

Matrix Algebra and Random Vectors

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Outline

- Eigenvalues and Eigenvectors
- Positive Definite Matrices
- A Square-Root Matrix
- Random Vectors and Matrices
- Mean Vectors and Covariance Matrices
- Matrix Inequalities and Maximization

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- Eigenvalues and Eigenvectors
- Positive Definite Matrices
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Questions

- What are the eigenvalues and eigenvectors?
- How to compute eigenvalues and eigenvectors?
- What is a quadratic form?
- How to express the statistical distance as a quadratic form?

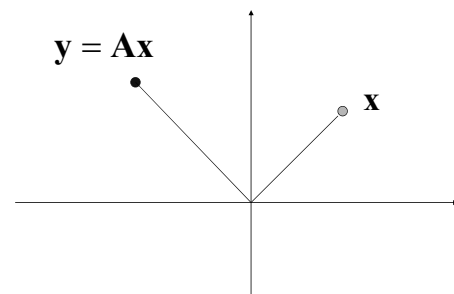
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Questions

- How to simplify a quadratic form?
- What is an orthogonal matrix?
- How to diagonalize a square matrix?
- What is the spectral decomposition?

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Concept of Mapping



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Eigenvalues

$$\mathbf{A}\mathbf{x} = \lambda\mathbf{x}$$

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

$$\mathbf{A} = \begin{bmatrix} 1 & 0 \\ 1 & 3 \end{bmatrix}$$

$$|\mathbf{A} - \lambda\mathbf{I}| = \begin{vmatrix} 1-\lambda & 0 \\ 1 & 3-\lambda \end{vmatrix} = (1-\lambda)(3-\lambda) = 0$$

$$\lambda_1 = 1, \quad \lambda_2 = 3$$

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Eigenvectors

$$(\mathbf{A} - \lambda_i\mathbf{I})\mathbf{x}_i = \mathbf{0}$$

$$\lambda_1 = 1$$

$$\begin{bmatrix} 0 & 0 \\ 1 & 2 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}, \quad \mathbf{x}_1 = \begin{bmatrix} -2 \\ 1 \end{bmatrix}$$

$$\lambda_2 = 3$$

$$\begin{bmatrix} -2 & 0 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}, \quad \mathbf{x}_2 = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

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Quadratic Form

$$Q(\mathbf{x}) = \mathbf{x}'\mathbf{A}\mathbf{x} = \sum_{i=1}^k \sum_{j=1}^k a_{ij}x_i x_j$$

$$Q(x) = \begin{bmatrix} x_1 & x_2 \end{bmatrix} \begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = x_1^2 + 2x_1x_2 + x_2^2$$

$$Q(x) = \begin{bmatrix} x_1 & x_2 & x_3 \end{bmatrix} \begin{bmatrix} 1 & 3 & 0 \\ 3 & -1 & -2 \\ 0 & -2 & 2 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}$$

$$= x_1^2 + 6x_1x_2 - x_2^2 - 4x_2x_3 + 2x_3^2$$

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General Statistical Distance

$$P(x_1, x_2, \dots, x_p), \quad O(0, 0, \dots, 0), \quad Q(y_1, y_2, \dots, y_p)$$

$$d(O, P) = \sqrt{[a_{11}x_1^2 + a_{22}x_2^2 + \dots + a_{pp}x_p^2 + 2a_{12}x_1x_2 + 2a_{13}x_1x_3 + \dots + 2a_{p-1,p}x_{p-1}x_p]}$$

$$d(P, Q) = \sqrt{[a_{11}(x_1 - y_1)^2 + a_{22}(x_2 - y_2)^2 + \dots + a_{pp}(x_p - y_p)^2 + 2a_{12}(x_1 - y_1)(x_2 - y_2) + 2a_{13}(x_1 - y_1)(x_3 - y_3) + \dots + 2a_{p-1,p}(x_{p-1} - y_{p-1})(x_p - y_p)]}$$

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General Statistical Distance

$$d^2(O, P) = [a_{11}x_1^2 + a_{22}x_2^2 + \dots + a_{pp}x_p^2 + 2a_{12}x_1x_2 + 2a_{13}x_1x_3 + \dots + 2a_{p-1,p}x_{p-1}x_p]$$

$$= \begin{bmatrix} x_1 & x_2 & \dots & x_p \end{bmatrix} \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1p} \\ a_{12} & a_{22} & \dots & a_{2p} \\ \vdots & \vdots & \ddots & \vdots \\ a_{1p} & a_{2p} & \dots & a_{pp} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_p \end{bmatrix}$$

$$= \mathbf{x}'\mathbf{A}\mathbf{x}$$

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Statistical Distance under Rotated Coordinate System

$$O(0,0), \quad P(\tilde{x}_1, \tilde{x}_2)$$

$$d(O, P) = \sqrt{\frac{\tilde{x}_1^2}{\tilde{s}_{11}} + \frac{\tilde{x}_2^2}{\tilde{s}_{22}}}$$

$$\tilde{x}_1 = x_1 \cos \theta + x_2 \sin \theta$$

$$\tilde{x}_2 = -x_1 \sin \theta + x_2 \cos \theta$$

$$d(O, P) = \sqrt{a_{11}x_1^2 + 2a_{12}x_1x_2 + a_{22}x_2^2}$$

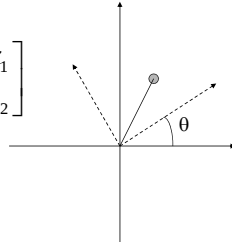
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Rotated Coordinate System

$$\tilde{x}_1 = x_1 \cos \theta + x_2 \sin \theta$$

$$\tilde{x}_2 = -x_1 \sin \theta + x_2 \cos \theta$$

$$\begin{bmatrix} \tilde{x}_1 \\ \tilde{x}_2 \end{bmatrix} = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$$



