Concise Numerical Mathematics

Robert Plato

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Preface to the English Edition

This textbook is a translation of *Numerische Mathematik kompakt* published by Vieweg Verlag, with only a few changes: most of the references to German monographs appearing in the German edition are replaced by references to English written textbooks, some new publications are added, and a few errors have been corrected. A webpage for this book is maintained on the AMS website at:

`http://www.ams.org/bookpages/gsm-57`.

I would like to thank Richard C. Le Borne and Sabine Le Borne (they are both at Tennessee Technological University, Cookeville) for the careful translation and for a very efficient and pleasant cooperation. I am grateful to several colleagues and students for suggestions on the German edition which are considered to some extent in this edition. Moreover, I express thanks to the Christian-Albrechts University for travel support in connection with this translation and for giving me the opportunity during the last two years to hold introductory courses on numerical mathematics for students of mathematics, engineering, and computer sciences. These courses were based on the Vieweg edition of this textbook. Additionally, I would like to thank Edward Dunne from the American Mathematical Society for several helpful suggestions and his patience.

Finally two comments on frequently used notations. The symbol $\triangle$ marks the end of an example, a remark, or an algorithm, and the symbol '— « —' is used as a ditto mark.

Berlin, Germany October 2002 Robert Plato

Preface to the German Edition

This textbook emerged from my two-semester courses in numerical mathematics which I have repeatedly taught since 1997 at the Technical University of Berlin. These lectures were attended primarily by students of mathematics and to a smaller extent by students of physics and computer sciences.

In its current form this textbook addresses students and graduates of mathematics, computer sciences, and natural and engineering sciences. In a concise form several basic topics of numerical mathematics with important applications are treated:

- interpolation, fast Fourier transform and integration,
- direct and iterative solution of linear systems of equations,
- iterative methods for nonlinear systems of equations,
- numerical solution of initial and boundary value problems for ordinary differential equations,
- eigenvalue problems for matrices,
- approximation theory and computer arithmetic.

For the purpose of conciseness, the numerical solution of partial differential equations as well as nonlinear optimization is not treated here.

The intention of this textbook is to consider topics in an elementary and clear form, thereby only requiring a basic knowledge of calculus and linear

algebra. Moreover, many of the presented methods are illustrated by figures. For numerous algorithms, practical and relevant work estimates are given and pseudo codes are provided that can be used for implementations. The approximately 120 exercises presented with different levels of difficulty proved to be good in the courses.

I used preliminary versions of this textbook as lecture notes for my two-semester courses in numerical mathematics, each course meeting four hours per week. The first six chapters were always considered in the first part, and Chapters 7–13 were treated in the second part of these lectures. In a one-semester course in numerical mathematics, an alternative is to consider numerical integration (Chapter 6) only briefly, and then to present the foundations of one-step methods for the numerical solution of initial value problems for ordinary differential equations (Chapter 7) and relaxation methods for the iterative solution of linear systems of equations (Chapter 10).

For this textbook there exists an online service which is available under `http://www.math.tu-berlin.de/numerik/plato/viewegbuch`. It contains hints for the presented exercises and MATLAB routines for some of the pseudo codes presented in the textbook. Moreover, this online service will contain a list of possibly necessary corrections. Comments on this textbook can be sent to my email address, `plato@math.tu-berlin.de`.

I would like to thank my colleagues Prof. Dr. R. D. Grigorieff and Dipl. Math. Etienne Emmrich for several suggestions which are considered in this textbook to a large extent. I am indebted to Till Tantau and Olivier Pfeiffer and some other participants of the lectures for several minor but important improvements. Finally I would like to thank Prof. Dr. Chuck Groetsch, Prof. Dr. Martin Hanke-Bourgeois and Prof. Dr. Hans-Jürgen Reinhardt for their support of this book project and Ulrike Schmickler-Hirzebruch from the publisher Vieweg for her pleasant cooperation.

Berlin, May 2000 Robert Plato

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Bibliography

[AMS90] S. F. Ashby, T. A. Manteuffel, and P. Saylor, *A taxonomy for conjugate gradient methods*, SIAM J. Numer. Anal. **27** (1990), no. 6, 1542–1568.

[Bau87] J. Baumeister, *Stable Solution of Inverse Problems*, 1st ed., Vieweg, Braunschweig/Wiesbaden, 1987.

[BCP96] K. E. Brenan, S. L. Cambell, and L. R. Petzold, *Numerical Solution of Initial-Value Problems in Differential-Algebraic Equations*, 1st ed., SIAM, Philadelphia, Reprint, 1996.

[BLP01] J. R. Bunch, R. C. Le Borne and I. K. Proudler, *A conceptual framework for consistency, conditioning, and stability issues in signal processing*, IEEE Trans. Signal Processing **49(4)** (2001), 1971–1981.

