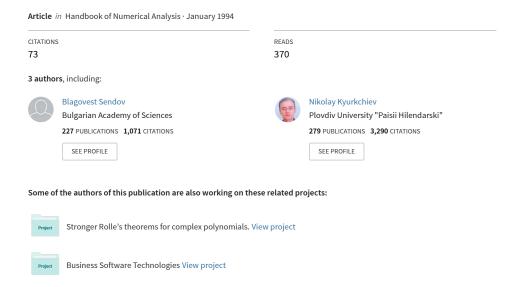
See discussions, stats, and author profiles for this publication at: https://www.researchgate.net/publication/266287614

### Numerical solution of polynomial equations



## HANDBOOK of NUMERICAL ANALYSIS

P. G. CIARLET and J. L. LIONS • Editors

Volume III

Techniques of Scientific Computing (Part 1)

Numerical Methods for Solids (Part 1)

Solution of Equations in **R**<sup>n</sup> (Part 2)

# NUMERICAL SOLUTION OF POLYNOMIAL EQUATIONS

## Contents

Preface	629
CHAPTER I. Properties of Algebraic Equations	631
1. Existence of the roots	631
2. Newton's formula and symmetric functions	635
3. Resolvent and discriminant of polynomials	637
4. Algebraic equations from first till fourth degree	639
5. Number of roots in an interval	640
6. Number of roots in a domain	645
7. Algebraic equations with a negative real part of the roots	648
8. Number of roots in a disc	650
9. The Gauss-Lucas theorem and Sendov's conjecture	651
10. Distribution of the roots on the plane	654
CHAPTER II. Localization Bounds	657
11. Elementary bounds	657
12. Estimations of the unique positive root	673
13. Sendov's method for localization of all positive roots	683
CHAPTER III. Local and Global Methods	683
14. Bernoulli's iteration	687
15. Graeffe's method	689
<ul><li>16. The method of Laguerre</li><li>17. The Lehmer-Schur method</li></ul>	693 697
	606
CHAPTER IV. Iterative Methods for Computation of All Roots	699
18. Iterative methods without derivatives	699
19. Iterative methods with derivatives	710
20. Simultaneous approximation of multiple roots	724
21. Multi-point methods for simultaneous approximation	733
22. Factorization of a polynomial	735
23. Interval methods for polynomial root determining	739
CHAPTER V. Computational Complexity (Renegar and Neff Approach)	747
24. Definitions and notation	74
25. The lower bound (Renegar approach)	748
26. Algorithm for the upper bound (Neff approach)	752
27. Approximate factorization	754

<ul><li>28. <i>q</i>-Splittings of the complex plane</li><li>29. Approximating the factors by contour integration</li><li>30. Finding a balanced splitting point</li></ul>	756 759 762
References	767
Subject Index	777

- ABEL, N. (1826), Beweis der Unmoglichkeit, algebraische Gleichungen von hoheren Graden als dem vierten allgemein aufzulosen, *Grelles J.* 1, S. 65.
- ABERTH, O. (1973), Iteration method for finding all zeros of a polynomial simultaneously, *Math. Comput.* 27, 339-344.
- Aitken, A. (1926), On Bernoulli's numerical solution of algebraic equations, *Proc. Roy. Soc. Edinburgh* 46, 289-305.
- ALEFELD, G. and J. HERZBERGER (1974a), On the convergence speed of some algorithms for the simultaneous approximation of polynomial roots, SIAM J. Numer. Anal. 11, 237–243.
- ALEFELD, G. and J. HERZBERGER (1974b), Einfuhrung in die Intervallrechnung (B. I. Wissenschaftsverlag, Zurich).
- Alefeld, G. and J. Herzberger (1983), Introduction to interval computations (Academic Press, New York).
- ALEXANDER, J. (1915), Functions which map the interior of the unit circle upon simple regions, Annals of Math. 17, 12-22.
- Andreev, A. and N. Kjurkchiev (1987), Two-sided methods for solving the polynomial equation, *Math. Balkanica (New Series)* 1, 72–82.
- Andreev, A. and N. Kjurkchiev (1989), Two-sided methods for solving equations, *IMACS Ann. Comput. Appl. Math.* 7, 161–172.
- Angelova, E. and Kh. Semerdzhiev (1982), Methods for the simultaneous approximate derivation of the roots of algebraic, trigonometric and exponential equations, *USSR Comput. Math. Math. Phys.* **22** (1), 226–232 (in Russian).
- ASCHER, M. (1970), in: Problems and Solutions, Amer. Math. Monthly 77, 380.
- ATANASSOVA, L., N. KJURKCHIEV and A. ANDREEV (1988), Recursive generated iterative functions for approximate solution of algebraic equations, *Serdica* 14, 271–277 (in Russian).
- ATANASSOVA, L., T. DJUKANOVA and N. KJURKCHIEV (1985), Methods with 3R+4 rate of convergence for computing the roots of an algebraic equation, *Annuaire Univ. Sofia Fac. Math. Mec.* **79** (1) (in Russian).
- Ballieu, R. (1947), Sur des limitations des recines d'une equation algebrique, *Acad. Roy. Belg. Bull. Cl. Sci.* 33, 743-750.
- BAREISS, E. (1960), Resultant procedure and the mechanization of the Graeffe Process, *J. ACM* 7, 346–386.
- Barrstow, L. (1914), Investigations relating to the stability of the aeroplane, *Reports* and *Memoranda* 154, Advisory Committee for Aeronautics.
- Barmish, B. (1984), Invariance of the strict Hurwitz property for polynomials with perturbed coefficients, *IEEE Trans. Automat. Contr.* **29** (10), 935–936.
- BAUDET, G. (1978), Asynchronous iterative methods for multiprocessors, J. ACM 25 (2), 226-244. Bell, H. (1965), Gershgorin's theorem and the zeros of polynomials, Amer. Math. Monthly 72, 292-295.
- BEN-OR, M., E. FEIG, D. KOZEN, P. TIWARI (1988), A fast parallel algorithm for determining all roots of a polynomial with real roots, SIAM J. Comput. 17, 1081–1092.