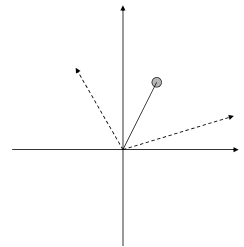
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Coordinate Transformation

$$\mathbf{y} = \mathbf{B}\mathbf{x}$$

$$\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_k \end{bmatrix} = \begin{bmatrix} b_{11} & b_{12} & \cdots & b_{1k} \\ b_{21} & b_{22} & \cdots & b_{2k} \\ \vdots & \vdots & \ddots & \vdots \\ b_{k1} & b_{k2} & \cdots & b_{kk} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_k \end{bmatrix}$$

$$\mathbf{y} = \begin{bmatrix} \mathbf{b}_1 \\ \mathbf{b}_2 \\ \vdots \\ \mathbf{b}_k \end{bmatrix} \mathbf{x}$$



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Quadratic Form in Transformed Coordinate Systems

$$\begin{aligned} Q(\mathbf{x}) &= \mathbf{x}' \mathbf{A} \mathbf{x} \\ &= (\mathbf{B}^{-1} \mathbf{y})' \mathbf{A} (\mathbf{B}^{-1} \mathbf{y}) \\ &= \mathbf{y}' \mathbf{B}^{-1'} \mathbf{A} \mathbf{B}^{-1} \mathbf{y} \\ &= \mathbf{y}' \mathbf{\Lambda} \mathbf{y} = Q(\mathbf{y}) \end{aligned}$$

$$\mathbf{B}^{-1'} \mathbf{A} \mathbf{B}^{-1} = \mathbf{\Lambda}$$

$$\mathbf{A} \mathbf{B}^{-1} = \mathbf{B}' \mathbf{\Lambda}$$

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Diagonalized Quadratic Form

$$\mathbf{\Lambda} = \begin{bmatrix} \lambda_1 & 0 & \cdots & 0 \\ 0 & \lambda_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \lambda_k \end{bmatrix}$$

$$Q(\mathbf{y}) = \mathbf{y}' \mathbf{\Lambda} \mathbf{y} = \sum_{i=1}^k \lambda_i y_i^2$$

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Orthogonal Matrix

$$\mathbf{A} \mathbf{A}' = \mathbf{A}' \mathbf{A} = \mathbf{I}$$

$$\mathbf{A}^{-1} = \mathbf{A}'$$

$$\begin{bmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

$$\begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix}^{-1} = \begin{bmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{bmatrix}$$

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Diagonalization

$$\mathbf{B}^{-1} = \mathbf{B}'$$

$$\mathbf{A} \mathbf{B}' = \mathbf{B}' \mathbf{\Lambda}$$

$$\begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1k} \\ a_{21} & a_{22} & \cdots & a_{2k} \\ \vdots & \vdots & \ddots & \vdots \\ a_{k1} & a_{k2} & \cdots & a_{kk} \end{bmatrix} \begin{bmatrix} \mathbf{b}_1 & \mathbf{b}_2 & \cdots & \mathbf{b}_k \end{bmatrix} =$$

$$\begin{bmatrix} \mathbf{b}_1 & \mathbf{b}_2 & \cdots & \mathbf{b}_k \end{bmatrix} \begin{bmatrix} \lambda_1 & 0 & \cdots & 0 \\ 0 & \lambda_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \lambda_k \end{bmatrix}$$

$$\mathbf{A} \mathbf{b}_i = \lambda_i \mathbf{b}_i$$

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Spectral Decomposition

$$AB' = B' A$$

$$A = B' \Lambda B$$

$$A = \begin{bmatrix} \mathbf{e}_1 & \mathbf{e}_2 & \dots & \mathbf{e}_k \end{bmatrix} \begin{bmatrix} \lambda_1 & 0 & \dots & 0 \\ 0 & \lambda_2 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & \lambda_k \end{bmatrix} \begin{bmatrix} \mathbf{e}_1' \\ \mathbf{e}_2' \\ \vdots \\ \mathbf{e}_k' \end{bmatrix}$$

$$= \sum_{i=1}^k \lambda_i \mathbf{e}_i \mathbf{e}_i'$$

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Question

- What is a positive definite matrix?
- Why to learn the concept of positive definite matrix?

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Positive Definite Matrix

- Matrix A is non-negative definite if

$$\mathbf{x}' A \mathbf{x} \geq 0$$

for all $\mathbf{x}' = [x_1, x_2, \dots, x_k]$

- Matrix A is positive definite if

$$\mathbf{x}' A \mathbf{x} > 0$$

for all non-zero $\mathbf{x}$

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Positive Definite Matrix

$$3x_1^2 + 2x_2^2 - 2\sqrt{2}x_1x_2 = \begin{bmatrix} x_1 & x_2 \end{bmatrix} \begin{bmatrix} 3 & -\sqrt{2} \\ -\sqrt{2} & 2 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$$

