Iterative Techniques in Matrix Algebra

Relaxation Techniques for Solving Linear Systems

Numerical Analysis (9th Edition)

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Outline

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1. Residual Vectors & the Gauss-Seidel Method
2. Relaxation Methods (including SOR)

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1. Residual Vectors & the Gauss-Seidel Method
2. Relaxation Methods (including SOR)
3. Choosing the Optimal Value of ω
4. The SOR Algorithm

Residual Vectors & the Gauss-Seidel Method

Motivation

- We have seen that the rate of convergence of an iterative technique depends on the spectral radius of the matrix associated with the method.

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Residual Vectors & the Gauss-Seidel Method

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- One way to select a procedure to accelerate convergence is to choose a method whose associated matrix has minimal spectral radius.
- We start by introducing a new means of measuring the amount by which an approximation to the solution to a linear system differs from the true solution to the system.

Residual Vectors & the Gauss-Seidel Method

Motivation

- We have seen that the rate of convergence of an iterative technique depends on the spectral radius of the matrix associated with the method.
- One way to select a procedure to accelerate convergence is to choose a method whose associated matrix has minimal spectral radius.
- We start by introducing a new means of measuring the amount by which an approximation to the solution to a linear system differs from the true solution to the system.
- The method makes use of the vector described in the following definition.

Residual Vectors & the Gauss-Seidel Method

Definition

Suppose $\tilde{\mathbf{x}} \in \mathbb{R}^n$ is an approximation to the solution of the linear system defined by

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

The residual vector for $\tilde{\mathbf{x}}$ with respect to this system is

$$\mathbf{r} = \mathbf{b} - A\tilde{\mathbf{x}}$$

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Comments

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Comments

- A residual vector is associated with each calculation of an approximate component to the solution vector.
- The true objective is to generate a sequence of approximations that will cause the residual vectors to converge rapidly to zero.

Residual Vectors & the Gauss-Seidel Method

Looking at the Gauss-Seidel Method

Suppose we let

$$\mathbf{r}_i^{(k)} = (r_{1i}^{(k)}, r_{2i}^{(k)}, \ldots, r_{ni}^{(k)})^t$$

denote the residual vector for the Gauss-Seidel method

Residual Vectors & the Gauss-Seidel Method

Looking at the Gauss-Seidel Method

Suppose we let

$$\mathbf{r}_i^{(k)} = (r_{1i}^{(k)}, r_{2i}^{(k)}, \ldots, r_{ni}^{(k)})^t$$

denote the residual vector for the Gauss-Seidel method corresponding to the approximate solution vector $\mathbf{x}_i^{(k)}$ defined by

$$\mathbf{x}_i^{(k)} = (x_1^{(k)}, x_2^{(k)}, \ldots, x_{i-1}^{(k)}, x_i^{(k-1)}, \ldots, x_n^{(k-1)})^t$$

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$$\mathbf{x}_i^{(k)} = (x_1^{(k)}, x_2^{(k)}, \ldots, x_{i-1}^{(k)}, x_i^{(k-1)}, \ldots, x_n^{(k-1)})^t$$

The m-th component of $\mathbf{r}_i^{(k)}$ is

$$r_{mi}^{(k)} = b_m - \sum_{j=1}^{i-1} a_{mj} x_j^{(k)} - \sum_{j=i}^{n} a_{mj} x_j^{(k-1)}$$

Residual Vectors & the Gauss-Seidel Method

$$r_{mi}^{(k)} = b_m - \sum_{j=1}^{i-1} a_{mj} x_j^{(k)} - \sum_{j=i}^{n} a_{mj} x_j^{(k-1)}$$

Looking at the Gauss-Seidel Method (Cont'd)

Equivalently, we can write $r_{mi}^{(k)}$ in the form:

$$r_{mi}^{(k)} = b_m - \sum_{j=1}^{i-1} a_{mj} x_j^{(k)} - \sum_{j=i+1}^{n} a_{mj} x_j^{(k-1)} - a_{mi} x_i^{(k-1)}$$

for each $m = 1, 2, \ldots, n$.

