

# Direct algorithms of solution of eigenvalue problem

## INTRODUCTION

In the last two chapters, we studied the algorithms for linear equations  $\mathbf{Ax} = \mathbf{b}$ . In this and next chapter, we study the algorithms for an eigenvalue problem. The eigenvalue problem is to find  $\lambda$  and  $\mathbf{x}$  from the equation  $\mathbf{Ax} = \lambda\mathbf{x}$  or  $\mathbf{Ax} = \lambda\mathbf{Bx}$ , where  $\mathbf{A}$  and  $\mathbf{B}$  are two square matrices. About the mathematical theories and properties of an eigenvalue problem, see Section 1.4 for a brief exposition or [29] for a more detailed discussion.

For  $\mathbf{A} \in \mathbb{R}^{n \times n}$ , the eigenvalue  $\lambda$  is the root of the  $n$ th order polynomial  $\det(\mathbf{A} - \lambda\mathbf{I}) = 0$ . Similarly for  $\mathbf{A}, \mathbf{B} \in \mathbb{R}^{n \times n}$ , the generalized eigenvalue  $\lambda$  is the root of the  $n$ th order polynomial  $\det(\mathbf{A} - \lambda\mathbf{B}) = 0$ . If  $n = 1$ , the calculation of the eigenvalue is truly trivial. If  $n = 2, 3, 4$ , direct algorithms are possible. These direct algorithms actually can be used as building blocks for iterative algorithms for  $n > 4$ . In Section 6.1, we list two MATLAB functions to calculate the eigenvalues for the case  $n = 2$ . If  $n > 4$ , no direct algorithms are possible. However, the algorithms presented in this chapter are like direct algorithms in real applications: the experience shows that they (nearly) never fail to converge in a fixed number of iterations. In the next chapter, we study the other iterative algorithms that do not have these preferred characteristics.

In Section 6.2, we present four useful auxiliary algorithms for the symmetric eigenvalue problem. For a symmetric matrix  $\mathbf{A} \in \mathbb{R}^{n \times n}$ , its eigenvalues are real and thus can be ordered ascendingly,  $\lambda_1 \leq \lambda_2 \leq \cdots \leq \lambda_{n-1} \leq \lambda_n$ . The first algorithm, which is implemented in `seig.m`, calculates an integer pair  $[k, l]$ ,  $k \leq l$  from a given interval  $[\alpha, \beta]$ ,  $\alpha \leq \beta$ , such that  $\alpha \leq \lambda_k$  and  $\lambda_l \leq \beta$ . The second algorithm, which is implemented in `seig2.m`, is the inverse function of `seig.m`. The two algorithms are useful when only approximate bound for an eigenvalue is needed. There are two similar algorithms, `vseig.m` and `rvseig.m`, for the symmetric positive definite generalized eigenvalue problem.

The key algorithm of the chapter is QR iteration algorithm, which is presented in Section 6.4. QR iteration is an extension of the power iteration and subspace iteration method. The power iteration and subspace iteration methods do not belong to the ‘direct’ eigenvalue algorithms that are the topic of this chapter. We defer their full presentation in the next chapter. However, we start the presentation of QR algorithm with a brief introduction of the two algorithms in Section 6.3. Two algorithms, `eigUnsymByQR.m` and `eigSymByQR.m`, are presented in Section 6.4. The second one is a specialized QR algorithm for symmetric matrices.

Section 6.5 presents the inverse iteration algorithm to calculate the eigenvectors from the given eigenvalues. Section 6.6 presents an orthogonal similarity transformation to order the eigenvalues in real Schur form of an unsymmetric matrix. The algorithm is useful to obtain the invariant subspace corresponding to the given eigenvalues of an unsymmetric matrix.

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