$$= \mathbf{x} A \mathbf{x}$$

$$\lambda_1 = 4, \lambda_2 = 1$$

$$A = 4\mathbf{e}_1\mathbf{e}_1' + \mathbf{e}_2\mathbf{e}_2'$$

$$\mathbf{x}' A \mathbf{x} = 4\mathbf{x}'\mathbf{e}_1\mathbf{e}_1'\mathbf{x} + \mathbf{x}'\mathbf{e}_2\mathbf{e}_2'\mathbf{x} = 4y_1^2 + y_2^2 \geq 0$$

$$y_1 = \mathbf{x}'\mathbf{e}_1 = \mathbf{e}_1'\mathbf{x}, y_2 = \mathbf{x}'\mathbf{e}_2 = \mathbf{e}_2'\mathbf{x}$$

$$\mathbf{y} = E\mathbf{x}, E \text{ orthogonal and } E^{-1} = E'$$

$$\mathbf{x}' A \mathbf{x} > 0 \text{ for all } \mathbf{x}' \neq \mathbf{0}$$

$$\therefore A \text{ is positive definite}$$

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Question

- How to find the square-root of a symmetric square matrix?
- Why to learn the square-root matrix?

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Inverse and Square-Root Matrix

$$\mathbf{A} = \sum_{i=1}^k \lambda_i \mathbf{e}_i \mathbf{e}_i' = \mathbf{P} \mathbf{\Lambda} \mathbf{P}',$$

$$\mathbf{A}^{-1} = \mathbf{P} \mathbf{\Lambda}^{-1} \mathbf{P}'$$

$$\mathbf{A}^n = (\mathbf{P} \mathbf{\Lambda} \mathbf{P}') (\mathbf{P} \mathbf{\Lambda} \mathbf{P}') \cdots (\mathbf{P} \mathbf{\Lambda} \mathbf{P}') = \mathbf{P} \mathbf{\Lambda}^n \mathbf{P}'$$

$$\lambda_i > 0, i = 1, \dots, k$$

$$\mathbf{A}^{1/2} = \sum_{i=1}^k \sqrt{\lambda_i} \mathbf{e}_i \mathbf{e}_i' = \mathbf{P} \mathbf{\Lambda}^{1/2} \mathbf{P}'$$

$$\mathbf{A}^{1/2} \mathbf{A}^{1/2} = \mathbf{A}$$

$$(\mathbf{A}^{1/2})' = \mathbf{A}^{1/2}$$

$$\mathbf{A}^{-1/2} = (\mathbf{A}^{1/2})^{-1}$$

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Question

- What is a random vector?
- What is a random matrix?
- How to find the expectation of a random matrix?

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Random Vectors and Random Matrices

- Random vector
 - Vector whose elements are random variables
- Random matrix
 - Matrix whose elements are random variables

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Expected Value of a Random Matrix

$$E(\mathbf{X}) = \begin{bmatrix} E(X_{11}) & E(X_{12}) & \cdots & E(X_{1p}) \\ E(X_{21}) & E(X_{22}) & \cdots & E(X_{2p}) \\ \vdots & \vdots & \ddots & \vdots \\ E(X_{p1}) & E(X_{p2}) & \cdots & E(X_{pp}) \end{bmatrix}$$

$$E(X_{ij}) = \begin{cases} \int_{-\infty}^{\infty} x_{ij} f_{ij}(x_{ij}) dx_{ij} \\ \sum_{\text{all } x_{ij}} x_{ij} p_{ij}(x_{ij}) \end{cases}$$

$$E(\mathbf{AXB}) = \mathbf{AE}(\mathbf{X})\mathbf{B}$$

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Questions

- What is the population?
- How to compute population mean vectors and population covariance matrices?
- What is the statistical independence?
- If $\text{cov}(x_1, x_2) = 0$, will x_1 and x_2 be statistical independent?

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Questions

- How to compute the population correlation coefficient matrix?
- How to partition the covariance matrix?
- How to compute population mean vector and covariance matrix of a linear combination of random vectors?

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Questions

- What are the sample mean vectors and the sample covariance matrices?
- How to partition a sample mean vector and a sample covariance matrix?

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Population Mean Vectors

Random vector $\mathbf{X} = [X_1 \ X_2 \ \cdots \ X_p]$

Joint probability density function

$$f(\mathbf{x}) = f(x_1, x_2, \dots, x_p)$$

Marginal probability distribution $f(x_i)$

$$\mu_i = E(X_i)$$

$$\sigma_i^2 = E(X_i - \mu_i)^2$$

$$\boldsymbol{\mu} = E(\mathbf{X}) = [\mu_1 \ \mu_2 \ \cdots \ \mu_p]$$

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Covariance

$$\text{Cov}(X_i, X_k) = E(X_i - \mu_i)(X_k - \mu_k)$$

$$= \begin{cases} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} (x_i - \mu_i)(x_k - \mu_k) f_{ik}(x_i, x_k) dx_i dx_k \\ \sum_{\text{all } x_i \text{ all } x_k} (x_i - \mu_i)(x_k - \mu_k) p_{ik}(x_i, x_k) \end{cases}$$

$$= \sigma_{ik}$$

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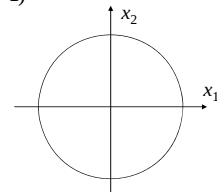
Statistically Independent

$$\begin{aligned}
 P[X_i \leq x_i \text{ and } X_k \leq x_k] &= P[X_i \leq x_i]P[X_k \leq x_k] \\
 f_{ik}(x_i, x_k) &= f_i(x_i)f_k(x_k) \\
 f_{12 \dots p}(x_1, x_2, \dots, x_p) &= f_1(x_1)f_2(x_2) \cdots f_p(x_p) \\
 \text{Cov}(X_i, X_k) &= 0 \text{ if } X_i, X_k \text{ are independent} \\
 &\text{(the converse is not true in general)}
 \end{aligned}$$

