

# AN AUGMENTED ITERATIVE METHOD FOR LARGE LINEAR TOEPLITZ SYSTEMS

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## ABSTRACT

Efficiently solving a large linear system of equations,  $\mathbf{Ax} = \mathbf{b}$ , is still a challenging problem. Such a system appears in many applications in signal processing, especially in some problems in acoustics where we deal with very long impulse responses, i.e.  $\mathbf{x}$  is long. In this paper, we show how to efficiently use the so-called basic iterative algorithms when the matrix  $\mathbf{A}$  is Toeplitz, symmetric, and positive definite. We also propose an improved version that converges much faster than some other iterative methods. We present some simulations and compare the new method to the conjugate gradient algorithm.

## 1 Introduction

Efficiently solving a large linear system of equations,  $\mathbf{Ax} = \mathbf{b}$ , is still a challenging problem. Such equations appear in many applications in signal processing, especially in some problems in acoustics where we deal with very long impulse responses, i.e.  $\mathbf{x}$  is long. In the rest of this paper, we assume that  $\mathbf{A}$  is a square matrix of size  $n \times n$ , which is symmetric and positive definite (s.p.d.).

There are basically two different approaches to solve such a linear system. The first is to use a direct method such as Gaussian elimination. It requires  $\mathcal{O}(n^3)$  arithmetic operations and the obtained solution  $\mathbf{x}$  is exact [1]. Unfortunately, this technique becomes impractical when  $n$  is large. In contrast to the direct methods are the iterative methods [2]. These methods generate a sequence of approximate solutions  $\{\mathbf{x}_k\}$  with an arithmetic complexity per iteration much smaller than that of a direct method, since only matrix-vector multiplications and vector additions are needed. Further, if the matrix  $\mathbf{A}$  is sparse, its sparsity can be fully exploited. Of course, the value of an iterative method depends on how quickly the iterates  $\mathbf{x}_k$  converge. Ideally, an iterative method should have a much lower complexity than that of a direct method, should converge fast, and its convergence rate should be independent of the size  $n$ .

Roughly speaking, there are two classes of iterative methods: the basic iterative methods (which we discuss briefly in Section 2) and the subspace iteration methods of which the conjugate gradient algorithm (CGA) is a particular case [3].

The methods in the first category are, in general, less complex than those in the second, but converge much slower.

The CGA is one of the best known iterative techniques for solving sparse symmetric positive definite linear systems. Briefly, the method utilizes orthogonal projection onto a space called the Krylov subspace [4], [5], defined by the vectors  $\mathbf{r}_0, \mathbf{A}\mathbf{r}_0, \dots, \mathbf{A}^{k-1}\mathbf{r}_0$ , where  $\mathbf{r}_0 = \mathbf{Ax}_0 - \mathbf{b}$  is the residual for the initial vector  $\mathbf{x}_0$ . Eventually, for  $k = n$  the Krylov vectors span the whole space, so the CGA gives the exact solution after at most  $n$  iterations. Therefore, the method can also be seen as a direct solution method. A nice feature of the CGA is that it is parameter-free.

In this paper, we show how to apply the so-called basic iterative algorithms to a Toeplitz system using  $\mathcal{O}(n \log n)$  operations per iteration. Then, we propose an improved version. We also compare this method, by simulations, to the CGA and show that it is less complex and converges faster in general.

## 2 Basic Iterative Algorithms

In this section we give a brief review of basic iterative methods for solving the linear system

$$\mathbf{Ax} = \mathbf{b}, \quad (1)$$

The linear system (1) may be rewritten as follows

$$(\mathbf{A} + \mathbf{T})\mathbf{x} = \mathbf{b} + \mathbf{T}\mathbf{x}, \quad (2)$$

where  $\mathbf{T}$  is an appropriately chosen preconditioning matrix. We assume that  $(\mathbf{A} + \mathbf{T})$  is nonsingular. From (2) we deduce the straightforward iterative algorithm [1]:

$$\mathbf{x}_{k+1} = \mathbf{H}\mathbf{x}_k + \mathbf{v} \quad (3)$$

where

$$\mathbf{H} = (\mathbf{A} + \mathbf{T})^{-1}\mathbf{T} \quad (4)$$

is the iteration matrix and

$$\mathbf{v} = (\mathbf{A} + \mathbf{T})^{-1}\mathbf{b}. \quad (5)$$

For this algorithm,  $\mathbf{T}$  can in general be singular. The matrix  $\mathbf{T}$  must be such that  $\mathbf{y}_k = \mathbf{T}\mathbf{x}_k$  is simple to compute,  $(\mathbf{A} + \mathbf{T})$

