

Lecture 6: Stationary iterative methods



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1. Splitting and stationary iterative method

Definition 1

A *splitting* of $\mathbf{A} \in \mathbb{C}^{n \times n}$ is a decomposition $\mathbf{A} = \mathbf{M} - \mathbf{K}$, with \mathbf{M} nonsingular.

Remark 2

A splitting yields a stationary iterative method as follows. The equation

$$\mathbf{Ax} = (\mathbf{M} - \mathbf{K})\mathbf{x} = \mathbf{b}$$

implies

$$\mathbf{x} = \mathbf{M}^{-1}\mathbf{Kx} + \mathbf{M}^{-1}\mathbf{b} := \mathbf{Rx} + \mathbf{c}.$$

Given a starting vector $\mathbf{x}^{(0)}$, we obtain a stationary iterative method

$$\mathbf{x}^{(m)} = \mathbf{Rx}^{(m-1)} + \mathbf{c}, \quad m = 1, 2, \dots$$

We note that $\mathbf{R} = \mathbf{M}^{-1}\mathbf{K} = \mathbf{M}^{-1}(\mathbf{M} - \mathbf{A}) = \mathbf{I} - \mathbf{M}^{-1}\mathbf{A}$.

2. Convergence criterion

Definition 3

The spectral radius of a matrix $\mathbf{A} \in \mathbb{C}^{n \times n}$ is $\rho(\mathbf{A}) = \max_{\lambda \in \Lambda(\mathbf{A})} |\lambda|$.

Exercise. Assume that \mathbf{A} is singular and has a splitting $\mathbf{A} = \mathbf{M} - \mathbf{K}$ with \mathbf{M} nonsingular. Prove that the spectral radius $\rho(\mathbf{M}^{-1}\mathbf{K}) \geq 1$.

Proposition 4

Let $\|\cdot\|$ denote a matrix norm on $\mathbb{C}^{n \times n}$ induced by a vector norm $\|\cdot\|$ on \mathbb{C}^n . For any $\mathbf{A} \in \mathbb{C}^{n \times n}$, we have $\rho(\mathbf{A}) \leq \|\mathbf{A}\|$.

Lemma 5

For any given $\mathbf{A} \in \mathbb{C}^{n \times n}$ and $\varepsilon > 0$ there exists an induced matrix norm $\|\cdot\|_*$ (induced by a vector norm $\|\cdot\|_*$ on \mathbb{C}^n) such that

$$\rho(\mathbf{A}) \leq \|\mathbf{A}\|_* \leq \rho(\mathbf{A}) + \varepsilon.$$

The norm $\|\cdot\|_*$ depends on both \mathbf{A} and ε .

Proof.

Let $\mathbf{A} = \mathbf{S}\mathbf{J}\mathbf{S}^{-1}$ be a Jordan form of \mathbf{A} . Let

$$\mathbf{D}_\varepsilon = \text{diag}\{1, \varepsilon, \varepsilon^2, \dots, \varepsilon^{n-1}\}.$$

Now for all $\mathbf{x} \in \mathbb{C}^n$ and for all $\mathbf{B} \in \mathbb{C}^{n \times n}$, define the vector norm

$$\|\mathbf{x}\|_\star := \|(\mathbf{SD}_\varepsilon)^{-1}\mathbf{x}\|_\infty$$

and the corresponding induced matrix norm

$$\begin{aligned}\|\mathbf{B}\|_\star &:= \sup_{\mathbf{x} \in \mathbb{C}^n, \mathbf{x} \neq \mathbf{0}} \frac{\|\mathbf{Bx}\|_\star}{\|\mathbf{x}\|_\star} = \sup_{\mathbf{x} \in \mathbb{C}^n, \mathbf{x} \neq \mathbf{0}} \frac{\|(\mathbf{SD}_\varepsilon)^{-1}\mathbf{Bx}\|_\infty}{\|(\mathbf{SD}_\varepsilon)^{-1}\mathbf{x}\|_\infty} \\ &= \sup_{\mathbf{y} \in \mathbb{C}^n, \mathbf{y} \neq \mathbf{0}} \frac{\|(\mathbf{SD}_\varepsilon)^{-1}\mathbf{B}(\mathbf{SD}_\varepsilon)\mathbf{y}\|_\infty}{\|\mathbf{y}\|_\infty} \\ &= \|\mathbf{D}_\varepsilon^{-1}\mathbf{S}^{-1}\mathbf{BSD}_\varepsilon\|_\infty.\end{aligned}$$

The statement follows from $\|\mathbf{A}\|_\star = \|\mathbf{D}_\varepsilon^{-1}\mathbf{JD}_\varepsilon\|_\infty \leq \rho(\mathbf{A}) + \varepsilon$. □

Theorem 6

The stationary iteration $\mathbf{x}^{(m)} = \mathbf{R}\mathbf{x}^{(m-1)} + \mathbf{c}$ converges to the solution of $(\mathbf{I} - \mathbf{R})\mathbf{x} = \mathbf{c}$ for all starting vectors $\mathbf{x}^{(0)}$ if and only if $\rho(\mathbf{R}) < 1$.