- Bernoulli, D. (1728), Comment. Petropolitanae 3.
- Bialas, S. and J. Garloff (1985), Stability of polynomials under coefficient perturbation, *IEEE Trans. Automat. Contr.* **30** (3), 310-312.
- BIEHLER, C. (1879), Sur une classe d'equations algebriques dont toutes les racines sont reelles, J. Reine Angew. Math. 87, 350-352.
- BOJANOV, B. (1970), On an estimation of the roots of algebraic equations, Appl. Math. 11 (2), 195-205.
- BOJANOV, B., Q. RAHMAN and J. SZYNAL (1985), On a conjecture of Sendov about the critical points of a polynomial, *Math. Z.* 190, 281–285.
- Borsch-Supan, W. (1963), A posteriori error bounds for the zeros of polynomials, *Numer. Math.* 5, 380–398.
- Borsch-Supan, W. (1970), Residuenabschatzung für Polynom-Nullstellen mittels Lagrange-Interpolation, Numer. Math. 14, 287–296.
- Brauer, A. (1957), The theorems of Ledermann and Ostrowski on positive matrices, *Duke Math. J.* **24**, 265–274.
- Brauer, A. and I. Gentry (1974), Bounds for the greatest characteristic root of an irreducible nonnegative matrix, *Linear Algebra Appl.* 8, 105-107.
- Brauer, A. and I. Gentry (1976), Bounds for the greatest characteristic root of an irreducible nonnegative matrix II, *Linear Algebra Appl.* 13, 109–114.
- Brodetsky, S. and G. Smeal (1924), On Graeffe's method for complex roots of algebraic equations, *Math. Proc. Cambridge Philos. Soc.* 22, 83–87.
- Broyden, C. and J. Ford (1975), A new method of polynomial deflation, J. Inst. Math. Appl. 16, 271-281.
- BUDAN, J. (1826), Nouvelle methode pour la resolution des equations numeriques (Paris, 2nd ed.). BURMEISTER, W. and J. SCHMIDT (1982), On the R-order of coupled sequences II, Computing 29, 73–81.
- Burmeister, W. and J. Schmidt (1983), On the R-order of coupled sequences III, Computing 30, 157-169.
- Burmeister, W. and J. Schmidt (1985), Characterization of the best R orders of coupled sequences arising in iterative processes, in: *Numerical Methods* and *Applications '84* (BAN, Sofia) 191–202.
- BURMEISTER, W. and J. SCHMIDT (1988), On the *R*-order of coupled sequences arising in single-step type methods, *Numer. Math.* **53**, 653–661.
- Cascio, M., L. Pasquini and D. Trigiante (1983), Simultaneous determination of polynomial complex roots and multiplicities: Algorithm and problems involved, Tech. rep. Dip. di Metodi e Modelli Matematici per le scienze Applicate, Univ. Roma La Sapienza.
- Cascio, M., L. Pasquini and D. Trigiante (1984), Un polialgoritmo a convergenza rapida per la determinazione simultanea degli zeri reali di un polinomio e delle loro molteplicita, *Monografia di Soft. Matem.* N. 30, Pubbl. dell'IAC.
- Cauchy, A. (1829), Sur la resolution des equations numeriques et sur la theory d'elicifation, *Oeuvres* (12) 19, 87–161.
- Chung, S. (1972), An algorithm for the zeros of transcendental functions, *Numer. Math.* **32**, 351–371. Chung, S. (1976), Generalization and acceleration of an algorithm of Sebastiao e Silva and its duales, *Numer. Math.* **25**, 365–377.
- Cohen, J. (1979), Random evolutions and the spectral radius of a nonnegative matrix, *Math. Proc. Cambridge Philos. Soc.* **86**, 349–350.
- COHN, A. (1922), Über die Anzahl der Wurzeln einer algebraischen Gleichung in einem Kreis, *Math.* Z. **14**, 110–138.
- Cosnard, M. and P. Fraigniaud (1989), Asynchronous Durand-Kerner and Aberth polynomial root finding methods on a distributed memory multi-computer, in: *Parallel Computing* '89, Leiden.
- Dandelin (1826), Recherches sur la resolution des equations numeriques, Nouveaux Mem. de l'Acad. Roy. des Sci., et Belles Lettres de Bruxelles 3, 1-71.
- DATT, B. and N. Govié (1978), On the location of zeros of a polynomial, J. Approx. Theory 24, 78-82.

