Linear Algebra

Chapter 5: Orthogonality

University of Seoul
School of Computer Science
Minho Kim

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More on Projection onto a Line

The standard matrix of a projection onto the line through the origin with direction vector $\boldsymbol{d} = \begin{bmatrix} d_1 \\ d_2 \end{bmatrix}$: $P = \frac{1}{d_1^2 + d_2^2} \begin{bmatrix} d_1^2 & d_1 d_2 \\ d_1 d_2 & d_2^2 \end{bmatrix}$

- Can be written as

$$\begin{bmatrix} \cos^2\theta & \cos\theta\sin\theta \\ \cos\theta\sin\theta & \sin^2\theta \end{bmatrix} = R_\theta \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} R_{-\theta} = R_{\theta - \frac{\pi}{2}} \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} R_{\frac{\pi}{2} - \theta}$$

- $P = \boldsymbol{u}\boldsymbol{u}^T$ where $\boldsymbol{u} := \boldsymbol{d}/\|\boldsymbol{d}\|$. Why? (Geometrically)
  $P\boldsymbol{x} = \boldsymbol{u}(\boldsymbol{u} \cdot \boldsymbol{x}) = \boldsymbol{u}(\boldsymbol{u}^T\boldsymbol{x}) = (\boldsymbol{u}\boldsymbol{u}^T)\boldsymbol{x}$
- $P^T = P$
  $P^T = (\boldsymbol{u}\boldsymbol{u}^T)^T = \boldsymbol{u}\boldsymbol{u}^T = P$
- $P^2 = P$
  $P^2 = (\boldsymbol{u}\boldsymbol{u}^T)(\boldsymbol{u}\boldsymbol{u}^T) = \boldsymbol{u}(\boldsymbol{u}^T\boldsymbol{u})\boldsymbol{u}^T = \boldsymbol{u}(\boldsymbol{u} \cdot \boldsymbol{u})\boldsymbol{u}^T = \boldsymbol{u}\boldsymbol{u}^T = P$
- For a projection matrix $P \in \mathbb{R}^{2\times 2}$, the line onto which it projects vectors is the column space of P. Why?
  $P\boldsymbol{x} = (\boldsymbol{u}\boldsymbol{u}^T)\boldsymbol{x} = \boldsymbol{u}(\boldsymbol{u}^T\boldsymbol{x}) = (\boldsymbol{u} \cdot \boldsymbol{x})\boldsymbol{u}$

More on Projections onto Planes

Let

- $\mathscr{P}$ be a plane through the origin with normal $\boldsymbol{n}$ and
- $\mathrm{proj}_{\mathscr{P}}(\boldsymbol{v})$ be the projection of $\boldsymbol{v}$ onto $\mathscr{P}$.

Then

- What is $\mathrm{proj}_{\mathscr{P}}(\boldsymbol{v})$?
  Find c such that $(\boldsymbol{v} - c\boldsymbol{n}) \cdot \boldsymbol{n} = 0$.
  $\rightarrow c = \boldsymbol{v} \cdot \boldsymbol{n} \rightarrow \mathrm{proj}_{\mathscr{P}}(\boldsymbol{v}) = \boldsymbol{v} - (\boldsymbol{v} \cdot \boldsymbol{n})\boldsymbol{n}$
- Find $\mathrm{proj}_{\mathscr{P}}(\boldsymbol{v})$ using two direction vectors $\boldsymbol{u}_1$ and $\boldsymbol{u}_2$ such that $\|\boldsymbol{u}_1\| = \|\boldsymbol{u}_2\| = 1$ and $\boldsymbol{u}_1 \cdot \boldsymbol{u}_2 = 0$ (orthogonal unit vectors)
  $\rightarrow P = \boldsymbol{u}_1\boldsymbol{u}_1^T + \boldsymbol{u}_2\boldsymbol{u}_2^T$.
- $(\boldsymbol{v} - P\boldsymbol{v}) \perp \boldsymbol{u}_1$ and $(\boldsymbol{v} - P\boldsymbol{v}) \perp \boldsymbol{u}_2$?

