

Lecture 10: Jacobi method, Bisection method, Divide-and-conquer method



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1. Jacobi method

- The method is based on the fact that a 2×2 real symmetric matrix \mathbf{A} can be diagonalized in the form

$$\mathbf{J}_2 = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix}, \quad \mathbf{J}_2^\top \begin{bmatrix} a & d \\ d & b \end{bmatrix} \mathbf{J}_2 = \begin{bmatrix} \times & 0 \\ 0 & \times \end{bmatrix},$$

where θ satisfies $(b - a) \sin(2\theta) = 2d \cos(2\theta)$.

- Define the $m \times m$ Jacobi rotation matrix $\mathbf{J}(i, j; \theta)$, $i < j$,

$$\begin{aligned} \mathbf{J} = \mathbf{J}(i, j; \theta) &:= \mathbf{I} + \begin{bmatrix} \mathbf{e}_i & \mathbf{e}_j \end{bmatrix} \begin{bmatrix} \cos \theta - 1 & \sin \theta \\ -\sin \theta & \cos \theta - 1 \end{bmatrix} \begin{bmatrix} \mathbf{e}_i^\top \\ \mathbf{e}_j^\top \end{bmatrix} \\ &= \begin{bmatrix} \mathbf{I} & & & \\ & \cos \theta & \sin \theta & \\ & & \mathbf{I} & \\ & -\sin \theta & \cos \theta & \\ & & & \mathbf{I} \end{bmatrix} \begin{matrix} \text{row } i \\ \text{row } j \end{matrix}. \end{aligned}$$

The (i, j) and (j, i) entries of $\mathbf{B} := \mathbf{J}^\top \mathbf{A} \mathbf{J}$ are zeros via appropriate θ .

Remark 1

The Jacobi rotation matrix \mathbf{J} is orthogonal.

Remark 2

We have $\|\mathbf{B}\|_F = \|\mathbf{A}\|_F$ ($\|\cdot\|_F$ is invariant under orthogonal \mathbf{J}).

Theorem 3

Suppose that $a_{ij} = a_{ji} \neq 0$ and $i < j$. Let $\mathbf{J}(i, j; \theta)$ be the Jacobi rotation matrix such that the (i, j) and (j, i) entries of $\mathbf{B} = \mathbf{J}^\top \mathbf{A} \mathbf{J}$ are zeros. Then, for $k \neq i, j$, $b_{kk} = a_{kk}$ and

$$b_{ii}^2 + b_{jj}^2 = a_{ii}^2 + a_{jj}^2 + a_{ij}^2 + a_{ji}^2.$$

Remark 4 (Jacobi method: $\mathbf{A}^{(k)} = \mathbf{J}(i_k, j_k; \theta_k)^\top \mathbf{A}^{(k-1)} \mathbf{J}(i_k, j_k; \theta_k)$)

At each step a symmetric pair of zeros is introduced into the matrix (note that previous zeros maybe destroyed). The usual effect is that the sum of the squares of magnitude of off-diagonal entries shrink steadily.

2. Bisection method

- Consider an unreduced (all of its $(i+1, i)$ and $(i, i+1)$ entries are nonzero) tridiagonal real symmetric matrix \mathbf{A} :

$$\mathbf{A} = \begin{bmatrix} a_1 & b_1 & & & \\ b_1 & a_2 & b_2 & & \\ & b_2 & a_3 & \ddots & \\ & & \ddots & \ddots & b_{m-1} \\ & & & b_{m-1} & a_m \end{bmatrix}, \quad b_j \neq 0.$$

- Let $\mathbf{A}^{(1)}, \dots, \mathbf{A}^{(m)}$ denote its leading square principal submatrices of dimension $1, \dots, m$.

Proposition 5

The eigenvalues of $\mathbf{A}^{(k)}$ are distinct: $\lambda_1^{(k)} > \lambda_2^{(k)} > \dots > \lambda_k^{(k)}$.

Proposition 6

The eigenvalues of $\mathbf{A}^{(1)}, \dots, \mathbf{A}^{(m)}$ strictly interlace, i.e.,

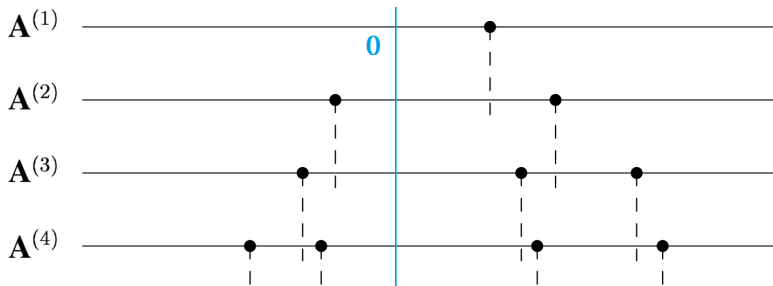
$$\lambda_j^{(k+1)} > \lambda_j^{(k)} > \lambda_{j+1}^{(k+1)},$$

for $k = 1, 2, \dots, m-1$ and $j = 1, 2, \dots, k$.