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Joint Probability Density Function

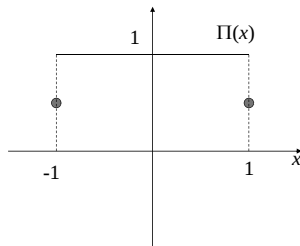
$$\begin{aligned}
 f(x_1, x_2) &= \begin{cases} f(\theta) = \frac{1}{2\pi}, x_1^2 + x_2^2 = 1, \theta = \text{atan } 2(x_2, x_1) \\ 0, \text{otherwise} \end{cases} \\
 &= \frac{1}{2\pi} \delta(x_1^2 + x_2^2 - 1)
 \end{aligned}$$



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Marginal Probability Density Function

$$\begin{aligned}
 f_1(x_1) &= \int_{-\infty}^{\infty} f(x_1, x_2) dx_2 = \int_{-\infty}^{\infty} \frac{1}{2\pi} \left\{ \delta(x_2 - \sqrt{1-x_1^2}) + \delta(x_2 + \sqrt{1-x_1^2}) \right\} dx_2 \\
 &= \begin{cases} \frac{1}{\pi}, |x_1| < 1 \\ \frac{1}{2\pi}, |x_1| = 1 \\ 0, \text{otherwise} \end{cases} \\
 &= \frac{1}{\pi} \Pi(x_1) \\
 f_2(x_2) &= \frac{1}{\pi} \Pi(x_2) \\
 f(x_1, x_2) &\neq f_1(x_1)f_2(x_2)
 \end{aligned}$$



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Marginal Means and Covariance

$$\begin{aligned}
 \mu_1 &= \int_{-\infty}^{\infty} x_1 f_1(x_1) dx_1 = \frac{1}{\pi} \int_{-1}^1 x_1 dx_1 = 0 \\
 \mu_2 &= 0 \\
 \text{Cov}(x_1, x_2) &= \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} (x_1 - \mu_1)(x_2 - \mu_2) f(x_1, x_2) dx_1 dx_2 \\
 &= \int_{-\pi}^{\pi} \int_0^{\infty} \rho \cos \theta \sin \theta f(\theta) \delta(\rho - 1) \rho d\rho d\theta \\
 &= \int_{-\pi}^{\pi} \cos \theta \sin \theta \frac{1}{2\pi} d\theta = 0
 \end{aligned}$$

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Population Variance-Covariance Matrices

$$\begin{aligned}
 \Sigma &= E(\mathbf{X} - \boldsymbol{\mu})(\mathbf{X} - \boldsymbol{\mu})' \\
 &= E \left(\begin{bmatrix} X_1 - \mu_1 \\ X_2 - \mu_2 \\ \vdots \\ X_p - \mu_p \end{bmatrix} \begin{bmatrix} X_1 - \mu_1 & X_2 - \mu_2 & \cdots & X_p - \mu_p \end{bmatrix} \right) \\
 &= \text{Cov}(\mathbf{X}) = \begin{bmatrix} \sigma_{11} & \sigma_{12} & \cdots & \sigma_{1p} \\ \sigma_{21} & \sigma_{22} & \cdots & \sigma_{2p} \\ \vdots & \vdots & \ddots & \vdots \\ \sigma_{p1} & \sigma_{p2} & \cdots & \sigma_{pp} \end{bmatrix}
 \end{aligned}$$

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Population Correlation Coefficients

$$\begin{aligned}
 \rho &= \begin{bmatrix} \rho_{11} & \rho_{12} & \cdots & \rho_{1p} \\ \rho_{21} & \rho_{22} & \cdots & \rho_{2p} \\ \vdots & \vdots & \ddots & \vdots \\ \rho_{p1} & \rho_{p2} & \cdots & \rho_{pp} \end{bmatrix} \\
 \rho_{ik} &= \frac{\sigma_{ik}}{\sqrt{\sigma_{ii}} \sqrt{\sigma_{kk}}} \\
 \rho_{ii} &= 1
 \end{aligned}$$

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Standard Deviation Matrix

$$\mathbf{V}^{1/2} = \begin{bmatrix} \sqrt{\sigma_{11}} & 0 & \cdots & 0 \\ 0 & \sqrt{\sigma_{22}} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \sqrt{\sigma_{pp}} \end{bmatrix}$$

$$\Sigma = \mathbf{V}^{1/2} \boldsymbol{\rho} \mathbf{V}^{1/2}$$

$$\boldsymbol{\rho} = \mathbf{V}^{-1/2} \Sigma \mathbf{V}^{-1/2}$$

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Correlation Matrix from Covariance Matrix

$$\Sigma = \begin{bmatrix} 4 & 1 & 2 \\ 1 & 9 & -3 \\ 2 & -3 & 25 \end{bmatrix} = \begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22} & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} \end{bmatrix}$$

$$\mathbf{V}^{1/2} = \begin{bmatrix} \sqrt{\sigma_{11}} & 0 & 0 \\ 0 & \sqrt{\sigma_{22}} & 0 \\ 0 & 0 & \sqrt{\sigma_{33}} \end{bmatrix} = \begin{bmatrix} 2 & 0 & 0 \\ 0 & 3 & 0 \\ 0 & 0 & 5 \end{bmatrix}$$

$$\mathbf{V}^{-1/2} = \begin{bmatrix} 1/2 & 0 & 0 \\ 0 & 1/3 & 0 \\ 0 & 0 & 1/5 \end{bmatrix}$$

$$\boldsymbol{\rho} = \mathbf{V}^{-1/2} \Sigma \mathbf{V}^{-1/2} = \begin{bmatrix} 1 & 1/6 & 1/5 \\ 1/6 & 1 & -1/5 \\ 1/5 & -1/5 & 1 \end{bmatrix}$$

