PCA

A tutorial on Principle Component Analysis

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1 Problem Setup

In this section, we introduce the PCA problem

Given n data points, we define *mean* and *variance* as follows

Definition 1 (mean and variance of$n$ data points)**.** *Let* $\mathcal{X} = \{x_1, x_2, ..., x_n\}$ *where* $x_i \in \mathbb{R}^d$, $x_i \in \mathbb{N} \cap [1, n]$. *Define*

$$\mu(\mathcal{X}) = \frac{1}{n}\sum_{i=1}^{n} x_i$$
$$\sigma(\mathcal{X}) = \frac{1}{n-1}\sum_{i=1}^{n} ||x_i - \mu(\mathcal{X})||_2^2$$

If data is centered, i.e $\mu(\mathcal{X}) = 0$, the variance can be rewritten as the sum of squared L2 norm of all data points, i.e $\sigma(\mathcal{X}) = \frac{1}{n-1}\sum_{i=1}^{n} ||x_i||_2^2$. Throughout this tutorial, we assume data is centered.

We also denote $X = [x_1, x_2, ..., x_n] \in \mathbb{R}^{d\times n}$ as the data matrix of $\mathcal{X}$ where each column of X corresponds to a data point in $\mathcal{X}$, we can rewrite *mean* and *variance* as follows

Definition 2 (mean and variance of a data matrix)**.** *Let* $X = [x_1, x_2, ..., x_n] \in \mathbb{R}^{d\times n}$ *be the data matrix of* n *data points in* $\mathbb{R}^d$

$$\mu(X) = \frac{1}{n} X\mathbf{1}_n = \mathbf{0}_d$$
$$\sigma(X) = \frac{1}{n-1}||X|_F^2 = \frac{1}{n-1}\operatorname{tr} X^T X$$

The PCA problem attempts to find a k-dimensional subspace of $\mathbb{R}^d$ denoted as $\mathcal{U}_k$ such as the orthogonal projection of $\mathcal{X}$ into $\mathcal{U}_k$ preserves as much variance of $\mathcal{X}$ as possible.

Let $U_k = [u_1, u_2, ..., u_k] \in \mathbb{R}^{d\times k}$ be the matrix of a orthogonal basis of $\mathcal{U}_k$, i.e $U_k^T U_k = I_k$. The PCA projection of $\mathcal{X}$ into $\mathcal{U}_k$ can be written as $X \mapsto U_k U_k^T X$.

Definition 3 (Principle Component Analysis)**.** *Let* $X \in \mathbb{R}^{d\times n}$

$$\operatorname{pca}_k X = \max_{U_k \in \mathbb{R}^{d\times k} \wedge U_k^T U_k = I_k} \sigma(U_k U_k^T X) \tag{1}$$

Some preliminary observations

- If data is centered, the projected data is also centered. $(U_k U_k^T X)\mathbf{1}_n = U_k U_k^T (X\mathbf{1}_n) = \mathbf{0}_d$
- the maximum variance of data after the project is achievable if and only if all data points lie in the subspace $\mathcal{U}_k$

To elaborate on the second observation, let V_k be the complement subspace of U_k in $\mathbb{R}^d$, i.e every vector $x \in \mathbb{R}^d$ can be expressed as $x = u+v$ where $u \in U_k$ and $v \in V_k$. Furthermore, the L2 norm of x can be expressed as $||x||_2^2 = ||u||_2^2 + ||v||_2^2$ (this is well-know Pythagorean theorem). Sum up all data points, we have $\sum_{i=1}^n ||x_i||_2^2 = \sum_{i=1}^n ||u_i||_2^2 + \sum_{i=1}^n ||v_i||_2^2$. Hence, $\sum_{i=1}^n ||x_i||_2^2 \geq \sum_{i=1}^n ||u_i||_2^2$. Since, the projected data is also centered, the RHS is the variance of projected data.

In machine learning, we often use the inner product of data points into the k *principle* directions as a dimensionality reduction method for downstream tasks. In this tutorial, we call it *PCA embedding*

Definition 4 (PCA Embedding)**.**

$$X \mapsto \hat{U}_k^T X \in \mathbb{R}^{k\times n} \tag{2}$$

where $\hat{U}_k$ is the optimal value of U_k.