$$
\begin{aligned}
(\boldsymbol{v} - (\boldsymbol{u}_1\boldsymbol{u}_1^T + \boldsymbol{u}_2\boldsymbol{u}_2^T)\boldsymbol{v}) \cdot \boldsymbol{u}_1 &= ((I - \boldsymbol{u}_1\boldsymbol{u}_1^T - \boldsymbol{u}_2\boldsymbol{u}_2^T)\boldsymbol{v})^T\boldsymbol{u}_1 \\
&= \boldsymbol{v}^T(I - \boldsymbol{u}_1\boldsymbol{u}_1^T - \boldsymbol{u}_2\boldsymbol{u}_2^T)\boldsymbol{u}_1 \\
&= \boldsymbol{v}^T(\boldsymbol{u}_1 - \boldsymbol{u}_1\boldsymbol{u}_1^T\boldsymbol{u}_1 - \boldsymbol{u}_2\boldsymbol{u}_2^T\boldsymbol{u}_1) \\
&= \boldsymbol{v}^T(\boldsymbol{u}_1 - \boldsymbol{u}_1 - 0) = 0
\end{aligned}
$$

More on Projections onto Planes (cont'd)

- $P = P^T$ and $P^2 = P$.
- $P = AA^T$ for some $A \in \mathbb{R}^{3\times 2}$.
  With $A := \begin{bmatrix} \boldsymbol{u}_1 & \boldsymbol{u}_2 \end{bmatrix}$,
  $$\begin{bmatrix} \boldsymbol{u}_1 & \boldsymbol{u}_2 \end{bmatrix} \begin{bmatrix} \boldsymbol{u}_1 & \boldsymbol{u}_2 \end{bmatrix}^T = \begin{bmatrix} \boldsymbol{u}_1 & \boldsymbol{u}_2 \end{bmatrix} \begin{bmatrix} \boldsymbol{u}_1^T \\ \boldsymbol{u}_2^T \end{bmatrix} = \boldsymbol{u}_1 \boldsymbol{u}_1^T + \boldsymbol{u}_2 \boldsymbol{u}_2^T$$
- $\mathrm{rank}(P) = 2$
  (See Theorem 3.25 (p.202) and Theorem 3.28, (p.205))
  $\mathrm{rank}(AA^T) = \mathrm{rank}(A^T) = \mathrm{rank}(A) = \mathrm{rank}(A^T A)$
  and
  $$A^T A = \begin{bmatrix} \boldsymbol{u}_1^T \\ \boldsymbol{u}_2^T \end{bmatrix} \begin{bmatrix} \boldsymbol{u}_1 & \boldsymbol{u}_2 \end{bmatrix} = \begin{bmatrix} \boldsymbol{u}_1^T \boldsymbol{u}_1 & \boldsymbol{u}_1^T \boldsymbol{u}_2 \\ \boldsymbol{u}_2^T \boldsymbol{u}_1 & \boldsymbol{u}_2^T \boldsymbol{u}_2 \end{bmatrix} = I_2$$

Outline

Orthogonal Sets of Vectors

What make the standard basis of $\mathbb{R}^n$ good?

- orthogonal to each other
- unit vectors

Definition: Orthogonal Set

A set of vectors $\{\boldsymbol{v}_1, \boldsymbol{v}_2, \ldots, \boldsymbol{v}_k\}$ in $\mathbb{R}^n$ is called an **orthogonal set** if all pairs of distinct vectors in the set are orthogonal – that is, if

$$\boldsymbol{v}_i \cdot \boldsymbol{v}_j = 0 \quad \text{whenever } i \neq j \quad \text{for } i, j = 1, 2, \ldots, k$$

- Geometrically, they are mutually **perpendicular**.

Orthogonal Basis

Why is it good that the vectors are orthogonal?

Theorem 5.1

If $\{\boldsymbol{v}_1, \boldsymbol{v}_2, \ldots, \boldsymbol{v}_k\}$ is an orthogonal set of nonzero vectors in $\mathbb{R}^n$, then these vectors are linearly independent.

$\rightarrow$ Can be used as a basis.

Definition

An **orthogonal basis** for a subspace W of $\mathbb{R}^n$ is a basis of W that is an orthogonal set.

- Given two orthogonal vectors, how can we get the third orthogonal vector in $\mathbb{R}^3$?
  $\boldsymbol{v}_3 = \boldsymbol{v}_1 \times \boldsymbol{v}_2$

Orthogonal Basis (cont'd)

- How to compute the coordinate of a vector w.r.t. an orthogonal basis?