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Partitioning Covariance Matrix

$$\mathbf{X} = \begin{bmatrix} X_1 \\ \vdots \\ X_q \\ \vdots \\ X_{q+1} \\ \vdots \\ X_p \end{bmatrix} = \begin{bmatrix} \mathbf{X}^{(1)} \\ \mathbf{X}^{(2)} \end{bmatrix}, \boldsymbol{\mu} = \begin{bmatrix} \boldsymbol{\mu}^{(1)} \\ \boldsymbol{\mu}^{(2)} \end{bmatrix}$$

$$(\mathbf{X} - \boldsymbol{\mu})(\mathbf{X} - \boldsymbol{\mu})' =$$

$$\begin{bmatrix} (\mathbf{X}^{(1)} - \boldsymbol{\mu}^{(1)})(\mathbf{X}^{(1)} - \boldsymbol{\mu}^{(1)})' & (\mathbf{X}^{(1)} - \boldsymbol{\mu}^{(1)})(\mathbf{X}^{(2)} - \boldsymbol{\mu}^{(2)})' \\ (\mathbf{X}^{(2)} - \boldsymbol{\mu}^{(2)})(\mathbf{X}^{(1)} - \boldsymbol{\mu}^{(1)})' & (\mathbf{X}^{(2)} - \boldsymbol{\mu}^{(2)})(\mathbf{X}^{(2)} - \boldsymbol{\mu}^{(2)})' \end{bmatrix}$$

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Partitioning Covariance Matrix

$$\Sigma = E(\mathbf{X} - \boldsymbol{\mu})(\mathbf{X} - \boldsymbol{\mu})' = \begin{bmatrix} \Sigma_{11} & \Sigma_{12} \\ \Sigma_{21} & \Sigma_{22} \end{bmatrix}$$

$$= \begin{bmatrix} \sigma_{11} & \cdots & \sigma_{1q} & | & \sigma_{1,q+1} & \cdots & \sigma_{1p} \\ \vdots & \ddots & \vdots & | & \vdots & \ddots & \vdots \\ \sigma_{q1} & \cdots & \sigma_{qq} & | & \sigma_{q,q+1} & \cdots & \sigma_{qp} \\ \vdots & \vdots & \vdots & | & \vdots & \vdots & \vdots \\ \sigma_{q+1,1} & \cdots & \sigma_{q+1,q} & | & \sigma_{q+1,q+1} & \cdots & \sigma_{q+1,p} \\ \vdots & \vdots & \vdots & | & \vdots & \ddots & \vdots \\ \sigma_{p1} & \cdots & \sigma_{pq} & | & \sigma_{p,q+1} & \cdots & \sigma_{pp} \end{bmatrix}$$

$$\Sigma_{21} = \Sigma'_{12}$$

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Linear Combinations of Random Variables

Linear combination $\mathbf{c}'\mathbf{X} = c_1X_1 + \cdots + c_pX_p$ has

$$\text{mean} = E(\mathbf{c}'\mathbf{X}) = \mathbf{c}'\boldsymbol{\mu}$$

$$\text{variance} = \text{Var}(\mathbf{c}'\mathbf{X}) = \mathbf{c}'\Sigma\mathbf{c}$$

where $\boldsymbol{\mu} = E(\mathbf{X})$ and $\Sigma = \text{Cov}(\mathbf{X})$

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Example of Linear Combinations of Random Variables

$$E(aX_1 + bX_2) = aE(X_1) + bE(X_2) = a\mu_1 + b\mu_2$$

$$\text{Var}(aX_1 + bX_2) = E[(aX_1 + bX_2) - (a\mu_1 + b\mu_2)]^2$$

$$= E[a(X_1 - \mu_1) + b(X_2 - \mu_2)]^2$$

$$= a^2\sigma_{11} + b^2\sigma_{22} + 2ab\sigma_{12}$$

$$\mathbf{c}' = [a, b], \mathbf{X}' = [X_1, X_2]$$

$$E(\mathbf{c}'\mathbf{X}) = \mathbf{c}'\boldsymbol{\mu}$$

$$\text{Var}(\mathbf{c}'\mathbf{X}) = [a \ b] \begin{bmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{12} & \sigma_{22} \end{bmatrix} \begin{bmatrix} a \\ b \end{bmatrix} = \mathbf{c}'\Sigma\mathbf{c}$$

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Linear Combinations of Random Variables

$$\mathbf{Z} = \begin{bmatrix} c_{11} & c_{12} & \cdots & c_{1p} \\ c_{21} & c_{22} & \cdots & c_{2p} \\ \vdots & \vdots & \ddots & \vdots \\ c_{p1} & c_{p2} & \cdots & c_{pp} \end{bmatrix} \mathbf{X} = \mathbf{C}\mathbf{X}$$

$$\boldsymbol{\mu}_Z = E(\mathbf{Z}) = E(\mathbf{C}\mathbf{X}) = \mathbf{C}\boldsymbol{\mu}_X$$

$$\boldsymbol{\Sigma}_Z = \text{Cov}(\mathbf{C}\mathbf{X}) = \mathbf{C}\boldsymbol{\Sigma}_X\mathbf{C}'$$