Proof.

For all $\mathbf{x}^{(0)}$, we have $\mathbf{x}^{(m)} - \mathbf{x} = \mathbf{R}(\mathbf{x}^{(m-1)} - \mathbf{x}) = \dots = \mathbf{R}^m(\mathbf{x}^{(0)} - \mathbf{x})$.

“ \Leftarrow ” : If $\rho(\mathbf{R}) < 1$, by Lemma 5 there exists an induced matrix norm $\|\cdot\|_*$ such that $\|\mathbf{R}\|_* < 1$, then $\|\mathbf{x}^{(m)} - \mathbf{x}\|_* \leq \|\mathbf{R}\|_*^m \|\mathbf{x}^{(0)} - \mathbf{x}\|_* \rightarrow 0$ for all $\mathbf{x}^{(0)}$, i.e., $\mathbf{x}^{(m)} \rightarrow \mathbf{x}$ as $m \rightarrow \infty$.

“ \Rightarrow ” : Proof by contradiction. Let $\mathbf{x}^{(0)} - \mathbf{x}$ be an eigenvector of \mathbf{R} corresponding to eigenvalue λ with $|\lambda| = \rho(\mathbf{R})$. If $\rho(\mathbf{R}) \geq 1$, then $\mathbf{x}^{(m)} - \mathbf{x} = \lambda^m(\mathbf{x}^{(0)} - \mathbf{x})$ will not approach $\mathbf{0}$. This is a contradiction. \square

Remark 7

A good stationary iterative method satisfies both (1) $\rho(\mathbf{R})$ is small (< 1) and (2) the action $\mathbf{R}\mathbf{x}^{(m-1)} + \mathbf{c}$ is computationally inexpensive.

- (1) and (2) are conflicting goals, and need to be balanced.
- If $\Lambda(\mathbf{R}) \subset [-\rho(\mathbf{R}), \rho(\mathbf{R})]$, then Chebyshev acceleration technique can be used. See Demmel's book ANLA, section 6.5.6.
- The iterative matrix \mathbf{R} is only theoretically useful and usually will not be formed explicitly.

3. Classical stationary iterative methods

- Let $\mathbf{A} = \mathbf{D} - \mathbf{L} - \mathbf{U}$, where
 - \mathbf{D} is the diagonal matrix with diagonal entries $d_{ii} = a_{ii}$,
 - $-\mathbf{L}$ is the strictly lower triangular part of \mathbf{A} ,
 - $-\mathbf{U}$ is the strictly upper triangular part of \mathbf{A} .
- Assume that \mathbf{A} has no zero diagonal entries. We will introduce
 - (1) Jacobi's method,
 - (2) Gauss–Seidel method,
 - (3) Successive overrelaxation: $SOR(\omega)$,
 - (4) Symmetric successive overrelaxation: $SSOR(\omega)$.

3.1. Jacobi's method

Algorithm 1: Jacobi's method (from $\mathbf{x}^{(m)}$ to $\mathbf{x}^{(m+1)}$)

for $j = 1$ to n

$$x_j^{(m+1)} = \frac{1}{a_{jj}} \left(b_j - \sum_{k \neq j} a_{jk} x_k^{(m)} \right)$$

end

- The splitting of Jacobi's method is $\mathbf{A} = \mathbf{D} - (\mathbf{L} + \mathbf{U})$. The corresponding \mathbf{R} and \mathbf{c} are

$$\mathbf{R} = \mathbf{D}^{-1}(\mathbf{L} + \mathbf{U}) = \mathbf{I} - \mathbf{D}^{-1}\mathbf{A}, \quad \mathbf{c} = \mathbf{D}^{-1}\mathbf{b}.$$

Theorem 8

If \mathbf{A} is Hermitian and $a_{ii} > 0$ for all i , then Jacobi's method converges for all starting vectors if and only if \mathbf{A} and $2\mathbf{D} - \mathbf{A}$ are both HPD.

3.2. Gauss–Seidel method

Algorithm 2: Gauss–Seidel method (from $\mathbf{x}^{(m)}$ to $\mathbf{x}^{(m+1)}$)

for $j = 1$ to n

$$x_j^{(m+1)} = \frac{1}{a_{jj}} \left(b_j - \sum_{k=1}^{j-1} a_{jk} x_k^{(m+1)} - \sum_{k=j+1}^n a_{jk} x_k^{(m)} \right)$$

end

- The splitting of Gauss–Seidel method is

$$\mathbf{A} = (\mathbf{D} - \mathbf{L}) - \mathbf{U}.$$

The corresponding \mathbf{R} and \mathbf{c} are

$$\mathbf{R} = (\mathbf{D} - \mathbf{L})^{-1} \mathbf{U}$$

and

$$\mathbf{c} = (\mathbf{D} - \mathbf{L})^{-1} \mathbf{b}.$$

3.3. Successive overrelaxation: SOR(ω), $\omega \in \mathbb{R}$

Algorithm 3: SOR(ω), here ω is the relaxation parameter

for $j = 1$ to n

$$x_j^{(m+1)} = (1 - \omega)x_j^{(m)} + \frac{\omega}{a_{jj}} \left(b_j - \sum_{k=1}^{j-1} a_{jk}x_k^{(m+1)} - \sum_{k=j+1}^n a_{jk}x_k^{(m)} \right)$$