Theorem 5.2

Let $\{\boldsymbol{v}_1, \boldsymbol{v}_2, \ldots, \boldsymbol{v}_k\}$ be an orthogonal basis for a subspace W of $\mathbb{R}^n$ and let $\boldsymbol{w}$ be any vector in W. Then the unique scalars $c_1, \ldots, c_k$ such that

$$\boldsymbol{w} = c_1\boldsymbol{v}_1 + \cdots + c_k\boldsymbol{v}_k$$

are given by

$$c_i = \frac{\boldsymbol{w} \cdot \boldsymbol{v}_i}{\boldsymbol{v}_i \cdot \boldsymbol{v}_i} \quad \text{for } i = 1, \ldots, k$$

- $\boldsymbol{w} = \sum_{i=1}^{k} \left(\frac{\boldsymbol{w} \cdot \boldsymbol{v}_i}{\boldsymbol{v}_i \cdot \boldsymbol{v}_i} \right) \boldsymbol{v}_i = \sum_{i=1}^{k} \mathrm{proj}_{\boldsymbol{v}_i}(\boldsymbol{w})$

Orthonormal Basis

- Even better basis?

Definition: Orthonormal Set and Basis

A set of vectors in $\mathbb{R}^n$ is an **orthonormal set** if it is an orthogonal set of unit vectors. An **orthonormal basis** for a subspace W of $\mathbb{R}^n$ is a basis of W that is an orthonormal set.

- If $\{\boldsymbol{q}_1, \ldots, \boldsymbol{q}_k\}$ is an orthonormal set of vectors,

$$\boldsymbol{q}_i \cdot \boldsymbol{q}_j = \begin{cases} 0 & \text{if } i \neq j \\ 1 & \text{if } i = j \end{cases}$$

- How can we convert an orthogonal basis into an orthonormal basis? $\rightarrow$ Normalize vectors ($\boldsymbol{v}_i \rightarrow \boldsymbol{v}_i / \|\boldsymbol{v}_i\|$)

Orthonormal Basis (cont'd)

- How to compute the coordinate of a vector w.r.t. an orthonormal basis?

Theorem 5.3

Let $\{\boldsymbol{q}_1, \boldsymbol{q}_2, \ldots, \boldsymbol{q}_k\}$ be an orthonormal basis for a subspace W of $\mathbb{R}^n$ and let $\boldsymbol{w}$ be any vector in W. Then

$$\boldsymbol{w} = (\boldsymbol{w} \cdot \boldsymbol{q}_1)\boldsymbol{q}_1 + \cdots + (\boldsymbol{w} \cdot \boldsymbol{q}_k)\boldsymbol{q}_k$$

and this representation is unique.

- Standard basis case ($\boldsymbol{q}_i = \boldsymbol{e}_i$)?

Orthogonal Matrices

- Given an orthonormal basis $\{\boldsymbol{q}_1, \ldots, \boldsymbol{q}_k\}$,

$$\begin{bmatrix} \boldsymbol{q}_1 & \cdots & \boldsymbol{q}_k \end{bmatrix}^T \begin{bmatrix} \boldsymbol{q}_1 & \cdots & \boldsymbol{q}_k \end{bmatrix} = ?$$

Theorem 5.4

The columns of an $m \times n$ matrix Q form an orthonormal set if and only if $Q^T Q = I_n$.

Definition: Orthogonal Matrix

An $n \times n$ matrix Q whose columns form an orthonormal set is called an **orthogonal matrix**.

- Square matrix
- Not an “orthonormal matrix”

Properties Orthogonal Matrices

Theorem 5.5

A square matrix Q is orthogonal if and only if $Q^{-1} = Q^T$.

- Example 5.7
  $\rightarrow$ Permutation matrices, rotation matrices

Theorem 5.6

Let Q be an $n \times n$ matrix. The following statements are equivalent:

a. Q is orthogonal.

b. $\|Q\boldsymbol{x}\| = \|\boldsymbol{x}\|$ for every $\boldsymbol{x}$ in $\mathbb{R}^n$. (**isometry**: length-preserving)

c. $(Q\boldsymbol{x}) \cdot (Q\boldsymbol{y}) = \boldsymbol{x} \cdot \boldsymbol{y}$ for every $\boldsymbol{x}$ and $\boldsymbol{y}$ in $\mathbb{R}^n$. (angle-preserving)

Properties of Orthogonal Matrices (cont'd)

- $Q^T Q = I \Rightarrow QQ^T = I$.
  What does it mean?