2 Reduction to Trace Optimization Problem

In this section, we find PCA solution by reducing it to Trace Optimization Problem

Definition 5 (Trace Optimization Problem)**.** *Given* $M \in \mathbb{R}^{d\times d}$ *symmetric positive semidefinite with* d *eigenvalues* $\lambda_1 \geq \lambda_2 \geq ... \geq \lambda_d \geq 0$*. Find a matrix* $U \in \mathbb{R}^{d\times k}$ *with* $U^T U = I_k$ *such as the trace* $\operatorname{tr} U^T M U$ *is maximized or minimized*

The optimal value of *Trace Optimization* is the sum of k largest / smallest eigenvalues.

$$\max_{U \in \mathbb{R}^{d\times k} \wedge U^T U = I_k} \operatorname{tr} U^T M U = \sum_{i=1}^{k} \lambda_i$$

$$\min_{U \in \mathbb{R}^{d\times k} \wedge U^T U = I_k} \operatorname{tr} U^T M U = \sum_{i=d-k+1}^{d} \lambda_i$$

In the case of PCA, the objective can be rewritten as

$$\begin{aligned}
\sigma(U_k U_k^T X) &= \mathrm{tr}(U_k U_k^T X)^T (U_k U_k^T X) \\
&= \mathrm{tr}\, X^T U_k (U_k^T U_k) U_k^T X \quad \text{(decompose)} \\
&= \mathrm{tr}\, X^T U_k U_k^T X \quad \text{(orthogonal of } U_k) \\
&= \mathrm{tr}\, U_k^T (X X^T) U_k \quad \text{(cyclic property of trace)}
\end{aligned} \tag{3}$$

Therefore, the solution of PCA can be obtained by solving *Trace Optimization* where $M = XX^T$. Let $X = U\Sigma V^T$ be the *Singular Value Decomposition* of X. We rewrite $XX^T = U\Sigma^2 U^T$. Hence, the solution is of PCA is the subspace with basis consists of k left singular vectors corresponding to the k largest singular values.

3 Equivalent to Low-Rank Approximation on Frobenius Norm

3.1 Low-Rank Approximation on Frobenius Norm (LRA-FN)

Given matrix $A \in \mathbb{R}^{m \times n}$, the problem of Low-Rank Approximation on Frobenius Norm (LRA-FN) seeks to find a rank-k approximation of A ($k \leq \min(m, n)$). Formally,

$$\min_{A_k \in \mathbb{R}^{m \times n} \wedge \mathrm{rank}\, A_k = k} ||A_k - A||_F^2 \tag{4}$$

The *Eckart–Young–Mirsky theorem* states that the optimality is achievable when the rank-k matrix A is the rank-k SVD of A_k, i.e $\hat{A}_k = U_k \Sigma_k V_k^T$. The optimal objective value is

$$\min_{A_k \in \mathbb{R}^{m \times n} \wedge \mathrm{rank}\, A_k = k} ||A_k - A||_F^2 = ||\hat{A}_k - A||_F^2 = \sum_{i=k+1}^{n} \sigma_i^2 \tag{5}$$

where $\sigma_1 \geq \sigma_2 \geq ... \geq \sigma_{\min(m,n)} \geq 0$ are the singular values of A.

We can rewrite the rank-k SVD decomposition of A as

$$U_k \Sigma_k V_k^T = U_k U_k^T A \tag{6}$$

Intuitively speaking, the best rank-k approximation of matrix A is achievable by orthogonally projecting its columns into the subspace constructed from k left singular vectors corresponding to k largest singular values. This operation is identical to PCA. In fact, LRA-FN and PCA are equivalent.

Theorem 1. *PCA and LRA-FN are equivalent*

3.2 PCA $\rightarrow$ LRA-FN

In this section, we find the solution of PCA from the solution of LRA-FN

In PCA, we want to find U_k such as $\sigma(U_k U_k^T X)$ is maximized. We can rewrite the objective as

$$\sigma(U_k U_k^T X) = ||U_k U_k^T X||_F^2 \tag{7}$$

Since $U_k U_k^T$ is a orthogonal projection, $U_k U_k^T x$ and $U_k U_k^T x - x$ are orthogonal for all $x \in \mathbb{R}^d$: $(U_k U_k^T x)^T (U_k U_k^T x - x) = 0$

Apply *Pythagorean theorem* for all columns of $U_k U_k^T X$

$$\begin{aligned} ||U_k U_k^T X||_F^2 + ||U_k U_k^T X - X||_F^2 = ||X||_F^2 \\ ||U_k U_k^T X||_F^2 = ||X||_F^2 - ||U_k U_k^T X - X||_F^2 \end{aligned} \tag{8}$$

By *LRA-FN*,

$$||U_k U_k^T X - X||_F^2 \geq ||\hat{U}_k \hat{U}_k^T X - X||_F^2 \tag{9}$$

Where $\hat{U}_k$ is the matrix of k left singular values of X corresponding to the k largest singular values.

