*$**

A Practical Example

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Outline

1. Eigenvalues & Eigenvectors

2. **Cholesky Decomposition**

3. Eigendecomposition & Diagonalization

Cholesky Decomposition

> ### Cholesky Decomposition
> A symmetric, positive definite matrix $\boldsymbol{A}$ can be factorized into a product $\boldsymbol{A} = \boldsymbol{L}\boldsymbol{L}^{\top}$, where $\boldsymbol{L}$ is a lower-triangular matrix with positive diagonal elements.

$$
\begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{bmatrix} = \begin{bmatrix} & & \\ & & \\ & & \end{bmatrix} \begin{bmatrix} & & \\ & & \\ & & \end{bmatrix}
$$

Example of Cholesky Factorization

$$\boldsymbol{A} = \left[\begin{array}{ccc} a_{11} & a_{21} & a_{31} \\ a_{21} & a_{22} & a_{32} \\ a_{31} & a_{32} & a_{33} \end{array} \right] = \boldsymbol{L}\boldsymbol{L}^{\top} = \left[\begin{array}{ccc} \ell_{11} & 0 & 0 \\ \ell_{21} & \ell_{22} & 0 \\ \ell_{31} & \ell_{32} & \ell_{33} \end{array} \right] \left[\begin{array}{ccc} \ell_{11} & \ell_{21} & \ell_{31} \\ 0 & \ell_{22} & \ell_{32} \\ 0 & 0 & \ell_{33} \end{array} \right].$$

We have

$$\boldsymbol{A} = \left[\begin{array}{ccc} \ell_{11}^2 & \ell_{21}\ell_{11} & \ell_{31}\ell_{11} \\ \ell_{21}\ell_{11} & \ell_{21}^2 + \ell_{22}^2 & \ell_{31}\ell_{21} + \ell_{32}\ell_{22} \\ \ell_{31}\ell_{11} & \ell_{31}\ell_{21} + \ell_{32}\ell_{22} & \ell_{31}^2 + \ell_{32}^2 + \ell_{33}^2 \end{array} \right]$$

Finally, solve $\ell_{11}, \ldots, \ell_{33}$.

Example Steps for Cholesky Factorization

$$\boldsymbol{A} = \begin{bmatrix} a_{11} & a_{21} & a_{31} \\ a_{21} & a_{22} & a_{32} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} = \begin{bmatrix} \ell_{11}^2 & \ell_{21}\ell_{11} & \ell_{31}\ell_{11} \\ \ell_{21}\ell_{11} & \ell_{21}^2 + \ell_{22}^2 & \ell_{31}\ell_{21} + \ell_{32}\ell_{22} \\ \ell_{31}\ell_{11} & \ell_{31}\ell_{21} + \ell_{32}\ell_{22} & \ell_{31}^2 + \ell_{32}^2 + \ell_{33}^2 \end{bmatrix}$$

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- $\ell_{11} = \sqrt{a_{11}}, \quad \ell_{21} = \dfrac{a_{21}}{\ell_{11}}, \quad \ell_{22} = \sqrt{a_{22} - \ell_{21}^2},$

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Motivations of Using Cholesky Decomposition

- Symmetric positive definite matrices require frequent manipulation.
  - E.g., Covariance matrix of a multivariate Gaussian variable.
  - The Cholesky factorization of the covariance matrix allows us to generate samples from a Gaussian distribution.

- Computing gradients in deep stochastic models such as variational auto-encoder (VAE).

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- Computing gradients in deep stochastic models such as variational auto-encoder (VAE).

- Compute determinants efficiently.
  - $\det(\boldsymbol{A}) = \det(\boldsymbol{L}) \det(\boldsymbol{L}^\top) = \det(\boldsymbol{L})^2$.
  - Note: $\det(\boldsymbol{L})$ can be computed efficiently ($\because$ triangular).

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$$\boldsymbol{D} = \begin{bmatrix} c_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & c_n \end{bmatrix}.$$

- **Question:** What are the determinant, cubic, and inverse of $\boldsymbol{D}$?

Similarity

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Two matrices $\boldsymbol{A}$ and $\boldsymbol{B} \in \mathbb{R}^{n \times n}$ are similar if there exists an invertible matrix $\boldsymbol{S} \in \mathbb{R}^{n \times n}$ such that $\boldsymbol{A} = \boldsymbol{S}^{-1} \boldsymbol{B} \boldsymbol{S}$.

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A matrix $\boldsymbol{A} \in \mathbb{R}^{n \times n}$ is diagonalizable if it is *similar* to a *diagonal* matrix..

- $\exists \boldsymbol{D} \in \mathbb{R}^{n \times n}$, such that $\boldsymbol{D} = \boldsymbol{P}^{-1}\boldsymbol{A}\boldsymbol{P}$.