Proof: See Golub and van Loan's book: Theorem 8.4.1, Page 468, *Matrix computations*, 4th edition.

- The interlacing property makes it possible to count the exact number of negative eigenvalues of a real symmetric tridiagonal matrix. For example,

$$\mathbf{A} = \begin{bmatrix} 1 & 1 & & \\ 1 & 0 & 1 & \\ & 1 & 2 & 1 \\ & & 1 & -1 \end{bmatrix}, \quad \begin{aligned} \det(\mathbf{A}^{(1)}) &= 1, \\ \det(\mathbf{A}^{(2)}) &= -1, \\ \det(\mathbf{A}^{(3)}) &= -3, \\ \det(\mathbf{A}^{(4)}) &= 4. \end{aligned}$$



Remark 7

In general, for any unreduced tridiagonal real symmetric \mathbf{A} , the number of negative eigenvalues is equal to the number of sign changes in the sequence

$$1, \det(\mathbf{A}^{(1)}), \det(\mathbf{A}^{(2)}), \dots, \det(\mathbf{A}^{(m)}),$$

which is known as a Sturm sequence. Here, we define a “sign change” to mean a transition from + or 0 to – or from – or 0 to + but not from + or – to 0.

Remark 8

By shifting \mathbf{A} by a multiple of the identity, we can determine the number of eigenvalues in any interval $[a, b)$: it is the number of eigenvalues in $(-\infty, b)$ minus the number in $(-\infty, a)$; i.e., we only need consider two matrices $\mathbf{A} - b\mathbf{I}$ and $\mathbf{A} - a\mathbf{I}$.

Remark 9

The determinants of the matrices $\{\mathbf{A}^{(k)}\}$ are related by a three-term recurrence relation:

$$\det(\mathbf{A}^{(k)}) = a_k \det(\mathbf{A}^{(k-1)}) - b_{k-1}^2 \det(\mathbf{A}^{(k-2)}).$$

Introducing the shift by $z\mathbf{I}$ and writing $p^{(k)}(z) = \det(\mathbf{A}^{(k)} - z\mathbf{I})$, we get

$$p^{(k)}(z) = (a_k - z)p^{(k-1)}(z) - b_{k-1}^2 p^{(k-2)}(z),$$

where $p^{(-1)}(z) = 0$, $p^{(0)}(z) = 1$.

3. Secular equation

Proposition 10

Let $\mathbf{D} \in \mathbb{R}^{m \times m}$ be a diagonal matrix with *distinct* diagonal entries $\{d_j\}$ and $\mathbf{w} \in \mathbb{R}^m$ be a vector with $w_j \neq 0$ for all j . Assume $\beta \in \mathbb{R}$ and $\beta \neq 0$. The eigenvalues of $\mathbf{D} + \beta \mathbf{w} \mathbf{w}^\top$ are the roots of the rational function

$$f(\lambda) = 1 + \beta \sum_{j=1}^m \frac{w_j^2}{d_j - \lambda}.$$

Proof.

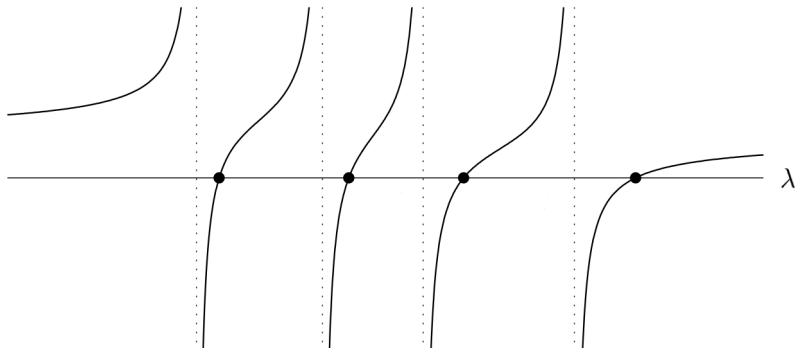
Suppose \mathbf{q} is an eigenvector of $\mathbf{D} + \beta \mathbf{w} \mathbf{w}^\top$. The statement follows from $\mathbf{w}^\top \mathbf{q} \neq 0$, $\lambda \neq d_j$ (why?) and $\mathbf{w}^\top \mathbf{q} (1 + \beta \mathbf{w}^\top (\mathbf{D} - \lambda \mathbf{I})^{-1} \mathbf{w}) = 0$. \square

Remark 11

The equation $f(\lambda) = 0$ is known as the secular equation.

Exercise: Assume \mathbf{D} , β and \mathbf{w} are those in Proposition 10. If λ is an eigenvalue of $\mathbf{D} + \beta\mathbf{w}\mathbf{w}^\top$, then $(\mathbf{D} - \lambda\mathbf{I})^{-1}\mathbf{w}$ is a corresponding eigenvector.