Residual Vectors & the Gauss-Seidel Method

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Looking at the Gauss-Seidel Method (Cont'd)

In particular, the ith component of $\mathbf{r}_i^{(k)}$ is

$$r_{ii}^{(k)} = b_i - \sum_{j=1}^{i-1} a_{ij} x_j^{(k)} - \sum_{j=i+1}^{n} a_{ij} x_j^{(k-1)} - a_{ii} x_i^{(k-1)}$$

Residual Vectors & the Gauss-Seidel Method

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so

$$a_{ii}x_i^{(k-1)} + r_{ii}^{(k)} = b_i - \sum_{j=1}^{i-1} a_{ij}x_j^{(k)} - \sum_{j=i+1}^{n} a_{ij}x_j^{(k-1)}$$

Residual Vectors & the Gauss-Seidel Method

$$\text{(E)} \qquad a_{ii}x_i^{(k-1)} + r_{ii}^{(k)} = b_i - \sum_{j=1}^{i-1} a_{ij}x_j^{(k)} - \sum_{j=i+1}^{n} a_{ij}x_j^{(k-1)}$$

Looking at the Gauss-Seidel Method (Cont'd)

Recall, however, that in the Gauss-Seidel method, $x_i^{(k)}$ is chosen to be

$$x_i^{(k)} = \frac{1}{a_{ii}}\left[b_i - \sum_{j=1}^{i-1} a_{ij}x_j^{(k)} - \sum_{j=i+1}^{n} a_{ij}x_j^{(k-1)}\right]$$

Residual Vectors & the Gauss-Seidel Method

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so (E) can be rewritten as

$$a_{ii}x_i^{(k-1)} + r_{ii}^{(k)} = a_{ii}x_i^{(k)}$$

Residual Vectors & the Gauss-Seidel Method

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Looking at the Gauss-Seidel Method (Cont'd)

Consequently, the Gauss-Seidel method can be characterized as choosing $x_i^{(k)}$ to satisfy

$$x_i^{(k)} = x_i^{(k-1)} + \frac{r_{ii}^{(k)}}{a_{ii}}$$

Residual Vectors & the Gauss-Seidel Method

A 2nd Connection with Residual Vectors

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- Consider the residual vector $\mathbf{r}_{i+1}^{(k)}$, associated with the vector $\mathbf{x}_{i+1}^{(k)} = (x_1^{(k)}, \ldots, x_i^{(k)}, x_{i+1}^{(k-1)}, \ldots, x_n^{(k-1)})^t$.

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- We have seen that the m-th component of $\mathbf{r}_i^{(k)}$ is

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Residual Vectors & the Gauss-Seidel Method

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A 2nd Connection with Residual Vectors (Cont'd)

Therefore, the ith component of $\mathbf{r}_{i+1}^{(k)}$ is

$$r_{i,i+1}^{(k)} = b_i - \sum_{j=1}^{i} a_{ij} x_j^{(k)} - \sum_{j=i+1}^{n} a_{ij} x_j^{(k-1)}$$

Residual Vectors & the Gauss-Seidel Method

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Therefore, the ith component of $\mathbf{r}_{i+1}^{(k)}$ is

$$\begin{aligned} r_{i,i+1}^{(k)} &= b_i - \sum_{j=1}^{i} a_{ij} x_j^{(k)} - \sum_{j=i+1}^{n} a_{ij} x_j^{(k-1)} \\ &= b_i - \sum_{j=1}^{i-1} a_{ij} x_j^{(k)} - \sum_{j=i+1}^{n} a_{ij} x_j^{(k-1)} - a_{ii} x_i^{(k)} \end{aligned}$$

Residual Vectors & the Gauss-Seidel Method

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A 2nd Connection with Residual Vectors (Cont'd)

By the manner in which $x_i^{(k)}$ is defined in

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we see that $r_{i,i+1}^{(k)} = 0$.

Residual Vectors & the Gauss-Seidel Method

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we see that $r_{i,i+1}^{(k)} = 0$. In a sense, then, the Gauss-Seidel technique is characterized by choosing each $x_{i+1}^{(k)}$ in such a way that the ith component of $\mathbf{r}_{i+1}^{(k)}$ is zero.

