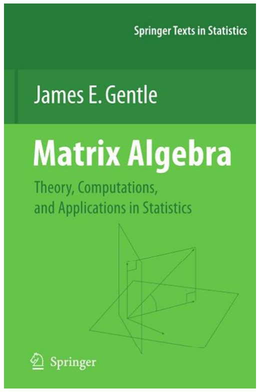
Theory of Matrices

Chapter 5. Matrix Transformations and Factorizations

5.9. Factorizations of Nonnegative Definite Matrices—Proofs of Theorems



Theorem 5.9.1

Theorem 5.9.1. Let A be a symmetric nonnegative definite matrix and let B be a symmetric nonnegative definite matrix such that $B^2 = A$. Then $B = VC^{1/2}V^T = VSV^T$ where $S = C^{1/2} = \text{diag}(c_1^{1/2}, c_2^{1/2}, \ldots, c_n^{1/2})$ where $c_1, c_2, \ldots, c_n$ are the eigenvalues of A and V is orthogonal.

Proof. By Theorem 3.8.A and Theorem 3.8.10, $A = VCV^T$ where V is orthogonal and $C = \text{diag}(c_1, c_2, \ldots, c_n)$. We have

$$\begin{aligned}(B - VC^{1/2}V^T)^2 &= (B - VC^{1/2}V^T)(B - VC^{1/2}V^T)\\ &= B^2 - VC^{1/2}V^TB - BVC^{1/2}V^T + (VC^{1/2}V^T)^2\\ &= A - VC^{1/2}V^TB - (VC^{1/2}V^TB^T)^T + A\\ &= 2A - VC^{1/2}V^TB - (VC^{1/2}V^TB)^T \qquad (*)\\ &\quad \text{since } B \text{ is symmetric.}\end{aligned}$$

Since B is symmetric nonnegative definite then, by Theorem 3.8.15(2), $B = UDU^T$ for orthogonal U and diagonal $D = \text{diag}(d_1, d_2, \ldots, d_n)$, where each d_i is nonnegative by Theorem 3.8.14.

Theorem 5.9.1 (continued 1)

Proof (continued). Now

$$\begin{aligned}V^TUD^2 &= V^TUD(U^TU)D(U^TU) \text{ since } U \text{ is orthogonal}\\ &= V^T(UDU^T)(UDU^T)U = V^TB^2U\\ &= V^TAU = V^T(VC^{1/2}V^T)^2U = V^TVC^{1/2}V^TVC^{1/2}V^TU\\ &= C^{1/2}C^{1/2}V^TU \text{ since } V \text{ is orthogonal}\\ &= CV^TU. \qquad (**)\end{aligned}$$

Let the (i,j) entry of V^TU be z_{ij}. Since D is diagonal, the (i,j) entry of V^TUD^2 is $z_{ij}d_j^2$. Since C is diagonal,the (i,j) entry of CV^TU is c_iz_{ij}. Since $V^TUD^2 = CV^TU$ by $(**)$, then $z_{ij}d_j^2 = c_iz_{ij}$ or $d_j^2z_{ij}^2 = c_iz_{ij}^2$ or $d_j|z_{ij}| = c_i^{1/2}|z_{ij}|$ or $d_j\,\text{sgn}(z_{ij})|z_{ij}| = c_i^{1/2}\text{sgn}(z_{ij})|z_{ij}|$, and so $d_jz_{ij} = c_i^{1/2}z_{ij}$. Now the (i,j) entry of V^TUD is $z_{ij}d_j$ and the (i,j) entry of $C^{1/2}V^TU$ is $c_i^{1/2}z_{ij}$. Hence $V^TUD = C^{1/2}V^TU$.

Theorem 5.9.1 (continued 2)

Proof (continued). We therefore have

$$\begin{aligned}VC^{1/2}V^TB &= VC^{1/2}V^T(UDU^T) \text{ since } B = UDU^T\\ &= VC^{1/2}(V^TUD)U^T\\ &= VC^{1/2}(C^{1/2}V^TU)U^T \text{ since } V^TUD = C^{1/2}V^TU\\ &= VCV^TUU^T = VCV^T \text{ since } U \text{ is orthogonal}\\ &= A \text{ since } A = VCV^T.\end{aligned}$$

From $(*)$ we have

$$\begin{aligned}(B - VC^{1/2}V^T)^2 &= 2A - VC^{1/2}V^TB - (VC^{1/2}V^TB)^T\\ &= 2A - A - A^T \text{ since } VC^{1/2}V^TB = A\\ &= 2A - 2A \text{ since } A \text{ is symmetric}\\ &= 0.\end{aligned}$$

Theorem 5.9.1 (continued 3)

Theorem 5.9.1. Let A be a symmetric nonnegative definite matrix and let B be a symmetric nonnegative definite matrix such that $B^2 = A$. Then $B = VC^{1/2}V^T = VSV^T$ where $S = C^{1/2} = \text{diag}(c_1^{1/2}, c_2^{1/2}, \ldots, c_n^{1/2})$ where $c_1, c_2, \ldots, c_n$ are the eigenvalues of A.

