

Wolfgang Hackbusch

Hierarchical Matrices: Algorithms and Analysis

Hierarchical Matrices Algorithms Computational Mathematics

**Julian M. Kunkel, Rio Yokota, Pavan
Balaji, David Keyes**



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Hierarchical Matrices: Algorithms and Analysis Wolfgang Hackbusch, 2015 This self contained monograph presents matrix algorithms and their analysis The new technique enables not only the solution of linear systems but also the approximation of matrix functions e g the matrix exponential Other applications include the solution of matrix equations e g the Lyapunov or Riccati equation The required mathematical background can be found in the appendix The numerical treatment of fully populated large scale matrices is usually rather costly However the technique of hierarchical matrices makes it possible to store matrices and to perform matrix operations approximately with almost linear cost and a controllable degree of approximation error For important classes of matrices the computational cost increases only logarithmically with the approximation error The operations provided include the matrix inversion and LU decomposition Since large scale linear algebra problems are standard in scientific computing the subject of hierarchical matrices is of interest to scientists in computational mathematics physics chemistry and engineering

Hierarchical Matrices: Algorithms and Analysis

Wolfgang Hackbusch, 2015-12-21 This self contained monograph presents matrix algorithms and their analysis The new technique enables not only the solution of linear systems but also the approximation of matrix functions e g the matrix exponential Other applications include the solution of matrix equations e g the Lyapunov or Riccati equation The required mathematical background can be found in the appendix The numerical treatment of fully populated large scale matrices is usually rather costly However the technique of hierarchical matrices makes it possible to store matrices and to perform matrix operations approximately with almost linear cost and a controllable degree of approximation error For important classes of matrices the computational cost increases only logarithmically with the approximation error The operations provided include the matrix inversion and LU decomposition Since large scale linear algebra problems are standard in scientific computing the subject of hierarchical matrices is of interest to scientists in computational mathematics physics chemistry and engineering

Matrix Computations and Semiseparable Matrices Raf Vandebril, Marc Van Barel, Nicola Mastronardi, 2008-01-14 In recent years several new classes of matrices have been discovered and their structure exploited to design fast and accurate algorithms In this new reference work Raf Vandebril Marc Van Barel and Nicola Mastronardi present the first comprehensive overview of the mathematical and numerical properties of the family's newest member semiseparable matrices The text is divided into three parts The first provides some historical background and introduces concepts and definitions concerning structured rank matrices The second offers some traditional methods for solving systems of equations involving the basic subclasses of these matrices The third section discusses structured rank matrices in a broader context presents algorithms for solving higher order structured rank matrices and examines hybrid variants such as block quasiseparable matrices An accessible case study clearly demonstrates the general topic of each new concept discussed Many of the routines featured are implemented in Matlab and can be downloaded from the Web for further

exploration *Hierarchical Matrices* Mario Bebendorf, 2008-06-25 Hierarchical matrices are an efficient framework for large scale fully populated matrices arising e.g. from the finite element discretization of solution operators of elliptic boundary value problems. In addition to storing such matrices approximations of the usual matrix operations can be computed with logarithmic linear complexity which can be exploited to setup approximate preconditioners in an efficient and convenient way. Besides the algorithmic aspects of hierarchical matrices the main aim of this book is to present their theoretical background. The book contains the existing approximation theory for elliptic problems including partial differential operators with nonsmooth coefficients. Furthermore it presents in full detail the adaptive cross approximation method for the efficient treatment of integral operators with non local kernel functions. The theory is supported by many numerical experiments from real applications.