- Davies, M. and B. Dawson (1978), An automatic search procedure for finding real zeros, *Numer. Math.* 31, 299-312.
- Dekker, T. (1968), Newton-Laguerre iteration, in: *Programmations en Mathematiques Numeriques*, Besanson, 7-14 September 1966 (Editions du Centre Nationale de la Recherche Scientifique, Paris) 189-200.
- DEUTSCH, E. (1971), in: Problems and Solutions, Amer. Math. Monthly 78, 799.
- Deutsch, E. (1979), Nested bounds for the Perron root of a nonnegative irreducible matrix, manuscript; see *Notices Amer. Math. Soc.* 26, A421-A422.
- Deutsch, E. (1981), Bounds for the Perron root of a nonnegative irreducible partitioned matrix, Pacific J. Math. 92, 49-56.
- Deutsch, E. (1982), Lower bounds for the Perron root of a nonnegative irreducible matrix, *Math. Proc. Cambridge Philos. Soc.* **92**, 49–54.
- DIMITROV, D. (1983), On a conjecture of Sendov, C. R. Acad. Bulgare Sci. 36 (5), 561-563.
- Dochev, K. (1962a), A modified Newton method for simultaneous approximate calculation of all roots of a given equation, *Phys. Math. J.* 5, 136–139.
- DOCHEV, K. (1962b), Über Newtonsche Iterationen, C. R. Acad. Bulgare Sci. 15 (7), 695-701.
- DOCHEV, K. and P. BYRNEV (1964), Certain modifications of Newton's method for the approximate solution of algebraic equations, *Z. Vycisl. Mat. i Mat. Fiz.* 4, 915–920 (in Russian).
- Dochev, K., P. Byrnev, and P. Russev (1969), On a method for calculation of the zeros of Laguerre entire functions, *Izv. Mat. Inst.* **10**, 155-160 (in Bulgarian).
- DURAND, E. (1960), Solution Numerique des Equations Algebraique (Masson et Compagnie, Paris). DVORCUK, J. (1967), Newton method for simultaneous finding of all roots of a polynomial, in: Sb. Vykumnych praci, Ustav Vypoctove Techn. CSAV a CVUT, 41-64.
- Dvorcuk, J. (1969), Factorization of a polynomial into quadratic factors by Newton method, *Apl. Mat.* 14, 54-80.
- EHRLICH, L. (1967), A modified Newton method for polynomials, Comm. ACM 10, 107-108.
- Eneström, G. (1920), Remarque sur un theoreme relatif aux racines de l'equation  $a_n x^n + \cdots + a_0 = 0$ . ou tous les coefficients sont reels et positifs,  $T\hat{o}hoku\ Math.\ J.\ 18$ , 34–36.
- FARMER, M. and G. LOIZOU (1975), A class of iteration functions for improving simultaneously, approximations to the roots of polynomials, *BIT* 15, 250–252.
- Farmer, M. and G. Loizou (1977), An algorithm for the total, or partial, factorization of a polynomial, *Math. Proc. Cambridge Philos. Soc.* **82**, 427–437.
- FOURIER, J. (1831), Analyse des equations determines, Livre I, Paris.
- FORD, J. (1977), A generalization of the Jenkins-Traub method, Math. Comput. 31 (137), 193-203.
  FRAIGNIAUD, P. (1989a), Analytic and asynchronous root finding methods on a distributed memory multicomputer, Research Report LIP- IMAG.
- Fraigniaud, P. (1989b), The Durand-Kerner polynomials root finding method in case of multiple roots, Research Report LIP-IMAG.
- FRIEDLAND, S. and S. KARLIN (1975), Some inequalities for the spectral radius of nonnegative matrices and applications, *Duke Math. J.* 42, 459–490.
- FUJIWARA, M. (1915), Über die Wurzeln der algebraischen Gleichungen, Tôhoku Math. J. 8, 78–85. FUJIWARA, M. (1916), Über die obere Schranke des absoluten Betrages der Wurzeln einer algebraischen Gleichung, Tôhoku Math. J. 10, 167–171.
- Gargantini, I. (1978), Further applications of circular arithmetic: Schroeder-like algorithms with error bounds for finding zeros of polynomials, SIAM J. Numer. Anal. 3, 497–510.
- GARGANTINI, I. (1980), Parallel square-root iterations for multiple roots, Comput. Math. Appl. 6, 279-288.
- Gargantini, I. (1981), An application of interval mathematics: A polynomial solver with degree four convergence, *Freiburger Intervall-Berichte* 7, 15–25.
- Gargantini, I. and P. Henrici (1974), Circular arithmetic and the determination of polynomial zeros, *Numer. Math.* 18, 305–320.
- GASKELL, R. (1958), Engineering Mathematics (Dzyden Press, New York), 244-251.
- GAUSS, K. (1850), Beitrage zur Theorie der algebraischen Gleichungen, Abh. Ges. Wiss. Gottingen 4; Ges. Werke 3, 73-102.

- GERSHGORIN, S. (1931), Über die Abgrenzung der Eigenwerte einer Matrix, *Izv. Akad. Nauk SSSR* 7, 749-754.
- GOODMAN, A., RAHMAN, Q. and J. RATTI (1969), On the zeros of a polynomial and its derivative, *Proc. Am. Math. Soc.* 21, 273–274.
- GRACE, J. (1902), On the zeros of a polynomial, Proc. Cambridge Philos. Soc. 11, 352-356.
- Graeffe, C. (1837), Die Auflösung der hoheren numerischen Gleichungen, als Beantwortung einer von der königlichen Akademie der Wissenschaften zu Berlin aufgestellten Preisfrage (Friedrich Schulthess, Zurich).
- Grau, A. (1963), On the reduction of number range in the use of the Graeffe process, J. ACM 10, 538-544.
- Green, M., A. Korsak and M. Pease (1976), Simultaneous iteration to wards all roots of a complex polynomial, SIAM Rev. 18, 501–502.
- Grobner, W. (1966), Matrizenrechnung (Bibliographisches Institut, Mannheim Vien-Zurich).
- Guggenheimer, H. (1986), Initial approximations in Durand-Kerner's root finding method, *BIT* 26 (4), 537-539.
- Guiver, J. and N. Bose (1983), Strictly Hurwitz property invariance of quartics under coefficient perturbation, *IEEE Trans. Automat. Contr.* 28, 106–107.
- HALL, C. and T. POPSCHING (1969), Bounds for the maximal eigenvalue of a nonnegative irreducible matrix, Duke Math. J. 36, 159–164.
- Halley, E. (1809), A new, exact, and easy method of finding the roots of any equations generally, and that without any previous reduction (abridged by C. Hutton, G. Shaw and R. Pearson), *Philos. Trans. Roy. Soc. London* 3.
- HANSEN, E. and M. PATRICK (1976), Estimating the multiplicity of a root, Numer. Math. 27, 121-131.
- HANSEN, E. and M. PATRICK (1977), A family of root finding methods, Numer. Math. 27, 257-269.
- HAUENSCHILD, M. (1974), Arithmetiken fur komplexe Kreise, Computing 13, 299-313.
- Heawood, P. (1907), Geometrical relations between the roots of f(x) = 0, f'(x) = 0, Quart. J. Math. 38, 84–107.
- HERMITE, C. (1866), Question 777, Nouv. Ann. Math. 5 (2), 432; Questions 778, 779, a. a. o., S. 479.
- HERMITE, C. (1879), Sur l'indice des fractions rationelles, Bull. Soc. Math. France 7, 128-131.
- Hermite, C. (1898), Sur un memoire de Laguerre concernant equations algebriques, Oeuvres de Laguerre, Paris, 461-468.
- Herzberger, J. (1986a), On the R-order of some requirences with applications to inclusion-methods, Computing 36, 175–180.
- Herzberger, J. (1986b), Bounds for the R-order of certain iterative numerical processes, BIT 26, 259-262.
- HERZBERGER, J. (1989), Iterationsferfahren hoherer Ordnung zur Einschliessung der Inversen einer Matrix, Z. Angew. Math. Mech. 69, 115–120.
- Herzberger, J. (1990), Using error-bounds for hyper-power methods to calculate inclusions for the Inverse of a matrix, BIT 30, 508-515.
- HILDEBRAND, F. (1956), Introduction to Numerical Analysis (McGraw-Hill, New York).
- HITCHCOCK, F. (1944), An improvement on the G. C. D. method for complex roots, *J. Math.* and *Phys.* 23, 69–74.
- HOUSEHOLDER, A. S. (1970), The Numerical Treatment of a Single Nonlinear Equation (McGraw-Hill, New York).
- HOUSEHOLDER, A. (1971), Generalizations of an algorithm of Sebastiao e Silva, Numer. Math. 16, 375–382.
- HOXHA, F. (1988), Calcul simultane des racines d'un polynome complexe: Contribution a l'algorithmique et mise *en* oeuvre sur un resean de processeur, These de l'Institut National Polytechnique de Toulouse.
- HURWITZ, A. (1896), Über die Bedingungen, unter welchen eine Gleichung nur Wurzeln mit negativen reelen Teilen besitzt, *Math. Ann.* 46, 273–284.
- ILIEV, L. (1949), Über Newtonsche Iterationen, Jahrb. Univ. Sofia, 1, 167-171 (in Bulgarian).
- ILIEV, L. (1987), Laguerre Entire Functions (BAN, Sofia).