Theorem 5.7

If Q is an orthogonal matrix, then its rows form an orthonormal set.

- More properties...

Theorem 5.8

Let Q be an orthogonal matrix.

a. Q^{-1} is orthogonal.

b. $\det Q = \pm 1$.

c. If λ is an eigenvalue of Q, then $|\lambda| = 1$.

d. If Q_1 and Q_2 are orthogonal $n \times n$ matrices, then so is $Q_1 Q_2$.

Outline

Orthogonal Complements

- How can we generalize the notion of "a normal vector to a plane" to higher dimensions?

Definition: Orthogonal Complement

Let W be a subspace of $\mathbb{R}^n$. We say that a vector $\boldsymbol{v}$ in $\mathbb{R}^n$ is **orthogonal to** W if $\boldsymbol{v}$ is orthogonal to every vector in W. The set of all vectors that are orthogonal to W is called the **orthogonal complement of** W, denoted $W^\perp$ ("W perp"). That is,

$$W^\perp = \{\boldsymbol{v} \text{ in } \mathbb{R}^n : \boldsymbol{v} \cdot \boldsymbol{w} = 0 \quad \text{for all } \boldsymbol{w} \text{ in } W\}$$

Properties of Orthogonal Complements

Theorem 5.9

Let W be a subspace in $\mathbb{R}^n$.

a. $W^\perp$ is a subspace of $\mathbb{R}^n$.

b. $(W^\perp)^\perp = W$

c. $W \cap W^\perp = \{\mathbf{0}\}$

d. If $W = \operatorname{span}(\boldsymbol{w}_1, \ldots, \boldsymbol{w}_k)$, then $\boldsymbol{v}$ is in $W^\perp$ if and only if $\boldsymbol{v} \cdot \boldsymbol{w}_i = 0$ for all $i = 1, \ldots, k$.

Fundamental Subspaces of a Matrix

- Orthogonal complements and the subspaces associated with an $m \times n$ matrix.

Theorem 5.10

Let A be an $m \times n$ matrix. Then the orthogonal complement of the row space of A is the null space of A, and the orthogonal complement of the column space of A is the null space of A^T:

$$(\mathrm{row}(A))^{\perp} = \mathrm{null}(A) \quad \text{and} \quad (\mathrm{col}(A))^{\perp} = \mathrm{null}(A^T)$$

- See Figure 5.6 on p.377.

Orthogonal Projections

- How can we generalize the projection of a vector onto a line or a plane?

Definition: Orthogonal Projection

Let W be a subspace of $\mathbb{R}^n$ and let $\{\boldsymbol{u}_1, \ldots, \boldsymbol{u}_k\}$ be an orthogonal basis for W. For any vector $\boldsymbol{v}$ in $\mathbb{R}^n$, the **orthogonal projection of $\boldsymbol{v}$ onto W** is defined as

$$\begin{aligned}\operatorname{proj}_W(\boldsymbol{v}) &= \left(\frac{\boldsymbol{u}_1 \cdot \boldsymbol{v}}{\boldsymbol{u}_1 \cdot \boldsymbol{u}_1}\right)\boldsymbol{u}_1 + \cdots + \left(\frac{\boldsymbol{u}_k \cdot \boldsymbol{v}}{\boldsymbol{u}_k \cdot \boldsymbol{u}_k}\right)\boldsymbol{u}_k \\ &= \operatorname{proj}_{\boldsymbol{u}_1}(\boldsymbol{v}) + \cdots + \operatorname{proj}_{\boldsymbol{u}_k}(\boldsymbol{v})\end{aligned}$$

The **component of $\boldsymbol{v}$ orthogonal to W** is the vector $\operatorname{perp}_W(\boldsymbol{v}) = \boldsymbol{v} - \operatorname{proj}_W(\boldsymbol{v})$

- "Orthogonal decomposition"
- See Figure 5.8 on p.380.

Orthogonal Decomposition

- Is the orthogonal decomposition unique?