# Iterative Methods For Toeplitz Systems

**Hung-cheong Chan, University of Hong  
Kong**



## **Iterative Methods For Toeplitz Systems:**

Iterative Methods for Toeplitz Systems Michael K. Ng, 2004 Toeplitz and Toeplitz related systems arise in a variety of applications in mathematics and engineering especially in signal and image processing This book deals primarily with iterative methods for solving Toeplitz and Toeplitz related linear systems discussing both the algorithms and their convergence theories A basic knowledge of real analysis elementary numerical analysis and linear algebra is assumed The first part of the book chapters one and two gives a brief review of some terms and results in linear algebra and the conjugate gradient method which are important topics for handling the mathematics later on in the book The second part of the book chapters three to seven presents the theory of using iterative methods for solving Toeplitz and Toeplitz related systems The third part of the book chapters eight to twelve presents recent results from applying the use of iterative methods in different fields of applications such as partial differential equations signal and image processing integral equations and queuing networks These chapters provide research and application oriented readers with a thorough understanding of using iterative methods enabling them not only to apply these methods to the problems discussed but also to derive and analyse new methods for other types of problems and applications

**Iterative Methods and Preconditioning for Large and Sparse Linear Systems with Applications** Daniele Bertaccini, Fabio Durastante, 2018-02-19 This book describes in a basic way the most useful and effective iterative solvers and appropriate preconditioning techniques for some of the most important classes of large and sparse linear systems The solution of large and sparse linear systems is the most time consuming part for most of the scientific computing simulations Indeed mathematical models become more and more accurate by including a greater volume of data but this requires the solution of larger and harder algebraic systems In recent years research has focused on the efficient solution of large sparse and or structured systems generated by the discretization of numerical models by using iterative solvers

*An Introduction to Iterative Toeplitz Solvers* Raymond Hon-Fu Chan, Xiao-Qing Jin, 2007-11-22 A practical introduction to current developments in using iterative methods for solving Toeplitz systems

*Preconditioned Iterative Methods for Indefinite Symmetric Toeplitz Systems* Paul Concus, Paul E. Saylor, 1989

*Iterative Methods for Large Linear Systems* David R. Kincaid, Linda J. Hayes, 2014-05-10 Iterative Methods for Large Linear Systems contains a wide spectrum of research topics related to iterative methods such as searching for optimum parameters using hierarchical basis preconditioners utilizing software as a research tool and developing algorithms for vector and parallel computers This book provides an overview of the use of iterative methods for solving sparse linear systems identifying future research directions in the mainstream of modern scientific computing with an eye to contributions of the past present and future Different iterative algorithms that include the successive overrelaxation SOR method symmetric and unsymmetric SOR methods local ad hoc SOR scheme and alternating direction implicit ADI method are also discussed This text likewise covers the block iterative methods asynchronous iterative procedures multilevel methods adaptive algorithms and domain decomposition

algorithms This publication is a good source for mathematicians and computer scientists interested in iterative methods for large linear systems

