SYMMETRIC POSITIVE DEFINITE (SPD) MATRICES

SPD LINEAR SYSTEMS

- **Symmetric positive definite matrices.**
- **The LDL^T decomposition; The Cholesky factorization**

Positive-Definite Matrices

➤ A real matrix is said to be positive definite if

$$(Au, u) > 0 \text{ for all } u \neq 0 \; u \in \mathbb{R}^n$$

➤ Let A be a real positive definite matrix. Then there is a scalar $\alpha > 0$ such that

$$(Au, u) \geq \alpha \|u\|_2^2.$$

➤ Consider now the case of Symmetric Positive Definite (SPD) matrices.

➤ Consequence 1: A is nonsingular

➤ Consequence 2: the eigenvalues of A are (real) positive

A few properties of SPD matrices

➤ Diagonal entries of A are positive

➤ Recall: the k-th principal submatrix A_k is the $k \times k$ submatrix of A with entries a_{ij}, $1 \leq i, j \leq k$ (Matlab: $A(1:k, 1:k)$).

✍1 Each A_k is SPD

✍2 Consequence: $Det(A_k) > 0$ for $k = 1, \cdots, n$. In fact A is SPD iff this condition holds.

✍3 If A is SPD then for any $n \times k$ matrix X of rank k, the matrix $X^T AX$ is SPD.

➤ The mapping : $x, y \quad \rightarrow \quad (x, y)_A \equiv (Ax, y)$

defines a proper inner product on $\mathbb{R}^n$. The associated norm, denoted by $\|.\|_A$, is called the energy norm, or simply the A-norm:

$$\|x\|_A = (Ax, x)^{1/2} = \sqrt{x^T Ax}$$

➤ Related measure in Machine Learning, Vision, Statistics: the Mahalanobis distance between two vectors:

$$d_A(x, y) = \|x - y\|_A = \sqrt{(x - y)^T A(x - y)}$$

Appropriate distance (measured in # standard deviations) if x is a sample generated by a Gaussian distribution with covariance matrix A and center y.

More terminology

➤ A matrix is Positive Semi-Definite if: $(Au, u) \geq 0$ *for all* $u \in \mathbb{R}^n$

➤ Eigenvalues of symmetric positive semi-definite matrices are real nonnegative, i.e., ...

➤ ... A can be singular [If not, A is SPD]

➤ A matrix is said to be Negative Definite if $-A$ is positive definite. Similar definition for Negative Semi-Definite

➤ A matrix that is neither positive semi-definite nor negative semi-definite is indefinite

✍D4 Show that if $A^T = A$ and $(Ax, x) = 0 \; \forall x$ then $A = 0$

✍D5 Show: $A \neq 0$ is indefinite iff $\exists \; x, y : (Ax, x)(Ay, y) < 0$

The LDL^T and Cholesky factorizations

✍D6 The (standard) LU factorization of an SPD matrix A exists

➤ Let $A = LU$ and $D = diag(U)$ and set $M \equiv (D^{-1}U)^T$.

Then $A = LU = LD(D^{-1}U) = LDM^T$

➤ Both L and M are unit lower triangular

➤ Consider $L^{-1}AL^{-T} = DM^TL^{-T}$

➤ Matrix on the right is upper triangular. But it is also symmetric. Therefore $M^TL^{-T} = I$ and so $M = L$

➤ Alternative proof: exploit uniqueness of LU factorization without pivoting + symmetry: $A = LDM^T = MDL^T \rightarrow M = L$

➤ The diagonal entries of D are positive [Proof: consider $L^{-1}AL^{-T} = D$]. In the end:

$$A = LDL^T = GG^T \text{ where } G = LD^{1/2}$$

➤ Cholesky factorization is a specialization of the LU factorization for the SPD case. Several variants exist.

First algorithm: row-oriented LDLT

Adapted from Gaussian Elimination. Main observation: The working matrix $A(k+1:n, k+1:n)$ in standard LU remains symmetric. $\rightarrow$ Work only on its upper triangular part & ignore lower part

1. For $k = 1 : n-1$ Do:
2. For $i = k+1 : n$ Do:
3. $piv := a(k, i)/a(k, k)$
4. $a(i, i:n) := a(i, i:n) - piv * a(k, i:n)$
5. End
6. End

➤ This will give the U matrix of the LU factorization. Therefore $D = diag(U)$, $L^T = D^{-1}U$.

Row-Cholesky (outer product form)

Scale the rows as the algorithm proceeds. Line 4 becomes

$$a(i,:) := a(i,:) - [a(k,i)/\sqrt{a(k,k)}] * \left[a(k,:)/\sqrt{a(k,k)}\right]$$

ALGORITHM : 1. *Outer product Cholesky*

1. For $k = 1 : n$ Do:
2. $\quad A(k, k : n) = A(k, k : n)/\sqrt{A(k,k)}$;
3. $\quad$ For $i := k+1 : n$ Do :
4. $\quad\quad A(i, i : n) = A(i, i : n) - A(k, i) * A(k, i : n)$;
5. $\quad$ End
6. End

➤ Result: Upper triangular matrix U such $A = U^T U$.

Example:

$$A = \begin{pmatrix} 1 & -1 & 2 \\ -1 & 5 & 0 \\ 2 & 0 & 9 \end{pmatrix}$$

✍07 Is A symmetric positive definite?

✍08 What is the LDL^T factorization of A ?

✍09 What is the Cholesky factorization of A ?

Column Cholesky. Let $A = GG^T$ with G = lower triangular. Then equate j-th columns:

$$a(:,j) = \sum_{k=1}^{j} g(:,k) g^T(k,j) \rightarrow$$

$$A(:,j) = \sum_{k=1}^{j} G(j,k)G(:,k)$$

$$= G(j,j)G(:,j) + \sum_{k=1}^{j-1} G(j,k)G(:,k) \rightarrow$$

$$G(j,j)G(:,j) = A(:,j) - \sum_{k=1}^{j-1} G(j,k)G(:,k)$$

➤ Assume that first $j-1$ columns of G already known.

➤ Compute unscaled column-vector:

$$v = A(:,j) - \sum_{k=1}^{j-1} G(j,k)G(:,k)$$

➤ Notice that $v(j) \equiv G(j,j)^2$.

➤ Compute $\sqrt{v(j)}$ and scale v to get j-th column of G.

ALGORITHM : 2. *Column Cholesky*

```
For j = 1 : n do
    For k = 1 : j − 1 do
        A(j : n, j) = A(j : n, j) − A(j, k) ∗ A(j : n, k)
    EndDo
    If A(j, j) ≤ 0 ExitError("Matrix not SPD")
    A(j, j) = sqrt(A(j, j))
    A(j + 1 : n, j) = A(j + 1 : n, j)/A(j, j)
EndDo
```

✍10 Try algorithm on:

$$A = \begin{pmatrix} 1 & -1 & 2 \\ -1 & 5 & 0 \\ 2 & 0 & 9 \end{pmatrix}$$