Theorem 5.11: The Orthogonal Decomposition Theorem

Let W be a subspace of $\mathbb{R}^n$ and let $\boldsymbol{v}$ be a vector in $\mathbb{R}^n$. Then there are unique vectors $\boldsymbol{w}$ in W and $\boldsymbol{w}^\perp$ in $W^\perp$ such that

$$\boldsymbol{v} = \boldsymbol{w} + \boldsymbol{w}^\perp$$

- $\mathrm{proj}_W(\boldsymbol{v})$ and $\mathrm{perp}_W(\boldsymbol{v})$ do not depend on the choice of orthogonal basis.
- Can be used to prove

$$(W^\perp)^\perp = W$$

Orthogonal Decomposition (cont'd)

- Relationship between the dimension of W and $W^\perp$

Theorem 5.13

If W is a subspace of $\mathbb{R}^n$, then

$$\dim W + \dim W^\perp = n$$

- Special case:

Corollary 5.14: The Rank Theorem

If A is an $m \times n$ matrix, then

$$\mathrm{rank}(A) + \mathrm{nullity}(A) = n$$

- $\mathrm{rank}(A) + \mathrm{nullity}(A^T) = m$

Outline

The Gram-Schmidt Process

- Given a subspace, how can we construct an orthogonal basis?
- The Gram-Schmidt Process: Starting from an arbitrary basis for a subspace, "orthogonalize" it one vector at a time.
  $\rightarrow$ Example 5.12

The Gram-Schmidt Process (cont'd)

Theorem 5.15: The Gram-Schmidt Process

Let $\{\boldsymbol{x}_1, \ldots, \boldsymbol{x}_k\}$ be a basis for a subspace W of $\mathbb{R}^n$ and define the following:

$$
\begin{aligned}
\boldsymbol{v}_1 &= \boldsymbol{x}_1, & W_1 &= \operatorname{span}(\boldsymbol{x}_1) \\
\boldsymbol{v}_2 &= \boldsymbol{x}_2 - \left(\frac{\boldsymbol{v}_1 \cdot \boldsymbol{x}_1}{\boldsymbol{v}_1 \cdot \boldsymbol{v}_1}\right)\boldsymbol{v}_1, & W_2 &= \operatorname{span}(\boldsymbol{x}_1, \boldsymbol{x}_2) \\
\boldsymbol{v}_3 &= \boldsymbol{x}_3 - \left(\frac{\boldsymbol{v}_1 \cdot \boldsymbol{x}_3}{\boldsymbol{v}_1 \cdot \boldsymbol{v}_1}\right)\boldsymbol{v}_1 - \left(\frac{\boldsymbol{v}_2 \cdot \boldsymbol{x}_3}{\boldsymbol{v}_2 \cdot \boldsymbol{v}_2}\right)\boldsymbol{v}_2, & W_3 &= \operatorname{span}(\boldsymbol{x}_1, \boldsymbol{x}_2, \boldsymbol{x}_3) \\
&\;\vdots \\
\boldsymbol{v}_k &= \boldsymbol{x}_k - \left(\frac{\boldsymbol{v}_1 \cdot \boldsymbol{x}_k}{\boldsymbol{v}_1 \cdot \boldsymbol{v}_1}\right)\boldsymbol{v}_1 - \left(\frac{\boldsymbol{v}_2 \cdot \boldsymbol{x}_k}{\boldsymbol{v}_2 \cdot \boldsymbol{v}_2}\right)\boldsymbol{v}_2 - \cdots \\
&\quad - \left(\frac{\boldsymbol{v}_{k-1} \cdot \boldsymbol{x}_k}{\boldsymbol{v}_{k-1} \cdot \boldsymbol{v}_{k-1}}\right)\boldsymbol{v}_{k-1}, & W_k &= \operatorname{span}(\boldsymbol{x}_1, \ldots, \boldsymbol{x}_k)
\end{aligned}
$$

Then for each $i = 1, \ldots, k$, $\{\boldsymbol{v}_1, \ldots, \boldsymbol{v}_k\}$ is an orthogonal basis for W_i. In particular, $\{\boldsymbol{v}_1, \ldots, \boldsymbol{v}_k\}$ is an orthogonal basis for W.