[BP94] A. Berman and R. Plemmons, *Nonnegative Matrices in the Mathematical Sciences*, 1st ed., SIAM, Philadelphia, Reprint, 1994.

[Bra94] D. Braess, *Finite Elements*, 2nd ed., Cambridge University Press, Cambridge, 2001.

[BS66] R. Bulirsch and J. Stoer, *Numerical treatment of ordinary differential equations by extrapolation methods*, Numer. Math. **8** (1966), 1–13.

[Bul64] R. Bulirsch, *Bemerkungen zur Romberg-Iteration*, Numer. Math. **6** (1964), 6–16.

[Col86] L. Collatz, *Differential Equations. An Introduction with Applications*, 1st ed., Wiley, New York, 1986.

[CT65] J. W. Cooley and J. W. Tukey, *An algorithm for the machine calculation of complex Fourier series*, Math. of Computations **19** (1965), 297–301.

[Dah59] G. Dahlquist, *Stability and error bounds in the numerical integration of ordinary differential equations*, Transactions of the Royal Institute of Technology, Stockholm **130** (1959).

[dB78] C. de Boor, *A Practical Guide to Splines*, 1st ed., Springer, Heidelberg, Berlin, 1978.

[DB02] P. Deuflhard and F. Bornemann, *Scientific Computing with Ordinary Differential equations*, 1st ed., Springer, New York, 2002.

[Deu83] P. Deuflhard, *Order and step-size control in extrapolation methods*, Numer. Math. **41** (1983), 399–422.

[Deu85] P. Deuflhard, *Recent progess in extrapolation methods for ordinary differential equations*, SIAM Review **27** (1985), 505–535.

[DFK+97] M. Daberkow, C. Fieker, J. Klüners, M. Pohst, K. Roegner, M. Schörnig, and K. Wildanger, *KANT V4*, J. Symbolic Computation **24** (1997), 267–283.

[DH03] P. Deuflhard and A. Hohmann, *Numerical Analysis in Modern Scientific Computing. An Introduction*, 2nd ed., Springer, New York, 2003.

[DS96] J. E. Dennis and R. B. Schnabel, *Numerical Methods for Unconstrained Optimization and Nonlinear Equations*, 1st ed., SIAM, Philadelphia, Reprint, 1996.

[DV84] K. Dekker and J. G. Verwer, *Stability of Runge-Kutta Methods for Stiff Nonlinear Differential Equations*, 1st ed., North-Holland, Amsterdam, 1984.

[EHN00] H. W. Engl, M. Hanke, and A. Neubauer, *Regularization of Inverse Problems*, 2nd ed., Kluwer, Dordrecht, 2000.

[Elm94] H. Elman, *Iterative methods for linear systems*, Advances in Numerical Analysis, Vol. III., Proceedings of the fifth summer school in numerical analysis, Lancaster University, UK, 1992 (Oxford) (J. Gilbert et al., eds.), Clarendon Press, 1994, pp. 69–118.

[FGN91] R. W. Freund, G. H. Golub, and N. M. Nachtigal, *Iterative solution of linear systems*, Acta Numerica (Cambridge), Cambridge Univ. Press, 1991, pp. 1–44.

[Fis96] B. Fischer, *Polynomial Based Iteration Methods for Symmetric Linear Systems*, 1st ed., Wiley-Teubner, Chichester, Stuttgart, 1996.

[Gau97] W. Gautschi, *Numerical Analysis - An Introduction*, 1st ed., Birkhäuser, Boston, Basel, Berlin, 1997.

[GL93] G. Golub and C. F. Van Loan, *Matrix Computations*, 2nd ed., The Johns Hopkins University Press, Baltimore, London, 1993.

[GO93] G. Golub and J. M. Ortega, *Scientific Computing. An Introduction with Parallel Computing*, 1st ed., Academic Press, New York, 1993.

[GO92] G. Golub and J. M. Ortega, *Scientific Computing and Differential Equations. An Introduction to Numerical Methods*, 2nd ed., Academic Press, New York, 1992.

[Gol91] D. Goldberg, *What every computer scientist should know about floating-point arithmetic*, ACM Computer Surveys **23** (1991), 5–48.

[Gra65] W. B. Gragg, *On extrapolation algorithms for ordinary initial value problems*, SIAM J. Numer. Anal. **2** (1965), 384–403.

[Gro93] C. W. Groetsch, *Inverse Problems in the Mathematical Sciences*, 1st ed., Vieweg, Braunschweig/Wiesbaden, 1993.

[GRT93] H. Goering, H. G. Roos, and L. Tobiska, *Finite-Element-Methode*, 3rd ed., Akademie-Verlag, Berlin, 1993.