Hence,

$$||U_k U_k^T X||_F^2 \leq ||X||_F^2 - ||\hat{U}_k \hat{U}_k^T X - X||_F^2 = \sum_{i=1}^{k} \sigma_i^2 \tag{10}$$

where $\sigma_1 \geq \sigma_2 \geq ... \geq \sigma_{\min(d,n)} \geq 0$ are the singular values of X.

$U_k = \hat{U}_k$ admits equality.

3.3 LRA-FN $\rightarrow$ PCA

In this section, we find the solution of LRA-FN from the solution of PCA

Given any rank-k approximation $A_k \in \mathbb{R}^{m \times n}$ of A, let $U_k \in \mathbb{R}^{m \times k}$ be a orthogonal basis of column space of A. We will prove that $U_k U_k^T A$ gives a better or as good approximation of A as A_k.

Theorem 2 (minimal distance)**.** *For any vector u in a k-dimensional subspace $\mathcal{U}_k$, the minimal distance to another vector $a \in \mathbb{R}^m$ is achievable when u is the projection of a onto $\mathcal{U}_k$.*

$$\min_{u \in \mathcal{U}_k} ||u - a||_2 = ||U_k U_k^T a - a||_2 \tag{11}$$

where columns of U_k is a orthogonal basis of $\mathcal{U}_k$

Apply theorem **??** to columns of A_k and A, we have

$$||A_k - A||_F \geq ||U_k U_k^T A - A||_F \tag{12}$$

By *Pythagorean theorem,*

$$||U_k U_k^T A - A||_F = ||A||_F - ||U_k U_k^T A||_F \tag{13}$$

By PCA, $||U_k U_k^T A||_F$ is maximal when U_k is the k left singular vectors corresponding to the k largest singular values.

$$||\hat{U}_k \hat{U}_k^T A||_F \geq ||U_k U_k^T A||_F \tag{14}$$

Hence,

$$\begin{aligned} ||A_k - A||_F &\geq ||U_k U_k^T A - A||_F \\ &= ||A||_F - ||U_k U_k^T A||_F \\ &\geq ||A||_F - ||\hat{U}_k \hat{U}_k^T A||_F \end{aligned} \tag{15}$$

The equality is admitted in both conditions (1) A_k is the orthogonal projection of A in some subspace of dimension k and (2) the subspace is from PCA.

4 Sequential PCA

In machine learning, sometimes, number of data points is very large and they come sequentially. Sequential PCA attempts to approximate the PCA in O(1) time. This section is a discussion on concept drifting in sequential PCA

Suppose there exists an algorithm producing PCA embedding $y_1^{(t)}, y_2^{(t)}, ..., y_t^{(t)} \in \mathbb{R}^k$ of input data point $x_1, x_2, ..., x_t \in \mathbb{R}^d$ after receiving data point x_t at time t. Let $U_k^{(t)} \in \mathbb{R}^{k \times d}$ be the approximated k-dimensional projection subspace of PCA at time t. When a new data point come, the algorithm yields a new approximation of the projection subspace $U_k^{(t+1)}$. Generally, the new approximation will be different. The authors in **?** introduced an update to all previous embedding vectors as

$$y_t^{(t_2)} \mapsto U_k^{(t_2)T} U_k^{(t_1)} y_t^{(t_1)} \tag{16}$$

The update can be decomposed into two steps: (1) map the embedding of x_t at time t_1: $y_t^{(t_1)} \in \mathbb{R}^k$ back to $\mathbb{R}^d$ (2) project the resulting vector / tensor into the new basis $U_k^{(t_2)}$ that yields the embedding of x_t at time t_2: $y_t^{(t_2)}$

5 Appendix

5.1 A proof of Trace Optimization Problem

We have

$$
\begin{aligned}
\operatorname{tr} U^T M U &= \operatorname{tr} M(UU^T) \quad \text{(cyclic property)} \\
&\leq \sum_{i=1}^{d} \sigma_i(M)\sigma_i(UU^T) \quad \text{(Von Neumann's Trace Inequality)} \\
&= \sum_{i=1}^{k} \sigma_i(M) \quad (U \text{ is orthogonal rank-}k)
\end{aligned} \tag{17}
$$

where $\sigma_i(A)$ is the i-th singular value of A sorted descending.

