Dimensionality Reduction: PCA

Nicholas Ruozzi
University of Texas at Dallas

Eigenvalues

- λ is an eigenvalue of a matrix $A \in \mathbb{R}^{n \times n}$ if the linear system $Ax = \lambda x$ has at least one non-zero solution
  - If $Ax = \lambda x$ we say that λ is an eigenvalue of A with corresponding eigenvector x
  - Could be multiple eigenvectors for the same λ

Eigenvalues of Symmetric Matrices

- If $A \in \mathbb{R}^{n \times n}$ is symmetric, then it has n linearly independent eigenvectors $v_1, \ldots, v_n$ corresponding to n real eigenvalues
  - Moreover, it has n linearly independent orthonormal eigenvectors:
    - $v_i^T v_j = 0$ for all $i \neq j$
    - $v_i^T v_i = 1$ for all i

Eigenvalues of Symmetric Matrices

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- A symmetric matrix is positive definite if and only if all of its eigenvalues are positive

Example

- The 2x2 identity matrix has all of its eigenvalues equal to 1 with orthonormal eigenvectors $\begin{bmatrix} 1 \\ 0 \end{bmatrix}$ and $\begin{bmatrix} 0 \\ 1 \end{bmatrix}$

- The matrix $\begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix}$ has eigenvalues 0 and 2 with orthonormal eigenvectors $\begin{bmatrix} \frac{-1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} \end{bmatrix}$ and $\begin{bmatrix} \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} \end{bmatrix}$

Eigenvalues

- Suppose $A \in \mathbb{R}^{n\times n}$ is symmetric

- Any $x \in \mathbb{R}^n$ can be written as $x = \sum_{i=1}^n c_i v_i$ where $v_1, \ldots, v_n$ are the eigenvectors of A

  - $Ax = \sum_{i=1}^n \lambda_i c_i v_i$
  - $A^2 x = \sum_{i=1}^n \lambda_i^2 c_i v_i$

    $\vdots$
  - $A^t x = \sum_{i=1}^n \lambda_i^t c_i v_i$

Eigenvalues

- Suppose $A \in \mathbb{R}^{n \times n}$ is symmetric
- Any $x \in \mathbb{R}^n$ can be written as $x = \sum_{i=1}^{n} c_i v_i$ where $v_1, \dots, v_n$ are the eigenvectors of A
  - $c_i = v_i^T x$, this is the projection of x along the line given by v_i (assuming that v_i is a unit vector)

Eigenvalues of Symmetric Matrices

- Let $Q \in \mathbb{R}^{n\times n}$ be the matrix whose i^{th} column is v_i and $D \in \mathbb{R}^{n\times n}$ be the diagonal matrix such that $D_{ii} = \lambda_i$
  - $Ax = QDQ^T x$
  - Can throw away some eigenvectors to approximate this quantity
    - For example, let Q_k be the matrix formed by keeping only the top k eigenvectors and D_k be the diagonal matrix whose diagonal consists of the top k eigenvalues

Frobenius Norm

- The Frobenius norm is a matrix norm written as

$$\|A\|_F = \sqrt{\sum_{i=1}^{n}\sum_{j=1}^{n}\left|A_{ij}\right|^2}$$

- $Q_k D_k Q_k^T$ is the best rank k approximation of the matrix symmetric matrix A with respect to the Frobenius norm

Principal Component Analysis

- Given a collection of data points sampled from some distribution $x_1, \ldots, x_p \in \mathbb{R}^n$
  - Construct the matrix $X \in \mathbb{R}^{n \times p}$ whose i^{th} column is x_i
- Want to reduce the dimensionality of the data while still maintaining a good approximation of the sample mean and variance

Principal Component Analysis

- Construct the matrix $W \in \mathbb{R}^{n \times p}$ whose i^{th} column is

$$x_i - \frac{\sum_j x_j}{p}$$

  – This gives the data a zero mean

- The matrix WW^T is the sample covariance matrix

  – WW^T is symmetric and positive semidefinite (simple proof later)

Principal Component Analysis

- PCA attempts to find a set of orthogonal vectors that best explain the variance of the sample covariance matrix
  - From our previous discussion, these are exactly the eigenvectors of WW^T

PCA in Practice

- Forming the matrix WW^T can require a lot of memory (especially if $n \gg p$)
  - Need a faster way to compute this without forming the matrix explicitly
  - Typical approach: use the singular value decomposition

Singular Value Decomposition (SVD)

- Every matrix $B \in \mathbb{R}^{n \times p}$ admits a decomposition of the form

$$B = U \Sigma V^T$$

  - where $U \in \mathbb{R}^{n \times n}$ is an orthogonal matrix, $\Sigma \in \mathbb{R}^{n \times p}$ is non-negative diagonal matrix, and $V \in \mathbb{R}^{p \times p}$ is an orthogonal matrix
  - A matrix $C \in \mathbb{R}^{m \times m}$ is orthogonal if $C^T = C^{-1}$. Equivalently, the rows and columns of C are orthonormal vectors

Singular Value Decomposition (SVD)

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Diagonal elements of Σ called singular values