**Matrix Methods** Vadim Olshevsky, 2010 Operators preserving primitivity for matrix pairs L B Beasley A E Guterman Decompositions of quaternions and their matrix equivalents D Janovsk G Opfer Sensitivity analysis of Hamiltonian and reversible systems prone to dissipation induced instabilities O N Kirillov Block triangular miniversal deformations of matrices and matrix pencils L Klimenko V V Sergeichuk Determining the Schein rank of boolean matrices E E Marenich Lattices of matrix rows and matrix columns Lattices of invariant column eigenvectors V Marenich Matrix algebras and their length O V Markova On a new class of singular nonsymmetric matrices with nonnegative integer spectra T Nahtman D von Rosen Reduction of a set of matrices over a principal ideal domain to the Smith normal forms by means of the same one sided transformation V M Prokip Nonsymmetric algebraic Riccati equations associated with an M matrix recent advances and algorithms D A Bini B Iannazzo B Meini F Poloni A generalized conjugate direction method for nonsymmetric large ill conditioned linear systems E R Boudinov A I Manevich There exist normal Hankel symbol symbol circulants of any order symbol V N Chugunov Kh D Ikramov On the treatment of boundary artifacts in image restoration by reflection and or anti reflection M Donatelli S Serra Capizzano Zeros of determinants of symbol matrices W Gander How to find a good submatrix S A Goreinov und weiteren Conjugate and semi conjugate direction methods with preconditioning projectors V P Il in Some relationships between optimal preconditioner and superoptimal preconditioner J B Chen und weiteren Scaling preconditioning and superlinear convergence in GMRES type iterations I Kaporin Toeplitz and Toeplitz block Toeplitz matrices and their correlation with syzygies of polynomials H Khalil B Mourrain M Schatzman Concepts of data sparse tensor product approximation in many particle modelling H J Flad und weiteren Separation of variables in nonlinear fermi equation Yu I Kuznetsov Faster multipoint polynomial evaluation via structured matrices B Murphy R E Rosholt Testing pivoting policies in Gaussian elimination B Murphy und weiteren Newton s iteration for matrix inversion advances and extensions V Y Pan Truncated decompositions and filtering methods with reflective antireflective boundary conditions a comparison C Tablino Possio Discrete time stability of a class of hermitian polynomial matrices with positive semidefinite coefficients H K Wimmer Splitting algorithm for solving mixed variational inequalities with inversely strongly monotone operators I Badriev O Zadvornov Multilevel algorithm for graph partitioning N S Bochkarev O V Diyankov V Y Pravilnikov 2D extension of singular spectrum analysis algorithm and elements of theory N E Golyandina K D Usevich Application of radon transform for fast solution of boundary value problems for elliptic PDE in domains with complicated geometry A I Grebennikov Application of a multigrid method to solving diffusion type equations M E Ladonkina O Yu Milukova V F Tishkin Monotone matrices and finite volume schemes for diffusion problems preserving non negativity of solution I V Kapyrin Sparse approximation of FEM matrix for sheet current integro differential equation M Khapaev M Yu Kupriyanov The method of magnetic field computation in presence of an ideal conductive multiconnected surface by using the integro differential equation of the first kind T Kochubey

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instead of blindly following readily available commercial tools

**Mathematical Methods for the Magnetohydrodynamics of Liquid Metals** Jean-Frédéric Gerbeau, Claude Le Bris, Tony Lelièvre, 2006-08-31 This comprehensive text focuses on mathematical and numerical techniques for the simulation of magnetohydrodynamic phenomena with an emphasis laid on the magnetohydrodynamics of liquid metals and on a prototypical industrial application Aimed at research mathematicians engineers and physicists as well as those working in industry and starting from a good understanding of the physics at play the approach is a highly mathematical one based on the rigorous analysis of the equations at hand and a solid numerical analysis to found the simulations At each stage of the exposition examples of numerical simulations are provided first on academic test cases to illustrate the approach next on benchmarks well documented in the professional literature and finally whenever possible on real industrial cases

Handbook of Linear Algebra Leslie Hogben, 2006-11-02 The Handbook of Linear Algebra provides comprehensive coverage of linear algebra concepts applications and computational software packages in an easy to use handbook format The esteemed international contributors guide you from the very elementary aspects of the subject to the frontiers of current research The book features an accessibl