Eigenvalue Algorithms for Symmetric Hierarchical Matrices Thomas Mach, 2012 This thesis is on the numerical computation of eigenvalues of symmetric hierarchical matrices. The numerical algorithms used for this computation are derivations of the LR Cholesky algorithm, the preconditioned inverse iteration and a bisection method based on LDL factorizations. The investigation of QR decompositions for H matrices leads to a new QR decomposition. It has some properties that are superior to the existing ones which is shown by experiments using the HQR decompositions to build a QR eigenvalue algorithm for H matrices does not progress to a more efficient algorithm than the LR Cholesky algorithm. The implementation of the LR Cholesky algorithm for hierarchical matrices together with deflation and shift strategies yields an algorithm that requires $O(n)$ iterations to find all eigenvalues. Unfortunately the local ranks of the iterates show a strong growth in the first steps. These H fill ins make the computation expensive so that $O(n)$ flops and $O(n)$ storage are required. Theorem 4.3.1 explains this behavior and shows that the LR Cholesky algorithm is efficient for the simple structured H matrices. There is an exact LDLT factorization for H matrices and an approximate LDLT factorization for H matrices in linear polylogarithmic complexity. This factorization can be used to compute the inertia of an H matrix. With the knowledge of the inertia for arbitrary shifts one can compute an eigenvalue by bisectioning. The slicing the spectrum algorithm can compute all eigenvalues of an H matrix in linear polylogarithmic complexity. A single eigenvalue can be computed in $O(kn \log 4n)$. Since the LDLT factorization for general H matrices is only approximative the accuracy of the LDLT slicing algorithm is limited. The local ranks of the LDLT factorization for indefinite matrices are generally unknown so that there is no statement on the complexity of the algorithm besides the numerical results in Table 5.7. The preconditioned inverse iteration computes the smallest eigenvalue and the corresponding eigenvector. This method is efficient since the number of iterations is independent of the matrix dimension. If other eigenvalues than the smallest are searched then preconditioned inverse iteration can not be simply applied to the shifted matrix since positive definiteness is necessary. The squared and shifted matrix $M - \mu I$ is positive definite. Inner eigenvalues can be computed by the combination of folded spectrum method and PINVIT. Numerical experiments show that the approximate inversion of $M - \mu I$ is more expensive than

the approximate inversion of M so that the computation of the inner eigenvalues is more expensive. We compare the different eigenvalue algorithms. The preconditioned inverse iteration for hierarchical matrices is better than the LDLT slicing algorithm for the computation of the smallest eigenvalues especially if the inverse is already available. The computation of inner eigenvalues with the folded spectrum method and preconditioned inverse iteration is more expensive. The LDLT slicing algorithm is competitive to H PINVIT for the computation of inner eigenvalues. In the case of large sparse matrices specially tailored algorithms for sparse matrices like the MATLAB function `eigs` are more efficient. If one wants to compute all eigenvalues then the LDLT slicing algorithm seems to be better than the LR Cholesky algorithm. If the matrix is small enough to be handled in dense arithmetic and is not an H1 matrix then dense eigensolvers like the LAPACK function `dsyev` are superior. The H PINVIT and the LDLT slicing algorithm require only an almost linear amount of storage. They can handle larger matrices than eigenvalue algorithms for dense matrices. For H1 matrices of local rank 1 the LDLT slicing algorithm and the LR Cholesky algorithm need almost the same time for the computation of all eigenvalues. For large matrices both algorithms are faster than the dense LAPACK function `dsyev`.

Integral Equation Methods for Evolutionary PDE Lehel Banjai, Francisco-Javier Sayas, 2022-11-08. This book provides a comprehensive analysis of time domain boundary integral equations and their discretisation by convolution quadrature and the boundary element method. Properties of convolution quadrature based on both linear multistep and Runge Kutta methods are explained in detail always with wave propagation problems in mind. Main algorithms for implementing the discrete schemes are described and illustrated by short Matlab codes. Translation to other languages can be found on the accompanying GitHub page. The codes are used to present numerous numerical examples to give the reader a feeling for the qualitative behaviour of the discrete schemes in practice. Applications to acoustic and electromagnetic scattering are described with an emphasis on the acoustic case where the fully discrete schemes for sound soft and sound hard scattering are developed and analysed in detail. A strength of the book is that more advanced applications such as linear and non linear impedance boundary conditions and FEM BEM coupling are also covered. While the focus is on wave scattering a chapter on parabolic problems is included which also covers the relevant fast and oblivious algorithms. Finally a brief description of data sparse techniques and modified convolution quadrature methods completes the book. Suitable for graduate students and above this book is essentially self contained with background in mathematical analysis listed in the appendix along with other useful facts. Although not strictly necessary some familiarity with boundary integral equations for steady state problems is desirable.