- ILIEV, L. and K. Dochev (1963), Über Newtonsche Iterationen, Wiss. Z. Tech. Univ. Dresden, 12 (1), 117–118.
- JAIN, V. (1990), On Cauchy's baund for zeros of a polynomial, Approx. Theory Appl. 6, 18-24.
- Jenkins, M. and J. Traub (1970), A three-stage algorithm for real polynomials using quadratic iteration, SIAM J. Numer. Anal. 7, 545-566.
- JOYAL, A., LABELLE, G. and Q. RAHMAN (1967), On the location of zeros of polynomials, *Canad. Math. Bull.* 10, 53-63.
- Kahan, W. (1967), Laguerre's method and a circle which contains at least one zero of a polynomial, SIAM J. Numer. Anal. 4, 474-482.
- Kakeya, S. (1912), On the limit of the roots of an algebraic equation with positive coefficients, *Tôhoku Math. J.* 2, 140-142.
- Kelleher, S. B. (1916), Des limites des zeros d'un polynome, J. Math. Pure Appl. 2, 169-171.
- Kerner, I. (1966a), Ein Gesamtschrittverfahren zur Berechnung der Nullstellen von Polynomen, Numer. Math. 8, 290-294.
- Kerner, I. (1966b), Algorithm 283, Comm. ACM 9, 273.
- Khapitonov, V. (1978), On a generalization of a stability criterion, *Izv. Acad. Nauk Kazakh. SSR Ser. Fiz.-Mat.* 1, 53–57 (in Russian).
- KJELBERG, G. (1984), Two observation on Durand-Kerner's root finding method, BIT 24, 556-559.
- KJURKCHIEV, N. (1981), Some modifications of Dvorcuk's method for factorization of a polynomial into quadratic factors, *Annuaire Univ. Sofia Fac. Math. Mec.* 75, 3–7.
- KJURKCHIEV, N. (1982), On some iterational schemes of Dochev's type with increased rate of convergence, *Annuaire Univ. Sofia Fac. Math. Mec.* **76**, 3–10.
- KJURKCHIEV, N. (1983a), Certain modification of Ehrlich's method for the approximate solution of algebraic equation, *Pliska* 5, 43–50 (in Russian).
- KJURKCHIEV, N. (1983b), Computational aspects and areas of application of the methods for simultaneous determination of all roots of an algebraic equation, *Annuaire Univ. Sofia Fac. Math. Mec.* 77, 11–16 (in Russian).
- KJURKCHIEV, N. (1991), Über die Konvergenzordnungen einiger Klassen Iterationsverfahren, Serdica 17, 139–143.
- KJURKCHIEV, N. (1992a), Note on the estimation of the order of convergence of some iterative methods, *BIT* 32, 525–528.
- KJURKCHIEV, N. (1992b), A note on a method for localization of the roots of algebraic equations, C. R. Acad. Bulgare Sci. 44 (9) (in print).
- KJURKCHIEV, N. and A. Andreev (1985), A modification of Weierstrass Dochev's method with rate of convergence R+2 for simultaneous determination of the zeros of a polynomial, C. R. Acad. Bulgare Sci. 38 (11), 1461–1463 (in Russian).
- KJURKCHIEV, N. and A. Andreev (1987), Ehrlich's method with raised speed of convergence, *Serdica* 13, 52–57.
- KJURKCHIEV, N. and A. Andreev (1989), Two-sided method for computation of all multiple roots of an algebraic polynomial, *Serdica* **15** (4), 302–304 (in Russian).
- KJURKCHIEV, N. and A. Andreev (1990), On Halley-like algorithms with high order of convergence for simultaneous approximation of multiple roots of polynomials, C. R. Acad. Bulgare Sci. 43 (9), 29–32
- KJURKCHIEV, N. and A. ANDREEV (1992), A generalization of the Alefeld-Herzberger's method, Computing 47, 355-360.
- KJURKCHIEV, N. and J. HERZBERGER (1992), A new lower bound for the zeros of polynomials, Serdica (in print).
- KJURKCHIEV, N. and R. IVANOV (1984), On some multi-stage schemes with a superlinear rate of convergence, *Annuaire Univ. Sofia Fac. Math. Mec.* 78, 132–136 (in Russian).
- KJURKCHIEV, N. and S. MARKOV (1983), Two interval methods for algebraic equations with real roots, *Pliska* 5, 118–131.
- KJURKCHIEV, N. and S. TASCHEV (1981), Method for simultaneous determination of the zeros of a polynomial, C. R. Acad. Bulgaire Sci. 34 (8), 1053-1055 (in Russian).