Outline

From Gauss-Seidel to Relaxation Methods

Reducing the Norm of the Residual Vector

- Choosing $x_{i+1}^{(k)}$ so that one coordinate of the residual vector is zero, however, is not necessarily the most efficient way to reduce the norm of the vector $\mathbf{r}_{i+1}^{(k)}$.

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to

$$x_i^{(k)} = x_i^{(k-1)} + \omega \frac{r_{ii}^{(k)}}{a_{ii}}$$

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then for certain choices of positive ω we can reduce the norm of the residual vector and obtain significantly faster convergence.

From Gauss-Seidel to Relaxation Methods

Introducing the SOR Method

- Methods involving

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are called relaxation methods.

From Gauss-Seidel to Relaxation Methods

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- We will be interested in choices of ω with $1 < \omega$, and these are called over-relaxation methods.
- They are used to accelerate the convergence for systems that are convergent by the Gauss-Seidel technique.
- The methods are abbreviated SOR, for Successive Over-Relaxation, and are particularly useful for solving the linear systems that occur in the numerical solution of certain partial-differential equations.

The SOR Method

A More Computationally-Efficient Formulation

Note that by using the i-th component of $\mathbf{r}_i^{(k)}$ in the form

$$r_{ii}^{(k)} = b_i - \sum_{j=1}^{i-1} a_{ij} x_j^{(k)} - \sum_{j=i+1}^{n} a_{ij} x_j^{(k-1)} - a_{ii} x_i^{(k-1)}$$

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we can reformulate the SOR equation

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for calculation purposes

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for calculation purposes as

$$x_i^{(k)} = (1-\omega)x_i^{(k-1)} + \frac{\omega}{a_{ii}}\left[b_i - \sum_{j=1}^{i-1} a_{ij}x_j^{(k)} - \sum_{j=i+1}^{n} a_{ij}x_j^{(k-1)}\right]$$

The SOR Method

A More Computationally-Efficient Formulation (Cont'd)

To determine the matrix form of the SOR method, we rewrite

$$x_i^{(k)} = (1-\omega)x_i^{(k-1)} + \frac{\omega}{a_{ii}}\left[b_i - \sum_{j=1}^{i-1} a_{ij}x_j^{(k)} - \sum_{j=i+1}^{n} a_{ij}x_j^{(k-1)}\right]$$

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as

$$a_{ii}x_i^{(k)} + \omega\sum_{j=1}^{i-1} a_{ij}x_j^{(k)} = (1-\omega)a_{ii}x_i^{(k-1)} - \omega\sum_{j=i+1}^{n} a_{ij}x_j^{(k-1)} + \omega b_i$$

The SOR Method

$$a_{ii}x_i^{(k)} + \omega \sum_{j=1}^{i-1} a_{ij}x_j^{(k)} = (1-\omega)a_{ii}x_i^{(k-1)} - \omega \sum_{j=i+1}^{n} a_{ij}x_j^{(k-1)} + \omega b_i$$

A More Computationally-Efficient Formulation (Cont'd)

In vector form, we therefore have

$$(D - \omega L)\mathbf{x}^{(k)} = [(1-\omega)D + \omega U]\mathbf{x}^{(k-1)} + \omega \mathbf{b}$$

The SOR Method

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A More Computationally-Efficient Formulation (Cont'd)

In vector form, we therefore have

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from which we obtain:

The SOR Method

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$$T_\omega \quad = \quad (D - \omega L)^{-1}[(1-\omega)D + \omega U]$$

The SOR Method

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Letting

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and

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gives the SOR technique the form

$$\mathbf{x}^{(k)} = T_\omega \mathbf{x}^{(k-1)} + \mathbf{c}_\omega$$

The SOR Method

Example

- The linear system $A\mathbf{x} = \mathbf{b}$ given by

$$\begin{aligned} 4x_1 + 3x_2 \qquad\quad &= 24 \\ 3x_1 + 4x_2 - \quad x_3 &= 30 \\ - \quad x_2 + 4x_3 &= -24 \end{aligned}$$

has the solution $(3, 4, -5)^t$.

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- The linear system $A\mathbf{x} = \mathbf{b}$ given by

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  has the solution $(3, 4, -5)^t$.
- Compare the iterations from the Gauss-Seidel method and the SOR method with $\omega = 1.25$ using $\mathbf{x}^{(0)} = (1, 1, 1)^t$ for both methods.