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SVD and PCA

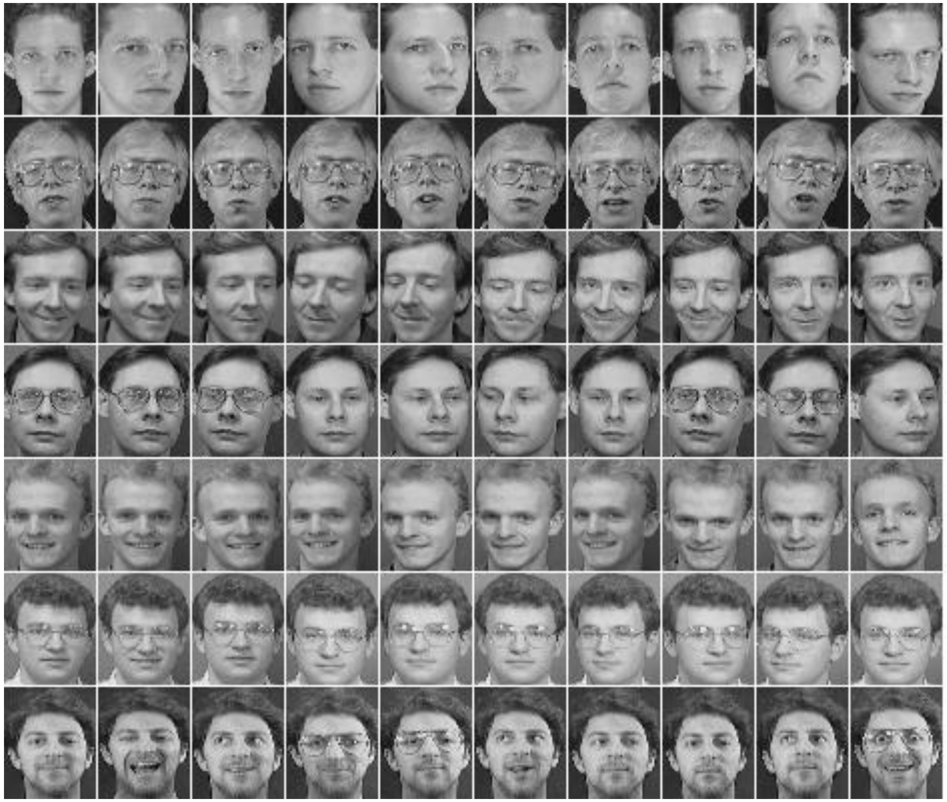
- Returning to PCA
  - Let $W = U\Sigma V^T$ be the SVD of W
  - $WW^T = U\Sigma V^T V\Sigma^T U^T = U\Sigma\Sigma^T U^T$
  - U is then the matrix of eigenvectors of WW^T
  - If we can compute the SVD of W, then we don't need to form the matrix WW^T

SVD and PCA

- For any matrix A, AA^T is symmetric and positive semidefinite
  - Let $A = U\Sigma V^T$ be the SVD of A
  - $AA^T = U\Sigma V^T V\Sigma^T U^T = U\Sigma\Sigma^T U^T$
  - U is then the matrix of eigenvectors of AA^T
  - The eigenvalues of AA^T are all non-negative because $\Sigma\Sigma^T = \Sigma^2$ which are the square of the singular values of A

An Example: "Eigenfaces"

- Let's suppose that our data is a collection of images of the faces of individuals



An Example: “Eigenfaces”

- Let’s suppose that our data is a collection of images of the faces of individuals
  - The goal is, given the "training data", to correctly label unseen images
  - Let’s suppose that each image is an $s \times s$ array of pixels: $x_i \in R^n, n = s^2$
  - As before, construct the matrix $W \in \mathbb{R}^{n \times p}$ whose i^{th} column is $x_i - \sum_j \frac{x_j}{m}$

An Example: “Eigenfaces”

- Forming the matrix WW^T requires a lot of memory
  - $s = 256$ means WW^T is 65536×65536
  - Need a faster way to compute this without forming the matrix explicitly
  - Could use the singular value decomposition

An Example: “Eigenfaces”

- A different approach when $p \ll n$
  - Compute the eigenvectors of $A^T A$ (this is an $p \times p$ matrix)
  - Let v be an eigenvector of $A^T A$ with eigenvalue λ
  - $AA^T Av = \lambda Av$
  - This means that Av is an eigenvector of AA^T with eigenvalue λ (or 0)
  - Save the top k eigenvectors - called eigenfaces in this example

An Example: “Eigenfaces”

- The data in the matrix is “training data”
  - Given a new image, we’d like to determine which, if any, member of the data set that it belongs to
- Step 1: Compute the projection of the recentered image to classify onto each of the k eigenvectors
  - This gives us a vector of weights $c_1, \ldots, c_k$

An Example: "Eigenfaces"

- The data in the matrix is "training data"
  - Given a new image, we'd like to determine which, if any, member of the data set that it belongs to
- Step 2: Determine if the input image is close to one of the faces in the data set
  - If the distance between the input and it's approximation is too large, then the input is likely not a face

An Example: “Eigenfaces”

- The data in the matrix is “training data”
  - Given a new image, we’d like to determine which, if any, member of the data set that it belongs to
- Step 3: Find the person in the training data that is closest to the new input
  - Replace each group of training images by its average
  - Compute the distance to the i^{th} average $\|c - a^i\|$ where a^i are the coefficients of the average face for person i