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Sample Mean Vector and Covariance Matrix

$$\bar{\mathbf{x}}' = [\bar{x}_1, \bar{x}_2, \dots, \bar{x}_p]$$

$$\mathbf{S}_n = \begin{bmatrix} s_{11} & \cdots & s_{1p} \\ \vdots & \ddots & \vdots \\ s_{1p} & \cdots & s_{pp} \end{bmatrix}$$

$$= \begin{bmatrix} \frac{1}{n} \sum_{j=1}^n (x_{j1} - \bar{x}_1)^2 & \cdots & \frac{1}{n} \sum_{j=1}^n (x_{j1} - \bar{x}_1)(x_{jp} - \bar{x}_p) \\ \vdots & \ddots & \vdots \\ \frac{1}{n} \sum_{j=1}^n (x_{j1} - \bar{x}_1)(x_{jp} - \bar{x}_p) & \cdots & \frac{1}{n} \sum_{j=1}^n (x_{jp} - \bar{x}_p)^2 \end{bmatrix}$$

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Partitioning Sample Mean Vector

$$\bar{\mathbf{x}} = \begin{bmatrix} \bar{x}_1 \\ \vdots \\ \bar{x}_q \\ \hline \bar{x}_{q+1} \\ \vdots \\ \bar{x}_p \end{bmatrix} = \begin{bmatrix} \bar{\mathbf{x}}^{(1)} \\ \hline \bar{\mathbf{x}}^{(2)} \end{bmatrix}$$

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Partitioning Sample Covariance Matrix

$$\mathbf{S}_n = \begin{bmatrix} \mathbf{S}_{11} & | & \mathbf{S}_{12} \\ \hline \mathbf{S}_{21} & | & \mathbf{S}_{22} \end{bmatrix} = \begin{bmatrix} s_{11} & \cdots & s_{1q} & | & s_{1,q+1} & \cdots & s_{1p} \\ \vdots & \ddots & \vdots & | & \vdots & \ddots & \vdots \\ s_{q1} & \cdots & s_{qq} & | & s_{q,q+1} & \cdots & s_{qp} \\ \hline s_{q+1,1} & \cdots & s_{q+1,q} & | & s_{q+1,q+1} & \cdots & s_{q+1,p} \\ \vdots & \ddots & \vdots & | & \vdots & \ddots & \vdots \\ s_{p1} & \cdots & s_{pq} & | & s_{p,q+1} & \cdots & s_{pp} \end{bmatrix}$$

$$\mathbf{S}_{21} = \mathbf{S}_{12}'$$

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Outline

- Eigenvalues and Eigenvectors
- Positive Definite Matrices
- A Square-Root Matrix
- Random Vectors and Matrices
- Mean Vectors and Covariance Matrices
- Matrix Inequalities and Maximization

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Questions

- What is the Cauchy-Schwarz inequality?
- How to prove the Cauchy-Schwarz inequality?
- What is the extended Cauchy-Schwarz inequality?
- How to prove the extended Cauchy-Schwarz inequality?

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Questions

- What is the maximization lemma?
- How to maximize a quadratic form for points on the unit sphere?
- What is the Rayleigh's quotient?
- How to maximize and minimize the Rayleigh's quotient?

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Cauchy-Schwarz Inequality

$(\mathbf{b}'\mathbf{d})^2 \leq (\mathbf{b}'\mathbf{b})(\mathbf{d}'\mathbf{d})$, with equality when $\mathbf{b} = c\mathbf{d}$

Proof :

$$\mathbf{b} - x\mathbf{d} \neq 0$$

$$0 < (\mathbf{b} - x\mathbf{d})'(\mathbf{b} - x\mathbf{d}) = \mathbf{b}'\mathbf{b} - 2x(\mathbf{b}'\mathbf{d}) + x^2(\mathbf{d}'\mathbf{d})$$

$$0 < \mathbf{b}'\mathbf{b} - \frac{(\mathbf{b}'\mathbf{d})^2}{\mathbf{d}'\mathbf{d}} + (\mathbf{d}'\mathbf{d})\left(x - \frac{\mathbf{b}'\mathbf{d}}{\mathbf{d}'\mathbf{d}}\right)^2$$

$$0 < \mathbf{b}'\mathbf{b} - \frac{(\mathbf{b}'\mathbf{d})^2}{\mathbf{d}'\mathbf{d}}$$

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Extended Cauchy-Schwarz Inequality

$\mathbf{B}$ positive definite

$(\mathbf{b}'\mathbf{d})^2 \leq (\mathbf{b}'\mathbf{B}\mathbf{b})(\mathbf{d}'\mathbf{B}^{-1}\mathbf{d})$ with equality when $\mathbf{b} = c\mathbf{B}^{-1}\mathbf{d}$