Integral Methods in Science and Engineering, Volume 2 Christian Constanda, Matteo Dalla Riva, Pier Domenico Lamberti, Paolo Musolino, 2017-09-08. This contributed volume contains a collection of articles on the most recent advances in integral methods. The second of two volumes this work focuses on the applications of integral methods to specific problems in science and engineering. Written by internationally recognized researchers the chapters in this book are based on talks given at the Fourteenth International Conference on

Integral Methods in Science and Engineering held July 25-29 2016 in Padova Italy A broad range of topics is addressed such as Boundary elements Transport problems Option pricing Gas reservoirs Electromagnetic scattering This collection will be of interest to researchers in applied mathematics physics and mechanical and petroleum engineering as well as graduate students in these disciplines and to other professionals who use integration as an essential tool in their work *Foundations of Computational Mathematics, Minneapolis 2002* Felipe Cucker, 2004-03-25 The Foundations of Computational Mathematics meetings are a platform for cross fertilization between numerical analysis mathematics and computer science This volume first published in 2004 contains the plenary presentations given by some of the leading authorities in the world and topics surveyed range from optimization to computer algebra image processing to differential equations quantum complexity to geometry The volume will be essential reading for all those wishing to be informed of the state of the art in computational mathematics **Spectral and High Order Methods for Partial Differential Equations ICOSAHOM 2016** Marco L. Bittencourt, Ney A. Dumont, Jan S. Hesthaven, 2017-11-07 This book features a selection of high quality papers chosen from the best presentations at the International Conference on Spectral and High Order Methods 2016 offering an overview of the depth and breadth of the activities within this important research area The carefully reviewed papers provide a snapshot of the state of the art while the extensive bibliography helps initiate new research directions Numerical Partial Differential Equations James H. Adler, Hans De Sterck, Scott MacLachlan, Luke Olsen, 2025-03-26 This comprehensive textbook focuses on numerical methods for approximating solutions to partial differential equations PDEs The authors present a broad survey of these methods introducing readers to the central concepts of various families of discretizations and solution algorithms and laying the foundation needed to understand more advanced material The authors include over 100 well established definitions theorems corollaries and lemmas and summaries of and references to in depth treatments of more advanced mathematics when needed Numerical Partial Differential Equations is divided into four parts Part I covers basic background on PDEs and numerical methods Part II introduces the three main classes of numerical methods for PDEs that are the book's focus finite difference finite element and finite volume methods Part III discusses linear solvers and finite element and finite volume methods at a more advanced level Part IV presents further high level topics on discretizations and solvers This book is intended for advanced undergraduate first year graduate and advanced graduate students in applied math as well as students in science and engineering disciplines The book will also appeal to researchers in the field of scientific computing Chapters are designed to be stand alone allowing distinct paths through the text making it appropriate for both single semester and multi semester courses It is appropriate for courses covering topics ranging from numerical methods for PDEs to numerical linear algebra *Exploiting Hidden Structure in Matrix Computations: Algorithms and Applications* Michele Benzi, Dario Bini, Daniel Kressner, Hans Munthe-Kaas, Charles Van Loan, 2017-01-24 Focusing on special matrices and matrices which are in some sense near to structured matrices this volume covers a broad range of topics of current interest in