The SOR Method

Solution (1/3)

The SOR Method

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For each $k = 1, 2, \ldots,$ the equations for the Gauss-Seidel method are

$$\begin{aligned} x_1^{(k)} &= -0.75x_2^{(k-1)} + 6 \\ x_2^{(k)} &= -0.75x_1^{(k)} + 0.25x_3^{(k-1)} + 7.5 \\ x_3^{(k)} &= 0.25x_2^{(k)} - 6 \end{aligned}$$

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\end{aligned}
$$

and the equations for the SOR method with $\omega = 1.25$ are

$$
\begin{aligned}
x_1^{(k)} &= -0.25x_1^{(k-1)} - 0.9375x_2^{(k-1)} + 7.5 \\
x_2^{(k)} &= -0.9375x_1^{(k)} - 0.25x_2^{(k-1)} + 0.3125x_3^{(k-1)} + 9.375 \\
x_3^{(k)} &= 0.3125x_2^{(k)} - 0.25x_3^{(k-1)} - 7.5
\end{aligned}
$$

The SOR Method: Solution (2/3)

Gauss-Seidel Iterations

k	0	1	2	3	$\cdots$	7
$x_1^{(k)}$	1	5.250000	3.1406250	3.0878906		3.0134110
$x_2^{(k)}$	1	3.812500	3.8828125	3.9267578		3.9888241
$x_3^{(k)}$	1	-5.046875	-5.0292969	-5.0183105		-5.0027940

The SOR Method: Solution (2/3)

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SOR Iterations ($\omega = 1.25$)

k	0	1	2	3	$\cdots$	7
$x_1^{(k)}$	1	6.312500	2.6223145	3.1333027		3.0000498
$x_2^{(k)}$	1	3.5195313	3.9585266	4.0102646		4.0002586
$x_3^{(k)}$	1	-6.6501465	-4.6004238	-5.0966863		-5.0003486

The SOR Method

Solution (3/3)

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For the iterates to be accurate to 7 decimal places,

- the Gauss-Seidel method requires 34 iterations,

The SOR Method

Solution (3/3)

For the iterates to be accurate to 7 decimal places,

- the Gauss-Seidel method requires 34 iterations,
- as opposed to 14 iterations for the SOR method with $\omega = 1.25$.

Outline

Choosing the Optimal Value of ω

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- An obvious question to ask is how the appropriate value of ω is chosen when the SOR method is used?
- Although no complete answer to this question is known for the general $n \times n$ linear system, the following results can be used in certain important situations.

Choosing the Optimal Value of ω

Theorem (Kahan)

If $a_{ii} \neq 0$, for each $i = 1, 2, \ldots, n$, then $\rho(T_\omega) \geq |\omega - 1|$. This implies that the SOR method can converge only if $0 < \omega < 2$.

Choosing the Optimal Value of ω

Theorem (Kahan)

If $a_{ii} \neq 0$, for each $i = 1, 2, \ldots, n$, then $\rho(T_\omega) \geq |\omega - 1|$. This implies that the SOR method can converge only if $0 < \omega < 2$.

The proof of this theorem is considered in Exercise 9, Chapter 7 of Burden R. L. & Faires J. D., Numerical Analysis, 9th Ed., Cengage, 2011.

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Theorem

If A is positive definite and tridiagonal, then $\rho(T_g) = [\rho(T_j)]^2 < 1$, and the optimal choice of ω for the SOR method is

$$\omega = \frac{2}{1 + \sqrt{1 - [\rho(T_j)]^2}}$$

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The SOR Method

Example

Find the optimal choice of ω for the SOR method for the matrix

$$A = \begin{bmatrix} 4 & 3 & 0 \\ 3 & 4 & -1 \\ 0 & -1 & 4 \end{bmatrix}$$

The SOR Method

Solution (1/3)

- This matrix is clearly tridiagonal, so we can apply the result in the SOR theorem if we can also show that it is positive definite.