Proof :

$$\mathbf{b}'\mathbf{d} = \mathbf{b}'\mathbf{I}\mathbf{d} = \mathbf{b}'\mathbf{B}^{1/2}\mathbf{B}^{-1/2}\mathbf{d} = (\mathbf{B}^{1/2}\mathbf{b})'(\mathbf{B}^{-1/2}\mathbf{d})$$

$$((\mathbf{B}^{1/2}\mathbf{b})'(\mathbf{B}^{-1/2}\mathbf{d}))^2 \leq (\mathbf{b}'\mathbf{B}^{1/2}\mathbf{B}^{1/2}\mathbf{b})(\mathbf{d}'\mathbf{B}^{-1/2}\mathbf{B}^{-1/2}\mathbf{d})$$

$$(\mathbf{b}'\mathbf{d})^2 \leq (\mathbf{b}'\mathbf{B}\mathbf{b})(\mathbf{d}'\mathbf{B}^{-1}\mathbf{d})$$

$$\mathbf{B}^{1/2} = \sum_{i=1}^p \sqrt{\lambda_i} \mathbf{e}_i \mathbf{e}_i'$$

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Maximization Lemma

$\mathbf{B}$ positive definite matrix, $\mathbf{d}$ given vector

$$\max_{\mathbf{x} \neq 0} \frac{(\mathbf{x}'\mathbf{d})^2}{\mathbf{x}'\mathbf{B}\mathbf{x}} = \mathbf{d}'\mathbf{B}^{-1}\mathbf{d}$$

maximum attained when $\mathbf{x} = c\mathbf{B}^{-1}\mathbf{d}$ for $c \neq 0$

Proof :

$$(\mathbf{x}'\mathbf{d})^2 \leq (\mathbf{x}'\mathbf{B}\mathbf{x})(\mathbf{d}'\mathbf{B}^{-1}\mathbf{d})$$

$$\mathbf{x}'\mathbf{B}\mathbf{x} > 0$$

$$\frac{(\mathbf{x}'\mathbf{d})^2}{\mathbf{x}'\mathbf{B}\mathbf{x}} \leq \mathbf{d}'\mathbf{B}^{-1}\mathbf{d}$$

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Maximization of Quadratic Forms for Points on the Unit Sphere

$\mathbf{B}$ positive definite matrix with eigen values

$\lambda_1 \geq \lambda_2 \geq \dots \geq \lambda_p > 0$ and associated eigenvectors

$\mathbf{e}_1, \mathbf{e}_2, \dots, \mathbf{e}_p \Rightarrow$

$$\max_{\mathbf{x} \neq 0} \frac{\mathbf{x}'\mathbf{B}\mathbf{x}}{\mathbf{x}'\mathbf{x}} = \lambda_1 \quad (\text{attained when } \mathbf{x} = \mathbf{e}_1)$$

$$\min_{\mathbf{x} \neq 0} \frac{\mathbf{x}'\mathbf{B}\mathbf{x}}{\mathbf{x}'\mathbf{x}} = \lambda_p \quad (\text{attained when } \mathbf{x} = \mathbf{e}_p)$$

$$\max_{\mathbf{x} \perp \mathbf{e}_1, \dots, \mathbf{e}_k} \frac{\mathbf{x}'\mathbf{B}\mathbf{x}}{\mathbf{x}'\mathbf{x}} = \lambda_{k+1} \quad (\text{attained when } \mathbf{x} = \mathbf{e}_{k+1})$$

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Maximization of Quadratic Forms for Points on the Unit Sphere

Proof :

$$\mathbf{B}^{1/2} = \mathbf{P}\mathbf{\Lambda}^{1/2}\mathbf{P}', \quad \mathbf{y} = \mathbf{P}'\mathbf{x}$$

$$\frac{\mathbf{x}'\mathbf{B}\mathbf{x}}{\mathbf{x}'\mathbf{x}} = \frac{\mathbf{x}'\mathbf{B}^{1/2}\mathbf{B}^{1/2}\mathbf{x}}{\mathbf{x}'\mathbf{P}\mathbf{P}'\mathbf{x}} = \frac{\mathbf{x}'\mathbf{P}\mathbf{\Lambda}^{1/2}\mathbf{P}'\mathbf{P}\mathbf{\Lambda}^{1/2}\mathbf{P}'\mathbf{x}}{\mathbf{y}'\mathbf{y}}$$

$$= \frac{\mathbf{y}'\mathbf{\Lambda}\mathbf{y}}{\mathbf{y}'\mathbf{y}} = \frac{\sum_{i=1}^p \lambda_i y_i^2}{\sum_{i=1}^p y_i^2} \leq \lambda_1 \frac{\sum_{i=1}^p y_i^2}{\sum_{i=1}^p y_i^2} = \lambda_1$$

$$\mathbf{x} = \mathbf{e}_1, \mathbf{y}' = (\mathbf{P}\mathbf{e})' = [1 \ 0 \ \dots \ 0], \frac{\mathbf{y}'\mathbf{\Lambda}\mathbf{y}}{\mathbf{y}'\mathbf{y}} = \lambda_1 = \frac{\mathbf{e}_1'\mathbf{B}\mathbf{e}_1}{\mathbf{e}_1'\mathbf{e}_1}$$

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Maximization of Quadratic Forms for Points on the Unit Sphere

$$\mathbf{x} = \mathbf{P}\mathbf{y} = y_1\mathbf{e}_1 + y_2\mathbf{e}_2 + \cdots + y_p\mathbf{e}_p$$