KJURKCHIEV, N., A. ANDREEV and V. POPOV (1984), Iterative methods for computation of all multiple roots of an algebraic polynomial, Annuaire Univ. Sofia Fac. Math. Mec. 78, 178-185 (in Russian).

Колма, Т. (1917), On the limits of the roots of an algebraic equation, Tôhoku Math. J. 11, 119-127. KRIER, N. (1973), Komplexe Kreisarithmetik, Ph. D. Thesis, Univ. Karlsruhe, Karlsruhe.

Kunieda, M. (1916), Note on the roots of algebraic equations, Tôhoku Math. J. 9, 167-173.

LAGOUANELLE, J. L. (1966), Sur une method de calcul de l'ordre de multiplicite des zeros d'un polynome, C. R. Acad. Sci. Paris 262A, 626-627.

LAGUERRE, E. (1880), Sur une methode pour obtenir par approximation les racines d'une equation algebrique qui a toutes ses racines reelles, Nouv. Ann. Math. 2s. 19; Oeuvres 1, 87-103.

LAGUERRE, E. (1898), Oeuvres 1, Paris.

LANDAU, E. (1906), Über den Picardischen Satz, Vierteljahrsschrift der Naturforschenden Geselschaft in Zurich 51, 252-318.

LANDAU, E. (1907), Sur quelques generalisations du theorème de M. Picard, Ann. Sci. École Norm. Sup. **24** (3), 179–201.

LAWRENCE, T. and E. LAWRENCE (1972), A new algorithm for factoring polynomials, Proc. IEEE 60 (6), 733-738.

LEDERMANN, W. (1950), Bounds for the greatest latent roots of a positive matrix, J. London Math. Soc. 25, 265-268.

Lobacevsky, N. (1834), Algebra ili vycislenie konecnuh, Polnoe Sobranie Socinenii 4 (1948).

Loizou, G. (1982), Une note sur le procede iterativ de Marica Presic, C. R. Acad. Sci. Paris 295, 707-710.

Loizou, G. (1983), Higher order iteration functions for simultaneously approximating polynomial zeros, Internat. J. Comput. Math. 14, 45-58.

Lossers, O. (1971), Amer. Math. Monthly 78, 681-683.

Lucas, F. (1874), Properietes geometriques des fractions rationelles, C. R. Acad. Sci. Paris 78, 140-144, 180-183, 271-274.

MAEHLY, H. (1954), Zur iterativen Auflosung algebraischer Gleichungen, Z. Angew. Math. Phys. 5, 260-263.

MAKRELOV, I. (1979), On a numerical method for simultaneous search of all zeroes of a given trigonometric polynomial, Travaux Sci. Univ. Plovdiv 17, 205-217.

MAKRELOV, I, and KH. SEMERDZHIEV (1983), A two analogue of a method of Ehrlich for simultaneous determination of all zeros of a trigonometric and exponential polynomials, C. R. Acad. Bulgare Sci. 36, 879-882 (in Russian).

MAKRELOV, I. and Kh. Semerdzhiev (1984a), Methods for the simultaneous finding of all roots of an algebraic and exponential polynomials, with given multiplicity, J. Comput. Math. Math. Phys. **24** (10), 1443–1453 (in Russian).

MAKRELOV, I. and Kh. SEMERDZHIEV (1984b), Methods of finding simultaneously all the roots of algebraic, trigonometric and exponential equations, J. Comput. Math. Math. Phys. 24 (5), 99-105 (in Russian).

MAKRELOV, I. and Kh. SEMERDZHIEV (1985a), Dochev's method of a generalized polynomial over an arbitrary Chebyshev system, C. R. Acad. Bulgare Sci. 38 (10), 1323-1326 (in Russian).

MAKRELOV, I. and KH. SEMERDZHIEV (1985b), On the convergence of two methods for the simultaneous finding of all roots of exponential equations, IMA J. Numer. Anal. 5, 191-200.

MAKRELOV, I., KH. SEMERDZHIEV and S. TAMBUROV (1985), Method for simultaneous finding of all zeros of a given generalized polynomial over Chebyshev system, Research Report JINR, Dubna P11-85-932 (in Russian).

MAKRELOV, I., KH. SEMERDZHIEV and S. TAMBUROV (1986a), A modified Ehrlich's method, C. R. Acad. Bulgare Sci. 39 (5), 43-46 (in Russian).

MAKRELOV, I., KH. SEMERDZHIEV and S. TAMBUROV (1986b), Method for simultaneous finding all roots of a generalized polynomial over an arbitrary Chebyshev system, Serdica 12, 351-357 (in Russian).

MARDEN, M. (1949), The Geometry of the Zeros of a Polynomial in a Complex Variable, Math. Surveys 3 (Amer. Math. Soc., Providence, RI).

MARDEN, M. (1983), Conjectures on the critical points of a polynomial, Amer. Math. Monthly 90, 267-276.

MARKOVITCH, D. (1939), Sur quelques limites superieures des modules des zeros d'un polynome, Mathematica 15, 8-11.