- Plot of the function $f(\lambda)$ for a problem of dimension 4. The poles of $f(\lambda)$ are the eigenvalues $\{d_j\}$ of \mathbf{D} , and the roots of $f(\lambda)$ (solid dots) are the eigenvalues of $\mathbf{D} + \beta\mathbf{w}\mathbf{w}^\top$. These roots can be determined rapidly.



Proposition 12

Let $\mathbf{D} \in \mathbb{R}^{m \times m}$ be a diagonal matrix and $\mathbf{w} \in \mathbb{R}^m$ be a vector. Assume $\beta \in \mathbb{R}$ and $\beta \neq 0$. Then there exist a permutation matrix \mathbf{P} and an orthogonal matrix \mathbf{V} such that

$$\mathbf{P}^\top \mathbf{V}^\top (\mathbf{D} + \beta \mathbf{w} \mathbf{w}^\top) \mathbf{V} \mathbf{P} = \begin{bmatrix} \mathbf{D}_1 + \beta \mathbf{w}_1 \mathbf{w}_1^\top & \mathbf{0} \\ \mathbf{0} & \mathbf{D}_2 \end{bmatrix},$$

where $\mathbf{D}_1 \in \mathbb{R}^{r \times r}$ is a diagonal matrix with distinct diagonal entries, $\mathbf{D}_2 \in \mathbb{R}^{(m-r) \times (m-r)}$ is a diagonal matrix, and $\mathbf{w}_1 \in \mathbb{R}^r$ is a vector with nonzero entries. More precisely,

$$\mathbf{V}^\top \mathbf{D} \mathbf{V} = \mathbf{D}, \quad \mathbf{P}^\top \mathbf{D} \mathbf{P} = \begin{bmatrix} \mathbf{D}_1 & \\ & \mathbf{D}_2 \end{bmatrix}, \quad \mathbf{P}^\top \mathbf{V}^\top \mathbf{w} = \begin{bmatrix} \mathbf{w}_1 \\ \mathbf{0} \end{bmatrix}.$$

- **Exercise:** Prove Proposition 12.

4. Divide-and-conquer

Remark 13

A symmetric tridiagonal matrix can be written as the sum of a 2×2 block diagonal matrix with tridiagonal blocks and a rank-one correction.

- Let $\mathbf{T} \in \mathbb{R}^{m \times m}$ be symmetric, tridiagonal, and unreduced. For any n in the range $1 \leq n < m$, we can write

$$\mathbf{T} = \begin{bmatrix} \hat{\mathbf{T}}_1 & \\ & \hat{\mathbf{T}}_2 \end{bmatrix} + \beta \begin{bmatrix} \mathbf{e}_n \\ \mathbf{e}_1 \end{bmatrix} \begin{bmatrix} \mathbf{e}_n^\top & \mathbf{e}_1^\top \end{bmatrix}.$$

$$\mathbf{T} = \begin{array}{|c|c|} \hline \mathbf{T}_1 & \\ \hline \beta & \mathbf{T}_2 \\ \hline \end{array} = \begin{array}{|c|c|} \hline \hat{\mathbf{T}}_1 & \\ \hline & \hat{\mathbf{T}}_2 \\ \hline \end{array} + \begin{array}{|c|c|} \hline & \\ \hline \beta & \beta \\ \hline \beta & \beta \\ \hline \end{array}$$

- Suppose that the eigen decompositions $\hat{\mathbf{T}}_1 = \mathbf{Q}_1 \mathbf{D}_1 \mathbf{Q}_1^\top$ and $\hat{\mathbf{T}}_2 = \mathbf{Q}_2 \mathbf{D}_2 \mathbf{Q}_2^\top$ have been computed (\mathbf{D}_1 and \mathbf{D}_2 are diagonal, and \mathbf{Q}_1 and \mathbf{Q}_2 are orthogonal). Then we have

$$\mathbf{T} = \begin{bmatrix} \mathbf{Q}_1 & \\ & \mathbf{Q}_2 \end{bmatrix} \left(\begin{bmatrix} \mathbf{D}_1 & \\ & \mathbf{D}_2 \end{bmatrix} + \beta \begin{bmatrix} \mathbf{u} \\ \mathbf{v} \end{bmatrix} \begin{bmatrix} \mathbf{u}^\top & \mathbf{v}^\top \end{bmatrix} \right) \begin{bmatrix} \mathbf{Q}_1^\top & \\ & \mathbf{Q}_2^\top \end{bmatrix},$$

where $\mathbf{u} := \mathbf{Q}_1^\top \mathbf{e}_n$ and $\mathbf{v} := \mathbf{Q}_2^\top \mathbf{e}_1$. The problem is reduced to find the eigenvalues of a diagonal matrix plus a rank-one correction.

Remark 14

Suppose that the eigenvalues of $\hat{\mathbf{T}}_1$ and $\hat{\mathbf{T}}_2$ are known. A nonlinear but rapid calculation can be used to get from the eigenvalues of $\hat{\mathbf{T}}_1$ and $\hat{\mathbf{T}}_2$ to those of \mathbf{T} itself by the secular equation. The divide-and-conquer algorithm is based on recursive use of this idea.