$\mathbf{x} \perp \mathbf{e}_1, \dots, \mathbf{e}_k$ implies

$$0 = \mathbf{e}_i' \mathbf{x} = y_1 \mathbf{e}_i' \mathbf{e}_1 + y_2 \mathbf{e}_i' \mathbf{e}_2 + \cdots + y_p \mathbf{e}_i' \mathbf{e}_p = y_i, i \leq k$$

$$\frac{\mathbf{x}' \mathbf{B} \mathbf{x}}{\mathbf{x}' \mathbf{x}} = \frac{\sum_{i=k+1}^p \lambda_i y_i^2}{\sum_{i=k+1}^p y_i^2} \leq \lambda_{k+1}$$

Taking $y_{k+1} = 1, y_{k+2} = \cdots = y_p = 0$ gives the asserted maximum

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Maximization of Quadratic Forms for Points on the Unit Sphere

$$\mathbf{x} = \frac{\mathbf{x}_0}{\sqrt{\mathbf{x}_0' \mathbf{x}_0}} \Rightarrow \mathbf{x}' \mathbf{x} = 1, \mathbf{x}' \mathbf{B} \mathbf{x} = \frac{\mathbf{x}_0' \mathbf{B} \mathbf{x}_0}{\mathbf{x}_0' \mathbf{x}_0}$$

$$\max_{\mathbf{x}' \mathbf{x} = 1} \mathbf{x}' \mathbf{B} \mathbf{x} = \max_{\mathbf{x}_0 \neq 0} \frac{\mathbf{x}_0' \mathbf{B} \mathbf{x}_0}{\mathbf{x}_0' \mathbf{x}_0} = \lambda_1$$

$$\min_{\mathbf{x}' \mathbf{x} = 1} \mathbf{x}' \mathbf{B} \mathbf{x} = \min_{\mathbf{x}_0 \neq 0} \frac{\mathbf{x}_0' \mathbf{B} \mathbf{x}_0}{\mathbf{x}_0' \mathbf{x}_0} = \lambda_p$$

$$\max_{\mathbf{x}' \mathbf{x} = 1, \mathbf{x} \perp \mathbf{e}_1, \dots, \mathbf{e}_k} \mathbf{x}' \mathbf{B} \mathbf{x} = \max_{\mathbf{x}_0 \neq 0, \mathbf{x}_0 \perp \mathbf{e}_1, \dots, \mathbf{e}_k} \frac{\mathbf{x}_0' \mathbf{B} \mathbf{x}_0}{\mathbf{x}_0' \mathbf{x}_0} = \lambda_{k+1}$$

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Rayleigh's Quotient

$$f(\mathbf{x}) = \frac{\mathbf{x}' \mathbf{B} \mathbf{x}}{\mathbf{x}' \mathbf{x}}$$

$$\mathbf{x} = \begin{bmatrix} x_1 & x_2 \end{bmatrix}$$

$$\mathbf{B} = \begin{bmatrix} \frac{1}{a^2} & 0 \\ 0 & \frac{1}{b^2} \end{bmatrix}, \quad a > b, \quad \lambda_1 = \frac{1}{b^2}, \quad \lambda_2 = \frac{1}{a^2}$$

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Rayleigh's Quotient in Polar Coordinates

$$\mathbf{x}' \mathbf{B} \mathbf{x} = \frac{x_1^2}{a^2} + \frac{x_2^2}{b^2} = \rho^2 \left(\frac{b^2 \cos^2 \theta + a^2 \sin^2 \theta}{a^2 b^2} \right)$$

$$\mathbf{x}' \mathbf{x} = x_1^2 + x_2^2 = \rho^2$$

$$\frac{\mathbf{x}' \mathbf{B} \mathbf{x}}{\mathbf{x}' \mathbf{x}} = \frac{b^2 \cos^2 \theta + a^2 \sin^2 \theta}{a^2 b^2}$$

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Equation of the Ellipse in Polar Coordinates

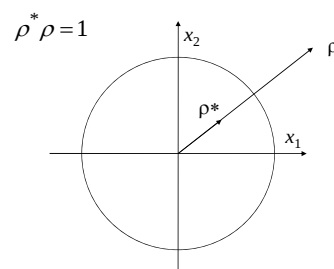
$$\frac{x_1^2}{a^2} + \frac{x_2^2}{b^2} = 1$$

$$\rho^2 = \left(\frac{b^2 \cos^2 \theta + a^2 \sin^2 \theta}{a^2 b^2} \right)^{-1}$$

$$\frac{\mathbf{x}' \mathbf{B} \mathbf{x}}{\mathbf{x}' \mathbf{x}} = \frac{1}{\rho^2} = \rho^{*2}$$

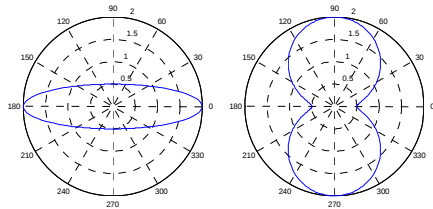
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Inversion with Respect to the Unit Circle



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Ellipse and Its Inversion with Respect to the Unit Circle



$$a = 2, \quad b = 0.5$$

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Maximum and Minimum of Rayleigh's Quotient

$$a = 2, \quad b = 0.5$$

$$\max_{\mathbf{x} \neq 0} \frac{\mathbf{x}' \mathbf{B} \mathbf{x}}{\mathbf{x}' \mathbf{x}} = \lambda_1 = \frac{1}{b^2} = 4$$

$$\min_{\mathbf{x} \neq 0} \frac{\mathbf{x}' \mathbf{B} \mathbf{x}}{\mathbf{x}' \mathbf{x}} = \lambda_2 = \frac{1}{a^2} = 0.25$$

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