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The SOR Method

Solution (1/3)

- This matrix is clearly tridiagonal, so we can apply the result in the SOR theorem if we can also show that it is positive definite.
- Because the matrix is symmetric, the theory tells us that it is positive definite if and only if all its leading principle submatrices has a positive determinant.
- This is easily seen to be the case because

$$\det(A) = 24, \quad \det\left(\begin{bmatrix} 4 & 3 \\ 3 & 4 \end{bmatrix}\right) = 7 \quad \text{and} \quad \det([4]) = 4$$

The SOR Method

Solution (2/3)

We compute

$$T_j = D^{-1}(L + U)$$

The SOR Method

Solution (2/3)

We compute

$$\begin{aligned} T_j &= D^{-1}(L+U) \\ &= \begin{bmatrix} \frac{1}{4} & 0 & 0 \\ 0 & \frac{1}{4} & 0 \\ 0 & 0 & \frac{1}{4} \end{bmatrix} \begin{bmatrix} 0 & -3 & 0 \\ -3 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix} \end{aligned}$$

The SOR Method

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We compute

$$
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T_j &= D^{-1}(L+U) \\
&= \begin{bmatrix} \frac{1}{4} & 0 & 0 \\ 0 & \frac{1}{4} & 0 \\ 0 & 0 & \frac{1}{4} \end{bmatrix} \begin{bmatrix} 0 & -3 & 0 \\ -3 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix} \\
&= \begin{bmatrix} 0 & -0.75 & 0 \\ -0.75 & 0 & 0.25 \\ 0 & 0.25 & 0 \end{bmatrix}
\end{aligned}
$$

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so that

$$T_j - \lambda I = \begin{bmatrix} -\lambda & -0.75 & 0 \\ -0.75 & -\lambda & 0.25 \\ 0 & 0.25 & -\lambda \end{bmatrix}$$

The SOR Method

Solution (3/3)

Therefore

$$\det(T_j - \lambda I) = \begin{vmatrix} -\lambda & -0.75 & 0 \\ -0.75 & -\lambda & 0.25 \\ 0 & 0.25 & -\lambda \end{vmatrix}$$

The SOR Method

Solution (3/3)

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$$\det(T_j - \lambda I) = \begin{vmatrix} -\lambda & -0.75 & 0 \\ -0.75 & -\lambda & 0.25 \\ 0 & 0.25 & -\lambda \end{vmatrix} = -\lambda(\lambda^2 - 0.625)$$

The SOR Method

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Thus

$$\rho(T_j) = \sqrt{0.625}$$

The SOR Method

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Thus

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and

$$\omega = \frac{2}{1 + \sqrt{1 - [\rho(T_j)]^2}} = \frac{2}{1 + \sqrt{1 - 0.625}} \approx 1.24.$$

The SOR Method

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This explains the rapid convergence obtained in the last example when using $\omega = 1.25$.

Outline

The SOR Algorithm (1/2)

To solve

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

given the parameter ω and an initial approximation $\mathbf{x}^{(0)}$:

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

given the parameter ω and an initial approximation $\mathbf{x}^{(0)}$:

INPUT the number of equations and unknowns n;
the entries a_{ij}, $1 \le i, j \le n$, of the matrix A;
the entries b_i, $1 \le i \le n$, of $\mathbf{b}$;
the entries XO_i, $1 \le i \le n$, of $\mathbf{XO} = \mathbf{x}^{(0)}$;
the parameter ω; tolerance TOL;
maximum number of iterations N.

OUTPUT the approximate solution $x_1, \ldots, x_n$ or a message that the number of iterations was exceeded.

The SOR Algorithm (2/2)

Step 1 Set $k = 1$

Step 2 While ($k \leq N$) do Steps 3–6:

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Step 3 For $i = 1, \ldots, n$

$$\text{set } x_i = (1-\omega)XO_i + \frac{1}{a_{ii}}\left[\omega\left(-\sum_{j=1}^{i-1} a_{ij}x_j - \sum_{j=i+1}^{n} a_{ij}XO_j + b_i\right)\right]$$

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Step 4 If $||\mathbf{x} - \mathbf{XO}|| < TOL$ then OUTPUT $(x_1, \ldots, x_n)$
STOP (*The procedure was successful*)

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Step 5 Set $k = k + 1$
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Step 7 OUTPUT ('Maximum number of iterations exceeded')
STOP (*The procedure was successful*)

Questions?