end

- The splitting of SOR(ω) is $\omega\mathbf{A} = (\mathbf{D} - \omega\mathbf{L}) - ((1 - \omega)\mathbf{D} + \omega\mathbf{U})$. The corresponding \mathbf{R} and \mathbf{c} are

$$\mathbf{R} = (\mathbf{D} - \omega\mathbf{L})^{-1}((1 - \omega)\mathbf{D} + \omega\mathbf{U}),$$

and

$$\mathbf{c} = \omega(\mathbf{D} - \omega\mathbf{L})^{-1}\mathbf{b}.$$

- $\omega = 1$: Gauss-Seidel method
- $0 < \omega < 2$: necessary condition for convergence (see Theorem 13)
- Optimal ω : see Ciaramella and Gander's book (Chapter 2).

3.4. Symmetric successive overrelaxation: SSOR(ω), $\omega \in \mathbb{R}$

Algorithm 4: SSOR(ω)

for $j = 1$ to n

$$x_j^{(m+1/2)} = (1 - \omega)x_j^{(m)} + \frac{\omega}{a_{jj}} \left(b_j - \sum_{k=1}^{j-1} a_{jk}x_k^{(m+1/2)} - \sum_{k=j+1}^n a_{jk}x_k^{(m)} \right)$$

end

for $j = n$ to 1

$$x_j^{(m+1)} = (1 - \omega)x_j^{(m+1/2)} + \frac{\omega}{a_{jj}} \left(b_j - \sum_{k=1}^{j-1} a_{jk}x_k^{(m+1/2)} - \sum_{k=j+1}^n a_{jk}x_k^{(m+1)} \right)$$

end

- This method uses two splittings:

$$\begin{aligned}\omega\mathbf{A} &= (\mathbf{D} - \omega\mathbf{L}) - ((1 - \omega)\mathbf{D} + \omega\mathbf{U}) \\ &= (\mathbf{D} - \omega\mathbf{U}) - ((1 - \omega)\mathbf{D} + \omega\mathbf{L}).\end{aligned}$$

The corresponding \mathbf{R} and \mathbf{c} are

$$\begin{aligned}\mathbf{R} &= (\mathbf{D} - \omega\mathbf{U})^{-1}((1 - \omega)\mathbf{D} + \omega\mathbf{L})(\mathbf{D} - \omega\mathbf{L})^{-1}((1 - \omega)\mathbf{D} + \omega\mathbf{U}), \\ \mathbf{c} &= \omega(2 - \omega)(\mathbf{D} - \omega\mathbf{U})^{-1}\mathbf{D}(\mathbf{D} - \omega\mathbf{L})^{-1}\mathbf{b}.\end{aligned}$$

3.5. Convergence (see Demmel's book ANLA, section 6.5.5)

Definition 9

\mathbf{A} is an irreducible matrix if there is no permutation matrix such that

$$\mathbf{PAP}^\top = \begin{bmatrix} \mathbf{A}_{11} & \mathbf{A}_{12} \\ \mathbf{0} & \mathbf{A}_{22} \end{bmatrix}.$$

Definition 10

A matrix $\mathbf{A} \in \mathbb{C}^{n \times n}$ is **weakly** row diagonally dominant if for all i ,

$$|a_{ii}| \geq \sum_{j \neq i} |a_{ij}|$$

with strict inequality at least once. A matrix \mathbf{A} is **strictly** row diagonally dominant if for all i :

$$|a_{ii}| > \sum_{j \neq i} |a_{ij}|.$$

Theorem 11

If \mathbf{A} is strictly row diagonally dominant, then both Jacobi's and Gauss–Seidel methods converge. In fact $\|\mathbf{R}_{\text{GS}}\|_\infty \leq \|\mathbf{R}_J\|_\infty < 1$.

Theorem 12

If \mathbf{A} is irreducible and weakly row diagonally dominant, then both Jacobi's and Gauss–Seidel methods converge, and $\rho(\mathbf{R}_{\text{GS}}) < \rho(\mathbf{R}_J) < 1$.

Theorem 13

For any matrix \mathbf{A} , it holds $\rho(\mathbf{R}_{\text{SOR}(\omega)}) \geq |\omega - 1|$. Therefore $0 < \omega < 2$ is required for the convergence of SOR(ω) for all starting vectors.

Theorem 14

If \mathbf{A} is Hermitian positive definite, then $\rho(\mathbf{R}_{\text{SOR}(\omega)}) < 1$ for all $0 < \omega < 2$, i.e., SOR(ω) converges for all $0 < \omega < 2$. Gauss–Seidel (SOR(1)) converges for Hermitian positive definite \mathbf{A} .