[Hac86] W. Hackbusch, *Elliptic Differential Equations*, 1st ed., Springer, New York, 1992.

[Hac94] W. Hackbusch, *Iterative Solution of Large Sparse Systems of Equations*, Springer, New York, Berlin, Heidelberg, 1994.

[HH91] G. Hämmerlin and K.-H. Hoffmann, *Numerical Mathematics*, 1st ed., Springer, New York, 1991.

[HH00] D. J. Higham and N. J. Higham, *MATLAB Guide*, 1st ed., SIAM, Philadelphia, 2000.

[Hig02] N. Higham, *Accuracy and Stability of Numerical Algorithms*, 2nd ed., SIAM, Philadelphia, 2002.

[HJ94] R. A. Horn and C. R. Johnson, *Matrix Analysis*, 1st ed., Cambridge University Press, Cambridge, Reprint, 1994.

[HL84] E. Hairer and C. Lubich, *Asymptotic expansion of the global error of fixed-stepsize methods*, Numer. Math. **45** (1984), 345–360.

[HNW93] E. Hairer, S. P. Nørsett, and G. Wanner, *Solving Ordinary Differential Equations I, Nonstiff Problems*, 2nd ed., Springer, Berlin, 1993.

[HS52] M. R. Hestenes and E. Stiefel, *Method of conjugate gradients for solving linear systems*, J. Res. Nat. Bur. Standards **Sec. B 49** (1952), 409–432, die CG-Erfinder.

[HS71] F. Hirzebruch and W. Scharlau, *Einführung in die Funktionalanalysis*, 1st ed., B. I. Wissenschaftsverlag, Mannheim/Wien/Zürich, 1971.

[HW96] E. Hairer and G. Wanner, *Solving Ordinary Differential Equations II, Stiff Problems*, 2nd ed., Springer, Berlin, 1996.

[JL95] M. Jung and U. Langer, *Methode der finiten Elemente für Ingenieure*, 1st ed., Teubner, Stuttgart, 2001.

[KÜ98] A. Krommer and C. Überhuber, *Computational Integration*, 1st ed., SIAM, Philadelphia, 1998.

[Kel95] C. T. Kelley, *Iterative Methods for Linear and Nonlinear Equations*, 1st ed., SIAM, Philadelphia, 1995.

[Kre98] R. Kress, *Numerical Analysis*, 1st ed., Springer-Verlag, Berlin, Heidelberg, New York, 1998.

[Lan70] S. Lang, *Linear Algebra*, 2nd ed., Addison-Wesley, Reading, 1970.

[LH95] C. L. Lawson and R. J. Hanson, *Solving Least Squares Problems*, 2nd ed., SIAM, Philadelphia, 1995.

[Loz58] S. M. Lozinskiĭ, *Error estimate for numerical integration of ordinary differential equations*, Izv. Vysš. Učebn. Zaved. Matematika **6** (1958), no. 6, 52–90. See also *Errata*, 12(5):222, 1959.

[Mae88] G. Maess, *Vorlesungen über Numerische Mathematik, Volumes 1 and 2*, 1st ed., Birkhäuser, Basel, 1985/88.

[ME77] R. Mennicken and E. Wagenführer, *Numerische Mathematik, Volumes 1 and 2*, 1st ed., Vieweg, Braunschweig/Wiesbaden, 1977.

[Mei99] A. Meister, *Numerik linearer Gleichungssysteme*, 1st ed., Vieweg, Braunschweig/Wiesbaden, 1999.

[Mol95] C. Moler, *A tale of two numbers*, SIAM News **28** (1995), no. 1, p. 1 and p. 16.

[Mär92] R. März, *Numerical methods for differential algebraic equations*, Acta Numerica Vol. 1 (Cambridge) (A. Iserles, ed.), Cambridge Univ. Press, 1992, pp. 141–198.

[NP84] A. S. Nemirovskiĭ and B. T. Polyak, *Iterative methods for solving linear ill-posed problems under precise information I*, Moscow Univ. Comput. Math. Cybern. **22** (1984), no. 3, 1–11.

[NRR92] N. M. Nachtigal, S. C. Reddy, and L. N. Reddy, *How fast are nonsymmetric matrix iterations?*, SIAM J. Matrix Anal. Appl. **13** (1992), no. 3, 778–795.

[NS96] S. G. Nash and A. Sofer, *Linear and Nonlinear Programming*, 1st ed., McGraw-Hill, New York, 1996.

[Oev96] W. Oevel, *Einführung in die Numerische Mathematik*, 1st ed., Spektrum, Heidelberg, 1996.