Eigenvectors & Diagonalization

- Let $\boldsymbol{A} \in \mathbb{R}^{n \times n}$ and $\lambda_1, \ldots, \lambda_n$ be a set of scalars.

- Let $\mathbf{p}_1, \ldots, \mathbf{p}_n$ be a set of vectors in $\mathbb{R}^n$.

- Let $\boldsymbol{D} \in \mathbb{R}^{n \times n}$ be a diagonal matrix with diagonal entries $\lambda_1, \ldots, \lambda_n$.

We can show that

$$\boldsymbol{AP} = \boldsymbol{PD}.$$

if and only if $\lambda_1, \ldots, \lambda_n$ are the eigenvalues of $\boldsymbol{A}$ and $\mathbf{p}_1, \ldots, \mathbf{p}_n$ are the corresponding eigenvectors of $\boldsymbol{A}$.

Proof of the Claim

We can see that

$$\boldsymbol{AP} = \boldsymbol{A}[\mathbf{p}_1, \ldots, \mathbf{p}_n] = [\boldsymbol{A}\mathbf{p}_1, \ldots, \boldsymbol{A}\mathbf{p}_n],$$

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Thus,

$$\begin{aligned} \boldsymbol{A}\mathbf{p}_1 &= \lambda_1\mathbf{p}_1 \\ &\vdots \\ \boldsymbol{A}\mathbf{p}_n &= \lambda_n\mathbf{p}_n \end{aligned}$$

Therefore, the columns of $\boldsymbol{P}$ are eigenvectors of $\boldsymbol{A}$.

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$\Rightarrow$ ($**$) $- \lambda_n \cdot$ ($*$):
$\alpha_1(\lambda_1 - \lambda_n)\mathbf{p}_1 + \alpha_2(\lambda_2 - \lambda_n)\mathbf{p}_2 + \cdots + \alpha_{n-1}(\lambda_{n-1} - \lambda_n)\mathbf{p}_{n-1} = \mathbf{0}$.

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- $\therefore \alpha_1 = \alpha_2 = \cdots = \alpha_n = 0.$

Eigendecomposition (Diagonalization)

Theorem [Eigendecomposition (Diagonalization)]

A square matrix $\boldsymbol{A} \in \mathbb{R}^{n \times n}$ can be factored into

$$\boldsymbol{A} = \boldsymbol{P}\boldsymbol{D}\boldsymbol{P}^{-1},$$

where $\boldsymbol{P} \in \mathbb{R}^{n \times n}$ and $\boldsymbol{D}$ is a diagonal matrix whose diagonal entries are the eigenvalues of $\boldsymbol{A}$

if and only if

the eigenvectors of $\boldsymbol{A}$ form a basis of $\mathbb{R}^n$.

Put it concisely

Theorem

For a square matrix $\boldsymbol{A} \in \mathbb{R}^{n \times n}$, the following statements are equivalent:

- $\boldsymbol{A}$ is diagonalizable.

- $\boldsymbol{A}$ has n linearly independent eigenvectors.

Remark

The spectral theorem tells us that:

> *We can find an orthonormal basis of the corresponding vector space consisting of eigenvectors of of a symmetric matrix $\boldsymbol{S} \in \mathbb{R}^{n \times n}$.*

Remark

The spectral theorem tells us that:

We can find an orthonormal basis of the corresponding vector space consisting of eigenvectors of of a symmetric matrix $S \in \mathbb{R}^{n \times n}$.

Theorem

A symmetric matrix $S \in \mathbb{R}^{n \times n}$ can be always diagonalized.

Example

Compute the eigendecomposition of $\boldsymbol{A} = \frac{1}{2} \begin{bmatrix} 5 & -2 \\ -2 & 5 \end{bmatrix}$.

1. Compute the eigenvalues and eigenvectors.

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   Set $\lambda_1 = \frac{7}{2}, \lambda_2 = \frac{3}{2}$.

2. Solving $\boldsymbol{A}\boldsymbol{p}_1 = \frac{7}{2}\boldsymbol{p}_1$ and $\boldsymbol{A}\boldsymbol{p}_2 = \frac{3}{2}\boldsymbol{p}_2$.

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⋆ Note that $\{\mathbf{p}_1, \mathbf{p}_2\}$ forms an orthonormal basis $\boldsymbol{P}^{-1} = \boldsymbol{P}^{\top}$. (Exercise)

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⋆ Note that $\{\mathbf{p}_1, \mathbf{p}_2\}$ forms an orthonormal basis $\boldsymbol{P}^{-1} = \boldsymbol{P}^{\top}$. (Exercise)

Finally we obtain $\boldsymbol{A} = \boldsymbol{PDP}^{-1}$.

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A Maclaurin Series expansion of $f(x)$ is

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Discussions