MARKOV, S. and N. KJURKCHIEV (1989), A method for solving algebraic equations, Z. Angew. Math. Mech. 69 (4), 106-109.

Marty, F. (1932), Sur une inegalite que verifient les zeros d'un polynome, Bull. Sci. Math. 56, 276-281.

MEIR, A. and A. SHARMA (1969), On Ilyeff's conjecture, Pac. J. Math. 31, 459-467.

MERIKOSKI, J. (1979), On a lower bound for the Perron eigenvalue, BIT 19, 39-42.

MIGNOTTE, M. (1976), Note sur la methode de Bernoulli, Numer. Math. 26, 325-326.

MILLER, M. (1990), Maximal polynomials and the Ilieff-Sendov conjecture, *Trans. of the Amer. Math. Soc.* **321** (1), 285-303.

MILOVANOVIC, G. and M. Petkovic (1983), On the convergence order of a modified method for simultaneous finding polynomial zeros, *Computing* 30, 171–178.

MILOVANOVIC, G. and M. PETKOVIC (1984), The methods of high order for the simultaneous determination of multiple polynomials zeros, *Izv. Univ. Nis*, 95–100.

MOHAMMAD, Q. (1965a), On the zeros of polynomials, Amer. Math. Monthly 72, 35-38.

MOHAMMAD, Q. (1965b), On the zeros of polynomials, Amer. Math. Monthly 72, 631-633.

MOHAMMAD, Q. (1967), Location of the zeros of polynomials, Amer. Math. Monthly 74, 290-292.

MONTEL, P. (1935), Sur quelques rapports nouveaux entre l'algebre et la theory des fonctions, *Mathematica* (Cluj) 9, 47-55.

MONTEL, P. (1935a), Sur quelques limites pour les modules des zeros des polynomes, Comment. Math. Helv. 7, 178-200.

MOORE, R. (1966), Interval Analysis (Prentice-Hall, Englewood Cliffs, New Jersey).

NEFF, A. (1990), Specified precision polynomial root isolation is in NC<sup>4</sup>, Research Report, RC 15653 (69571), IBM Research Division, T. J. Watson Research Center, Yorktown Heights, NY 10598.

Nourein, A. W. (1975), An iteration formula for simultaneous determination of the zeroes of a polynomial, *J. Comput. Appl. Math.* **4**, 251–254.

Nourein, A. W. (1977a), An improvement on two iteration methods for simultaneous determination of the zeros of polynomial, *Internat. J. Comput. Math.* 6, 241–252.

Nourein, A. W. (1977b), An improvement on Nourein's method for the simultaneous determination of the zeros of a polynomial (an algorithm), *J. Comput. Appl. Math.* 3, 109–110.

Obreshkov, N. (1924), Über die Wurzeln von algebraischen Gleichungen, *Jahresber. Deutsch. Math. Ver.* 33, 52–64.

Obreshkov, N. (1928), Über die Trennung der reellen Wurzeln von algebraischen Gleichungen, Jahresber. Deutsch. Math. Ver. 37, 234–237.

Obreshkov, N. (1952), Sur les racines des equations algebriques, Annuaire Univ. Sofia Fac. Math. Mec. 47, 67-83.

OBRESHKOV, N. (1962), Advanced algebra (Nauka i izkustvo, Sofia) (in Bulgarian).

Obreshkov, N. (1963a), Verteilung und Berechnung der Nullstellen reeller Polynome (VEB Deutscher Verlag der Wissenschafter, Berlin).

Obreshkov, N. (1963b), Sur la solution numerique des equations, Annuaire Univ. Sofia Fac. Math. Mec. 56, 73-83.

ORTEGA, J. and W. RHEINBOLDT (1970), Iterative Solution of Nonlinear Equations in Several Variables (Academic Press, New York).

OSTROWSKI, A. (1940), Recherches sur la methode de Graeffe et les zeros des polynomes et des series de Laurent, *Acta Math.* 72, 99-105.

OSTROWSKI, A. (1952), Bounds for the greatest latent root of a positive matrix, J. London Math. Soc. 27, 253-256.

OSTROWSKI, A. (1966), Solution of Equations and Systems of Eequations (Academic Press, New York, 2nd ed.).

OSTROWSKI, A. and H. Schneider (1960), Bounds for the maximal characteristic root of a nonnegative irreducible matrix, *Duke Math. J.* 27, 547–553.