5.2 A proof of Von Neumann's Trace Inequality

This proof is by user1551 from Mathematics Stack Exchange **?**

The Von Neumann's Trace Inequality is stated as follow:

Theorem 3. *Given two complex matrices $A, B \in \mathbb{R}^{n\times n}$ with singular values $\alpha_1 \geq \alpha_2 \geq ... \geq \alpha_n \geq 0$ and $\beta_1 \geq \beta_2 \geq ... \geq \beta_n \geq 0$*

$$
|\operatorname{tr} AB| \leq \sum_{i=1}^{n} \alpha_i\beta_i \tag{18}
$$

Lemma 1. *The Von Neumann's Trace Inequality can be reduced to*

$$
|\operatorname{tr} DUSV^*| \leq trDS \tag{19}
$$

such that U and V are unitary and $D = diag(d_1, d_2, ..., d_n)$, $S = diag(s_1, s_2, ..., s_n)$

Let P_k denotes the orthogonal projection matrix $I_k \bigoplus 0_{n-k} = diag(1, 1, ..., 1, 0, 0, ..., 0)$ (k times of 1)

We write D and S as the non-negatively weighted sum of P_ks

$$
D = (d_1 - d_2)P_1 + (d_2 - d_3)P_2 + ... + (d_{n-1} - d_n)P_{n-1} + d_n P_n \tag{20}
$$

and similarly for S. Conveniently, we write $D = \sum_k \alpha_k P_k$, $S = \sum_l \beta_l P_l$. Inequality **??** becomes

$$
|\sum_{k,l} \alpha_k\beta_l \operatorname{tr} P_k U P_l V^*| \leq \sum_{k,l} \alpha_k\beta_l \operatorname{tr} P_k P_l \tag{21}
$$

If we have $|\operatorname{tr} P_k U P_l V^*| \leq trP_kP_l$, *Triangle Inequality* implies the inequality **??**. ($|a + b| \leq |a| + |b|$)

Indeed, denote $U = [u_1, u_2, ..., u_n]$, $V = [v_1, v_2, ..., v_n]$, so that $P_k U P_l = [P_k u_1, P_k u_2, ..., P_k u_l, 0, ..., 0]$. Assuming $l \leq k$, we have

$$
\begin{aligned}
\left|\operatorname{tr}(P_k U P_l) V^*\right| &= \left|\operatorname{tr} V^*(P_k U P_l)\right| \quad \text{(cyclic property)} \\
&= \left|\sum_{i=1}^{n} \langle (P_k U P_l)_i, v_i \rangle\right| \quad \text{(unroll)} \\
&= \left|\sum_{i=1}^{l} \langle P_k u_i, v_i \rangle\right| \quad \text{(unroll)} \\
&\leq \left|\sum_{i=1}^{l} ||P_k u_i|| ||v_i||\right| \quad (\textit{Cauchy–Schwarz inequality}) \\
&= \sum_{i=1}^{l} ||P_k u_i|| \quad (\textit{unit vector}) \\
&= \sum_{i=1}^{l} 1 \quad (\textit{orthogonal projection matrix}) \\
&= l \\
&= \operatorname{tr} P_k P_l
\end{aligned} \tag{22}
$$

For the other case, $l > k$, we write $\left|\operatorname{tr}(P_k U P_l) V^*\right| = \left|\operatorname{tr} U(P_l V^* P_k)\right|$ then apply *Cauchy–Schwarz inequality* on row space instead.

5.2.1 Proof of lemma ??

SVD: $A = U_A \Sigma_A V_A^*$, $B = U_B \Sigma_B V_B^*$

$$
\begin{aligned}
\operatorname{tr} AB &= \operatorname{tr} U_A \Sigma_A V_A^* U_B \Sigma_B V_B^* \\
&= \operatorname{tr} \Sigma_A (V_A^* U_B) \Sigma_B (U_A^* V_B) * \quad \text{(cyclic property)} \\
&= \operatorname{tr} DUCV^*
\end{aligned} \tag{23}
$$