[OR70] J. M. Ortega and W. C. Rheinboldt, *Iterative Solution of Nonlinear Equations in Several Variables*, 1st ed., Academic Press, New York, San Francisco, London, 1970.

[Pan92] V. Pan, *Complexity of computations with matrices and polynomials*, SIAM Review **34** (1992), 225–262.

[Par88] B. N. Parlett, *The Symmetric Eigenvalue Problem*, 1st ed., SIAM, Philadelphia, Reprint, 1988.

[QSS00] A. Quarterioni, R. Sacco, and F. Saleri, *Numerical Mathematics*, 1st ed., Springer, New York, Berlin, Heidelberg, 2000.

[Rom55] W. Romberg, *Vereinfachte numerische Integration*, Det. Kong. Norske Videnskabers Selskab Forhandlinger **28** (Trondheim 1955), no. 7.

[SB02] J. Stoer and R. Bulirsch, *Introduction to Numerical Analysis*, 3rd ed., Springer-Verlag, New York, 2002.

[Sch77] H. Schwarz, *Elementare Darstellung der schnellen Fouriertransformation*, Computing **18** (1977), 107–116.

[Sch89] H. Schwarz, *Numerical Analysis: A Comprehensive Introduction*, 1st ed., Wiley, Chichester, 1989.

[Son89] P. Sonneveld, *CGS, a fast Lanczos-type solver for nonsymmetric linear systems*, SIAM J. Sci. Stat. Comput. **10** (1989), no. 1, 36–52.

[SS85] Y. Saad and M. H. Schultz, *Conjugate gradient-like algorithms for solving nonsymmetric linear systems*, Math. of Comput. **44** (1985), no. 170, 417–424.

[SS86] Y. Saad and M. H. Schultz, *GMRES: A generalized minimal residual algorithm for solving nonsymmetric linear systems*, SIAM J. Sci. Stat. Comput. **7** (1986), no. 3, 856–869.

[Sto83] J. Stoer, *Solution of large systems of equations by conjugate gradient type methods*, Mathematical Programming. The State of the Art. Bonn 1982 (Berlin, New York) (A. Bachem, M. Grötschel, and B. Korte, eds.), Springer-Verlag, 1983, Survey, pp. 540–565.

[Str69] V. Strassen, *Gaussian elimination is not optimal*, Numer. Math. **13** (1969), 354–356.

[SV01] J. Saranen and G. Vainikko, *Periodic Integral and Pseudodifferential Equations with Numerical Approximation*, 1st ed., Springer, Berlin, Heidelberg, New York, 2001.

[SW95] K. Strehmel and R. Weiner, *Numerik gewöhnlicher Differentialgleichungen*, 1st ed., Teubner, Stuttgart, 1995.

[TB97] L. N. Trefethen and D. Bau, *Numerical Linear Algebra*, 1st ed., SIAM, Philadelphia, 1997/2000.

[Ueb97] C. W. Überhuber, *Numerical Computation*, Volumes 1 and 2, 1st ed., Springer-Verlag, Berlin, Heidelberg, New York, 1997.

[vdV94] E. van de Velde, *Concurrent Scientific Computing*, 1st ed., Springer, New York, Berlin, Heidelberg, 1994.

[VvdV92] C. Vuik and H. A. van der Vorst, *A comparison of some GMRES-like methods*, Linear Algebra and its Applications **160** (1992), 131–162.

[Wal00] W. Walter, *Ordinary Differential Equations*, 1st ed., Springer, New York, 2000.

[Wat82] D. S. Watkins, *Understanding the QR algorithm*, SIAM Review **24** (1982), 427–440.

[Wil61] J. H. Wilkinson, *Error analysis of direct methods of matrix inversion* , J. Assoc. Comput. Machines **8** (1961), 281–330.

[Win89] G. Windisch, *M-matrices in Numerical Analysis*, 1st ed., Teubner, Leipzig, 1989.

[You71] D. Young, *Iterative Solution of Large Linear Systems*, 1st ed., Academic Press, New York, 1971.

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This textbook is a concise introduction to the fundamental concepts and methods of numerical mathematics. The author manages to cover the many important topics while avoiding redundancies and using well-chosen examples and exercises. The exposition is supplemented by numerous figures. Work estimates and pseudo codes are provided for many algorithms, which can be easily converted to computer programs. Topics covered include interpolation, the fast Fourier transform, iterative methods for solving systems of linear and nonlinear equations, numerical methods for solving ODEs, numerical methods for matrix eigenvalue problems, approximation theory, and computer arithmetic.

The book is suitable as a text for a first course in numerical methods for mathematics students or students in neighboring fields, such as engineering, physics, and computer science. In general, the author assumes only a knowledge of calculus and linear algebra.

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