- PAN, V. (1987), Sequential and parallel complexity of approximate evaluation of polynomial zeros, Comput. Math. Appl. 14, 591-622.
- Pan, V. (1992), Complexity of computations with matrices and polynomials, SIAM Rev. 34, 2, 225–262.
- Parlett, B. (1964), Laguerre's method applied to the matrix eigenvalue problem, *Math. Comp.* 18, 464–485.
- Pasquini, L. and D. Trigiante (1981), il metodo di continuazione e l'approssimazione simultanea degli zeri di un polinomo, Sem. Inst. Mat. Appl. Fac. Ing., Univ. Roma, 128-146.
- Pasquini, L. and D. Trigiante (1985), A globally convergent method for simultaneously finding polynomial roots, *Math. Comp.* 44, 135–149.
- PASTOR, R. (1932), Lecciones de Algebra, 2nd edition.
- Pellet, M. (1924), Sur la racine de plus petit module des equations, Bull. Sci. Math. 48, 265-267.
- Petkovic, M. (1981), On a generalization of the root iterations for polynomial complex zeros in circular interval arithmetics, *Computing* 27, 37–55.
- Petkovic, M. (1982), Generalized root iterations for the simultaneous determinations of multiple complex zeros, Z. Angew. Math. Mech. 62, 627-630.
- Petkovic, M. (1987), Some interval iterations for finding a zero of a polynomial with error bounds, *Comput. Math. Appl.* **14** (6), 479–495.
- Реткоvic, M. (1989a), On Halley-like algorithms for simultaneous approximation of polynomial complex zeros, SIAM J. Numer. Anal. 26 (3), 740–763.
- Petkovic, M. (1989b), Iterative Methods for Simultaneous Inclusion of Polynomial Zeros (Springer Verlag, Berlin).
- Petkovic, M. and J. Herzberger (1990), Inclusion of multiple polynomial roots in complex rectangular arithmetic, *IMACS Ann. Comput. Appl. Math.* 12.
- PETKOVIC, M. and G. MILOVANOVIC (1983), A note on some improvements of the simultaneous methods for determination of polynomial zeros, *J. Comput. Appl. Math.* **9**, 65–69.
- Petkovic, M., G. Milovanovic and L. Stefanovic (1986), Some higher order methods for the simultaneous approximation of multiple polynomial zeros, *Comput. Math. Appl.* 9, 951–962.
- Petkovic, M. and L. Cvetkovic (1990), On a hybrid method for a polynomial complex zero, in: *International Symposium on Computer Arithmetic, Scientific Computation and Mathematical Modelling*, Albena, Bulgaria, 23–27 September 1990 (Publishing House of the Bulgarian Academy of Sciences) 144–145.
- PETKOVIC, M. S. and L. D. PETKOVIC (1989), On the bounds of the R-order of some iterative methods, Z. Angew. Math. Mech. 69, T197-T198.
- Petkovic, M. and L. Stefanovic (1984), On the convergence order of accelerated root iterations, Numer. Math. 44, 463–476.
- Petkovic, M. and L. Stefanovic (1986), On some improvements of square root iteration for polynomial complex zeros, J. Comput. Appl. Math. 15, 13-25.
- PETKOVIC, M. and L. STEFANOVIC (1987a), On some iteration functions for the simultaneous computation of multiple complex polynomial zeros, *BIT* 27, 111–122.
- Petkovic, M. and L. Stefanovic (1987b), On some parallel higher-order methods of Halley's type for finding multiple polynomial zeros, in: *Numerical Methods* and *Approximation Theory*, III (Faculty of Electronic Engineering, Niš), 329–337.
- Petkov, M. and N. Kjurkchiev (1990), High accuracy localization estimates for roots of algebraic equations, *Math. Ed. Math.*, 388–391 (in Bulgarian).
- PHELPS, D. and R. RODRIGUEZ (1972), Some properties of extremal polynomials for the Ilieff conjecture, *Kodai Math. Sem. Rep.* 24, 172–175.
- Poincaré, H. (1883), Sur les equations algebriques, C. R. Acad. Sci. Paris 97, 1418-1419.
- POLYA, G. (1915), Über das Graeffesche Verfahren, Z. Math. Phys. 63, 275-290.
- Poulain, E. (1867), Theorems generaux-sur les equations algebraiques, *Nouv. Ann. Math.* 6 (2), 21-33.
- Presic, M. (1980), A convergence theorem for a method for simultaneous determination of all zeros of a polynomial, *Publ. Inst. Math. Beograd* **28** (5), 159–165.

Presic, S. B. (1966), Un procédé iterative pour la factorisation des polynomes, C. R. Acad. Sci. Paris 262, 862–863.

RAHMAN, Q. (1970), A bound for the moduli of the zeros of polynomials, Canad. Math. Bull. 13, 541-542.

RAHMAN, Q. (1972), Zeros of linear combinations of polynomials, Canad. Math. Bull. 15, 139-142.

RALL, L. (1966), Convergence of the Newton process to multiple solutions, Numer. Math. 9, 23-37.

RALSTON, A. (1965), A first Course in Numerical Analysis (McGraw-Hill, New York).

REICH, S. (1970a), in: Problems and Solutions, Amer. Math. Monthly 77, 655.

REICH, S. (1970b), in: Problems and Solutions, Amer. Math. Monthly 77, 532.

Renegar, J. (1987), On the worst case arithmetic complexity of approximating zeros of polynomials, J. of Complexity 3, 90–113.

RENYI, A. and P. Turan (1952), On the zeros of polynomials, Acta Math. Hungar. 3, 275-284.

RICE, T. and L. Jamieson (1989), A highly parallel algorithm for root extraction, *IEEE Trans. Comput.* **28** (3), 443–449.

RIORDAN, J. (1958), Introduction to Combinatorial Analysis (Wiley, New York).

ROKNE, J. and P. LANCASTER (1971), Complex interval arithmetic, Comm. ACM 14, 111-112.

ROUCHE, E. (1862), Memoire sur la serie de Lagrange, J. Ecole Polyt. 22, 217-218.

RUTISHAUSER, H. (1963), On a modification of the Q. D. Algorithm with Graeffe-type convergence, in: *Inform. Proc.* 1962 (North-Holland Publishing, Amsterdam) 93–96.

SAN JUAN, R. (1935), Complements a la methode de Graffe pour la resulation des equations algebriques, Bull. Sci. Math. 59, 104-109.

SAVENKO, S. (1964), Iteration method for solving algebraic equation, Z. Vycisl. Mat. i Mat. Fiz. 4, 738-744 (in Russian).

Schmeisser, G. (1969), Bemerkungen zu einer Vermutung von Ilieff, Math. Z. 111, 121-125.

Schmeisser, G. (1977), On Ilieff's conjecture, Math. Z. 156, 165-173.

SCHMIDT, J. (1981), On the R-order of coupled sequences, Computing 26, 333-342.

Schur, I. (1914), Zwei Satze uber algebraische Gleichungen mit lauter reellen Wurzeln, J. Reine Angew. Math. 144, 75–88.

Schur, I. (1921), Über algebraischen Gleichungen, die nur Wurzeln mit negativen Realteilen besitzen, Z. Angew. Math. Mech. 1, 307-311.

Schur, I. (1933), Untersuchungen über algebraische Gleichungen I., Bemerkungen zu einem Satz von E. Schmidt, Sitzungsber. Preuss. Acad. Wiss. Math.-Phys. Klasse, 403-428.