numerical linear algebra Exploitation of these less obvious structural properties can be of great importance in the design of efficient numerical methods for example algorithms for matrices with low rank block structure matrices with decay and structured tensor computations Applications range from quantum chemistry to queueing theory Structured matrices arise frequently in applications Examples include banded and sparse matrices Toeplitz type matrices and matrices with semi separable or quasi separable structure as well as Hamiltonian and symplectic matrices The associated literature is enormous and many efficient algorithms have been developed for solving problems involving such matrices The text arose from a C I M E course held in Cetraro Italy in June 2015 which aimed to present this fast growing field to young researchers exploiting the expertise of five leading lecturers with different theoretical and application perspectives Advanced Finite Element Methods with Applications Thomas Apel,Ulrich Langer,Arnd Meyer,Olaf Steinbach,2019-06-28 Finite element methods are the most popular methods for solving partial differential equations numerically and despite having a history of more than 50 years there is still active research on their analysis application and extension This book features overview papers and original research articles from participants of the 30th Chemnitz Finite Element Symposium which itself has a 40 year history Covering topics including numerical methods for equations with fractional partial derivatives isogeometric analysis and other novel discretization methods like space time finite elements and boundary elements analysis of a posteriori error estimates and adaptive methods enhancement of efficient solvers of the resulting systems of equations discretization methods for partial differential equations on surfaces and methods adapted to applications in solid and fluid mechanics it offers readers insights into the latest results *Euro-Par 2018: Parallel Processing* Marco Aldinucci,Luca Padovani,Massimo Torquati,2018-08-20 This book constitutes the proceedings of the 24th International Conference on Parallel and Distributed Computing Euro Par 2018 held in Turin Italy in August 2018 The 57 full papers presented in this volume were carefully reviewed and selected from 194 submissions They were organized in topical sections named support tools and environments performance and power modeling prediction and evaluation scheduling and load balancing high performance architectures and compilers parallel and distributed data management and analytics cluster and cloud computing distributed systems and algorithms parallel and distributed programming interfaces and languages multicore and manycore methods and tools theory and algorithms for parallel computation and networking parallel numerical methods and applications and accelerator computing for advanced applications *Algorithms for Sparse Linear Systems* Jennifer Scott,Miroslav Tůma,2023-04-29 Large sparse linear systems of equations are ubiquitous in science engineering and beyond This open access monograph focuses on factorization algorithms for solving such systems It presents classical techniques for complete factorizations that are used in sparse direct methods and discusses the computation of approximate direct and inverse factorizations that are key to constructing general purpose algebraic preconditioners for iterative solvers A unified framework is used that emphasizes the underlying sparsity structures and highlights the importance of understanding sparse direct methods when

developing algebraic preconditioners Theoretical results are complemented by sparse matrix algorithm outlines This monograph is aimed at students of applied mathematics and scientific computing as well as computational scientists and software developers who are interested in understanding the theory and algorithms needed to tackle sparse systems It is assumed that the reader has completed a basic course in linear algebra and numerical mathematics **Optimization,**

Discrete Mathematics and Applications to Data Sciences Ashkan Nikeghbali, Panos M. Pardalos, Michael Th.

Rassias, 2025-01-08 This book delves into the dynamic intersection of optimization and discrete mathematics offering a comprehensive exploration of their applications in data sciences Through a collection of high quality papers readers will gain insights into cutting edge research and methodologies that address complex problems across a wide array of topics The chapters cover an impressive range of subjects including advances in the study of polynomials combinatorial identities and global optimization algorithms Readers will encounter innovative approaches to predictive models for non performing loans rainbow greedy matching algorithms and the cost of detection in interaction testing The book also examines critical issues such as demand aggregation mid term energy planning and minimum cost energy flow Contributions from expert authors provide a deep dive into multilevel low rank matrices the protection of medical image authenticity and the mathematical intricacies of the Braess paradox This volume invites readers to explore diverse perspectives and theoretical insights that are both practical and forward thinking This publication is an invaluable resource for graduate students and advanced researchers in the fields of optimization and discrete mathematics It is particularly beneficial for those interested in their applications within data sciences Academics across these disciplines will find the book's content relevant to their work while practitioners seeking to apply these concepts in industry will appreciate its practical case studies Whether you are a scholar or a professional this book offers a wealth of knowledge that bridges theory with real world applications *Eigenvalue*