Proof (continued). Now B and $VC^{1/2}V^T$ are both symmetric, so $B - VC^{1/2}V^T$ is symmetric. In a symmetric matrix S, $S^2 = SS^T$ and the the (i,j) entries of S^2 are the inner product of the ith row of S with the ith column of S^T; that is, the (i,j) entry of S^2 is $\|s_i\|_F^2$ (the Frobenius norm or Euclidean matrix norm) where s_i is the ith column of S. So the only way $S^2 = 0$ for a symmetric matrix is when $S = 0$. Therefore we have $B = VC^{1/2}V^T$ and this is the unique square root of A. □

Theorem 5.9.2

Theorem 5.9.2. If A is a symmetric positive definite matrix, then A has a Cholesky factorization.

Proof. We give an inductive proof. If A is 1×1, say $A = [a_{11}]$, then $a_{11} > 0$ since A is positive definite and so we take $T = [\sqrt{a_{11}}]$. Then $T^T T = [\sqrt{a_{11}}][\sqrt{a_{11}}] = [a_{11}] = A$, and so A has a Cholesky factorization.

Now suppose all $n \times n$ symmetric positive definite matrices have Cholesky decompositions. Consider $(n+1) \times (n+1)$ matrix A.

Theorem 5.9.2

Theorem 5.9.2. If A is a symmetric positive definite matrix, then A has a Cholesky factorization.

Proof. We give an inductive proof. If A is 1×1, say $A = [a_{11}]$, then $a_{11} > 0$ since A is positive definite and so we take $T = [\sqrt{a_{11}}]$. Then $T^T T = [\sqrt{a_{11}}][\sqrt{a_{11}}] = [a_{11}] = A$, and so A has a Cholesky factorization.

Now suppose all $n \times n$ symmetric positive definite matrices have Cholesky decompositions. Consider $(n+1) \times (n+1)$ matrix A. Partition A as $A = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} = \begin{bmatrix} a_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix}$ where $A_{11} = [a_{11}]$. Consider the Schur complement of A_{11} in A, $Z = A_{22} - \frac{1}{a_{11}} A_{21} A_{12}$. By Exercise 5.9.A, $n \times n$ matrix Z is symmetric and positive definite. So by the induction hypothesis, Z has a Cholesky factorization, say $Z = T_Z^T T_Z$ where T_Z is an $n \times n$ upper triangular matrix with positive diagonal entries.

Theorem 5.9.2 (continued)

Proof (continued). Define T as $T = \begin{bmatrix} \sqrt{a_{11}} & \frac{1}{\sqrt{a_{11}}} A_{12} \\ 0 & T_Z \end{bmatrix}$. Since T_Z is upper triangular with positive diagonal entries, then T also has these two properties. Finally,

$$\begin{aligned} T^T T &= \begin{bmatrix} \sqrt{a_{11}} & 0 \\ \frac{1}{\sqrt{a_{11}}} A_{12}^T & T_Z^T \end{bmatrix} \begin{bmatrix} \sqrt{a_{11}} & \frac{1}{\sqrt{a_{11}}} A_{12} \\ 0 & T_Z \end{bmatrix} \\ &= \begin{bmatrix} a_{11} & A_{12} \\ A_{12}^T & \frac{1}{a_{11}} A_{12}^T A_{12} + T_Z^T T_Z \end{bmatrix} = \begin{bmatrix} a_{11} & A_{12} \\ A_{21} & \frac{1}{a_{11}} A_{21} A_{12} + Z \end{bmatrix} \\ &\quad \text{since } A_{12}^T = A_{21} \text{ because } A \text{ is symmetric} \\ &= \begin{bmatrix} a_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} = A, \text{ since } Z = A_{22} - \frac{1}{a_{11}} A_{21} A_{12}. \end{aligned}$$

So $(n+1) \times (n+1)$ matrix A has a Cholesky factorization and so the claim holds by induction. □

Theorem 5.9.A

Theorem 5.9.A. An invertible matrix A has a Cholesky factorization if and only if A is symmetric and positive definite.

Proof. If A is symmetric and positive definite, then it has a Cholesky factorization by Theorem 5.9.2 (whether A is invertible or not).

If A is invertible and has a Cholesky factorization, then $A = T^T T$ where T is an upper triangular matrix with positive diagonal entries. Then $A^T = (T^T T)^T = T^T (T^T)^T = T^T T = A$ and so A is symmetric. Let x be a nonzero in $\mathbb{R}^n$. Then

$$\begin{aligned} x^T A x &= x^T T^T T x = (xT)^T T x = \langle Tx, Tx \rangle \\ &= \|Tx\|_F \text{ (the Fobenius norm or Euclidean matrix norm of } Tx). \end{aligned} \quad (*)$$

Theorem 5.9.A (continued)

Theorem 5.9.A. An invertible matrix A has a Cholesky factorization if and only if A is symmetric and positive definite.

Proof (continued). Since A is hypothesized to be invertible, then $\det(A) \neq 0$ by Theorem 3.3.16 and

$$\begin{aligned} \det(A) &= \det(T^T T) \\ &= \det(T^T)\det(T) \text{ by Theorem 3.2.4} \\ &= \det(T)\det(T) \text{ by Theorem 3.1.A} \\ &= \det(T)^2 \end{aligned}$$

and so $\det(T) \neq 0$; that is, T is invertible. So for $x \neq 0$ we have $Tx \neq 0$ (since T is invertible implies a unique solution to $Tx = 0$ and, of course, 0 *is* that unique solution, see Note 3.5.A). Therefore $\|Tx\|_F \neq 0$ (since $\|\cdot\|_F$ is a norm) and so by $(*)$, $x^T A x > 0$ and A is positive definite. □