SEBASTIAO E SILVA, J. (1941), Sur une methode d'approximation semblable a celle de Gräffe, *Portugal. Math.* 2, 271–279.

SEBASTIAO E SILVA, J. (1946), Complementi al methodo di Gräffe per la risoluzione delle equazione algebriche, Intit. Veneto Sci. Lett. Arti Atti Cl. Sci. Fis. Mat. Natur. 8 (1), 335–343.

Sekulovski, R. (1972), Uopstenje iterative metode S. Presica za faktorizaciju polynoma, *Mat. Vesnik* 9, 257-264.

SEMERDZHIEV, KH. (1982), Method for the simultaneous computation of all multiple roots of an algebraic polynomial, C. R. Acad. Bulgare Sci. 35 (8), 1057–1060 (in Russian).

SEMERDZHIEV, KH. (1985), Methods of simultaneous deriving all roots of a given algebraic equation, Research Report JINR, Dubna (in Russian).

SEMERDZHIEV, KH. and S. PATEVA (1978), On a numerical method for simultaneous finding all roots of a given algebraic equation, *Travaux Sci. Univ. Plovdiv* 15, 263–273, (in Bulgarian).

SEMERDZHIEV, KH. and S. TAMBUROV (1984), A method for the determination of the multiplicities of the roots of an algebraic polynomial, C. R. Acad. Bulgare Sci. 37 (9), 1143–1145 (in Russian).

SEMERDZHIEV, KH. and S. TAMBUROV (1985), Method for determining all zeros of a generalized polynomial over an arbitrary Chebyshev system, Research Report JINR, Dubna P11-85-931 (in Russian).

Sendov, Bl. (1974), A method for simultaneous approximate calculation of all positive roots of a polynomial, *Izv. Vyssh. Uchebn. Zaved. Mat.* 5, 185–187 (in Russian).

Sendov, Bl. and V. Popov (1976), Numerical Methods, I (Nauka i izkustwo, Sofia) (in Bulgarian).

SIMEINOVIC, D. (1989), On the convergence of an iterative procedure for the simultaneous determination of all zeros of a polynomial, Z. Angew. Math. Mech. 69 (4), 108-110.

- STEFANOVIC, L. (1986), Some iterative methods for the simultaneous finding of polynomial zeros, Ph.D. Thesis, University of Niš (in Serbo-Croatian).
- STURM, J. (1829), Memoire sur la resolution des equations numeriques, Bull. Ferussac, Paris.
- Taschev, S. and N. Kjurkchiev (1983), Certain modifications of Newton's method for the approximate solution of algebraic equations, *Serdica* 9, 67–72 (in Russian).
- Taussky, O. (1949), A recurring theorem on determinants, Amer. Math. Monthly 56, 672-676.
- Tikoo, M. (1967), Location of the zeros of a polynomial, Amer. Math. Monthly 74, 688-690.
- Toya, T. (1933), Some remarks on Montel's paper concerning upper limit of absolute values of roots of algebraic equations, Sci. Reports Tokyo Bunrika Daigaku A1, 275–282.
- Traub, J. (1964), Iterative Methods for the Solution of Equations (Prentice-Hall, Englewood Cliffs, NJ).
- Turan, P. (1951), On approximative solution of algebraic equations, *Publ. Math. Debrecen* 2, 26–42. Van der Corput, J. (1946), Sur l'approximation de Laguerre des racines reelles, *Indag. Math.* 8, 581–588.
- Van Vleck, E. (1925), On limits to the absolute values of the roots of a polynomial, *Bull. Soc. Math. France* **53**, 105–125.
- VARGA, R. (1962), Matrix Iterative Analysis (Prentice-Hall, Englewood Cliffs, NJ).
- WALSH, J. (1924), An inequality for the roots of an algebraic equation, Ann. of Math. 25, 285–286. WANG, D. and Y. Wu (1987), Some modifications of the parallel Halley iteration method and their
- convergence, Computing 38, 75-87 WANG, X. and S. ZHENG (1984a), A family of parallel and interval iterations for finding all roots of a polynomial simultaneously with rapid convergence (I), J. Comput. Math. 1, 70-76.
- Wang, X. and S. Zheng (1984b), The quasi-Newton method in parallel circular iteration, *J. Comput. Math.* 4, 305-309.
- Wang, X. and S. Zheng (1985), A family of parallel and interval iterations for finding all roots of a polynomial simultaneously with rapid convergence (II), J. Comput. Math. 4, 433-444.
- WEIDNER, P. (1988), The Durand-Kerner methods for trigonometric and exponential polynomials, Computing 40, 175-179.
- WEIERSTRASS, K. (1903), Neuer Beweis des Satzes, dass jede Ganze Rationale Funktion einer Veranderlichen dargestellt werden kann als ein Product aus Linearen Funktionen derselben Veranderlichen, Ges. Werke 3, 251–269.
- WERNER, W. (1982), On the Simultaneous Determination of Polynomial Roots, Lecture Notes in Mathematics 953 (Springer, Berlin).
- Werner, W. (1983), Über Abschatzungen von Polynomnullstellen mittels des Gerschgorinschen Kreisesatzes, Z. Angew. Math. Mech. 63, T390-T391.
- WESTERFIELD, E. (1933), A new bound for the zeros of polynomials, Amer. Math. Monthly 40, 18-23.
- WILF, H. (1961), Perron-Frobenius theory and the zeros of polynomials, Proc. Amer. Math. Soc. 12, 247-250.
- WILIAMS, K. P. (1922), Note concerning the roots of an equation, Bull. Amer. Math. Soc. 28, 394–396.
  YOHE, J. (1977), The interval arithmetic package, MRC Technical Summary Report 1755, Mathematics Research Center, Univ. of Wisconsin, Madison.
- Zhidkov, E., I. Makrelov and Kh. Semerdzhiev (1983), Two methods for a simultaneous search for all roots of exponential equations, Research Report JINR, Dubna P11-83-764 (in Russian).