The QR Factorization

- Factorization of a matrix according to the Gram-Schmidt process.
- Applications:
  Approximation of eigenvalues (p.395), least squares approximation (Chap. 7)

$$W_i = \operatorname{span}(\boldsymbol{a}_1, \dots, \boldsymbol{a}_i) = \operatorname{span}(\boldsymbol{q}_1, \dots, \boldsymbol{q}_i)$$

$$\to \boldsymbol{a}_i = r_{1i}\boldsymbol{q}_1 + r_{2i}\boldsymbol{q}_2 + \cdots + r_{ii}\boldsymbol{q}_i, \quad \text{for } i = 1, \dots, n$$

$$\to A = \begin{bmatrix} \boldsymbol{a}_1 & \cdots & \boldsymbol{a}_n \end{bmatrix} = \begin{bmatrix} \boldsymbol{q}_1 & \cdots & \boldsymbol{q}_n \end{bmatrix} \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ & r_{22} & \cdots & r_{2n} \\ & & \ddots & \vdots \\ & & & r_{nn} \end{bmatrix} = QR$$

The QR Factorization (cont'd)

Theorem 5.16: The QR Factorization

Let A be an $m \times n$ matrix with linearly independent columns. Then A can be factored as $A = QR$, where Q is an $m \times n$ matrix with orthonormal columns and R is an invertible upper triangular matrix.

- Why is R invertible?
- How can we find R? (Example 5.15)
  $\to R = Q^T A$

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The Gram-Schmidt Process and the QR Factorization

Orthogonal Diagonalization of Symmetric Matrices

Applications

Real Symmetric Matrices

- Does a square matrix with real entries have real eigenvalues?
  $\rightarrow$ No. $\begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$
- Are all square matrices diagonalizable?
  $\rightarrow$ No. (Example 4.25 on p.301)

Real symmetric matrices are good!

- All eigenvalues are real.
- Always diagonalizable.

Real Symmetric Matrices (cont'd)

Definition: Orthogonally Diagonalizable

A square matrix A is **orthogonally diagonalizable** if there exists an orthogonal matrix Q and a diagonal matrix D such that $Q^T AQ = D$.

- Example 5.16
- Why is it good to be orthogonally diagonalizable?

Theorem 5.17

If A is orthogonally diagonalizable, then A is symmetric.

- How about the converse? Is every symmetric matrix is orthogonally diagonalizable?
  $\rightarrow$ Theorem 5.20 (p.400)

The (Real) Spectral Theorem

Theorem 5.18

If A is a real symmetric matrix, then the eigenvalues of A are real.

- Theorem 4.20 (p.294): "Eigenvectors corresponding to distinct eigenvalues are linearly independent."
  $\rightarrow$ How about symmetric matrices?

Theorem 5.19

If A is a symmetric matrix, then any two eigenvectors corresponding to distinct eigenvalues of A are orthogonal.

Theorem 5.20: The Spectral Theorem

Let A be an $n \times n$ real matrix. Then A is symmetric **if and only if** it is orthogonally diagonalizable.

Spectral Decomposition

$$
\begin{aligned}
A = QDQ^T &= \begin{bmatrix} \boldsymbol{q}_1 & \cdots & \boldsymbol{q}_n \end{bmatrix} \begin{bmatrix} \lambda_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \lambda_n \end{bmatrix} \begin{bmatrix} \boldsymbol{q}_1^T \\ \vdots \\ \boldsymbol{q}_n^T \end{bmatrix} \\
&= \begin{bmatrix} \lambda_1 \boldsymbol{q}_1 & \cdots & \lambda_n \boldsymbol{q}_n \end{bmatrix} \begin{bmatrix} \boldsymbol{q}_1^T \\ \vdots \\ \boldsymbol{q}_n^T \end{bmatrix} \\
&= \lambda_1 \boldsymbol{q}_1 \boldsymbol{q}_1^T + \cdots + \lambda_n \boldsymbol{q}_n \boldsymbol{q}_n^T
\end{aligned}
$$

- "Projection form of the Spectral Theorem"
- Steps
  1. $A = PDP^{-1}$ (diagonalization)
  2. $P \to Q$ (Gram-Schmidt process)
  3. $A = QDQ^T$ (orthogonal diagonalization)

Outline