Problems: Algorithms, Software and Applications in Petascale Computing Tetsuya Sakurai, Shao-Liang Zhang, Toshiyuki Imamura, Yusaku Yamamoto, Yoshinobu Kuramashi, Takeo Hoshi, 2018-01-03 This book provides state of the art and interdisciplinary topics on solving matrix eigenvalue problems particularly by using recent petascale and upcoming post petascale supercomputers It gathers selected topics presented at the International Workshops on Eigenvalue Problems Algorithms Software and Applications in Petascale Computing EPASA2014 and EPASA2015 which brought together leading researchers working on the numerical solution of matrix eigenvalue problems to discuss and exchange ideas and in so doing helped to create a community for researchers in eigenvalue problems The topics presented in the book including novel numerical algorithms high performance implementation techniques software developments and sample applications will contribute to various fields that involve solving large scale eigenvalue problems *Tensor Spaces and Numerical Tensor Calculus* Wolfgang Hackbusch, 2019-12-16 Special numerical techniques are already needed to deal with $n \times n$ matrices for large n Tensor data are of size $n \times n \times n \times \dots \times n$ where n exceeds the computer memory by far They appear for problems of high

spatial dimensions Since standard methods fail a particular tensor calculus is needed to treat such problems This monograph describes the methods by which tensors can be practically treated and shows how numerical operations can be performed Applications include problems from quantum chemistry approximation of multivariate functions solution of partial differential equations for example with stochastic coefficients and more In addition to containing corrections of the unavoidable misprints this revised second edition includes new parts ranging from single additional statements to new subchapters The book is mainly addressed to numerical mathematicians and researchers working with high dimensional data It also touches problems related to Geometric Algebra

The Isogeometric Boundary Element Method Gernot Beer,Benjamin Marussig,Christian Duenser,2019-09-21 This book discusses the introduction of isogeometric technology to the boundary element method BEM in order to establish an improved link between simulation and computer aided design CAD that does not require mesh generation In the isogeometric BEM non uniform rational B splines replace the Lagrange polynomials used in conventional BEM This may seem a trivial exercise but if implemented rigorously it has profound implications for the programming resulting in software that is extremely user friendly and efficient The BEM is ideally suited for linking with CAD as both rely on the definition of objects by boundary representation The book shows how the isogeometric philosophy can be implemented and how its benefits can be maximised with a minimum of user effort Using several examples ranging from potential problems to elasticity it demonstrates that the isogeometric approach results in a drastic reduction in the number of unknowns and an increase in the quality of the results In some cases even exact solutions without refinement are possible The book also presents a number of practical applications demonstrating that the development is not only of academic interest It then elegantly addresses heterogeneous and non linear problems using isogeometric concepts and tests them on several examples including a severely non linear problem in viscous flow The book makes a significant contribution towards a seamless integration of CAD and simulation which eliminates the need for tedious mesh generation and provides high quality results with minimum user intervention and computing

High Performance Computing Julian M. Kunkel,Rio Yokota,Pavan Balaji,David Keyes,2017-06-09 This book constitutes the refereed proceedings of the 32nd International Conference ISC High Performance 2017 held in Frankfurt Germany in June 2017 The 22 revised full papers presented in this book were carefully reviewed and selected from 66 submissions The papers cover the following topics applications and algorithms proxy applications architecture and system optimization and energy aware computing

Spectral and High Order Methods for Partial Differential Equations ICOSAHOM 2020+1 Jens M. Melenk,Illaria Perugia,Joachim Schöberl,Christoph Schwab,2023-06-30 The volume features high quality papers based on the presentations at the ICOSAHOM 2020 1 on spectral and high order methods The carefully reviewed articles cover state of the art topics in high order discretizations of partial differential equations The volume presents a wide range of topics including the design and analysis of high order methods the development of fast solvers on modern computer architecture and the application of

these methods in fluid and structural mechanics computations

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