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**Computational Methods in Physics** Simon Širca, Martin Horvat, 2025-04-01 This textbook provides a compendium of numerical methods to assist physics students and researchers in their daily work It carefully considers error estimates stability and convergence issues the choice of optimal methods and techniques to increase program execution speeds The book supplies numerous examples throughout the chapters that are concluded by more comprehensive problems with a strong physics background Instead of uncritically employing modern black box tools the readers are encouraged to develop a more ponderous and skeptical approach This revised and expanded edition now includes a new chapter on numerical integration and stable differentiation as well as fresh material on optimal filtering integration of gravitational many body problems computation of Poincar maps regularization of orbits singular Sturm Liouville problems techniques for time evolution and spatial treatment of semi infinite domains in spectral methods and phase retrieval It also brings updated discussions of algebraic problems involving sparse matrices and of high resolution schemes for partial differential equations

**Domain Decomposition Methods in Science and Engineering XXIII** Chang-Ock Lee, Xiao-Chuan Cai, David E. Keyes, Hyea Hyun Kim, Axel

Klawonn, Eun-Jae Park, Olof B. Widlund, 2017-03-15 This book is a collection of papers presented at the 23rd International Conference on Domain Decomposition Methods in Science and Engineering held on Jeju Island Korea on July 6-10 2015. Domain decomposition methods solve boundary value problems by splitting them into smaller boundary value problems on subdomains and iterating to coordinate the solution between adjacent subdomains. Domain decomposition methods have considerable potential for a parallelization of the finite element methods and serve a basis for distributed parallel computations.

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Numerical Methods for Nonlinear Elliptic Differential Equations Klaus Boehmer, 2010-10-07 Nonlinear elliptic problems play an increasingly important role in mathematics, science and engineering, creating an exciting interplay between the subjects. This is the first and only book to prove, in a systematic and unifying way, stability, convergence and computing results for the different numerical methods for nonlinear elliptic problems. The proofs use linearization, compact perturbation of the coercive principal parts or monotone operator techniques and approximation theory. Examples are given for linear to fully nonlinear problems, highest derivatives occur nonlinearly and for the most important space discretization methods: conforming and nonconforming finite element, discontinuous Galerkin, finite difference, wavelet and in a volume to follow spectral and meshfree methods. A number of specific long open problems are solved here: numerical methods for fully nonlinear elliptic problems, wavelet and meshfree methods for nonlinear problems and more general nonlinear boundary conditions. We apply it to all these problems and methods in particular to eigenvalues, monotone operators, quadrature approximations and Newton methods. Adaptivity is discussed for finite element and wavelet methods. The book has been written for graduate students and scientists who want to study and to numerically analyze nonlinear elliptic differential equations in Mathematics, Science and Engineering. It can be used as material for graduate courses or

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### **Table of Contents Iterative Methods For Toeplitz Systems**

1. Understanding the eBook Iterative Methods For Toeplitz Systems
  - The Rise of Digital Reading Iterative Methods For Toeplitz Systems
  - Advantages of eBooks Over Traditional Books
2. Identifying Iterative Methods For Toeplitz Systems
  - Exploring Different Genres
  - Considering Fiction vs. Non-Fiction
  - Determining Your Reading Goals
3. Choosing the Right eBook Platform
  - Popular eBook Platforms
  - Features to Look for in an Iterative Methods For Toeplitz Systems
  - User-Friendly Interface
4. Exploring eBook Recommendations from Iterative Methods For Toeplitz Systems
  - Personalized Recommendations
  - Iterative Methods For Toeplitz Systems User Reviews and Ratings
  - Iterative Methods For Toeplitz Systems and Bestseller Lists

5. Accessing Iterative Methods For Toeplitz Systems Free and Paid eBooks
  - Iterative Methods For Toeplitz Systems Public Domain eBooks
  - Iterative Methods For Toeplitz Systems eBook Subscription Services
  - Iterative Methods For Toeplitz Systems Budget-Friendly Options
6. Navigating Iterative Methods For Toeplitz Systems eBook Formats
  - ePub, PDF, MOBI, and More
  - Iterative Methods For Toeplitz Systems Compatibility with Devices
  - Iterative Methods For Toeplitz Systems Enhanced eBook Features
7. Enhancing Your Reading Experience
  - Adjustable Fonts and Text Sizes of Iterative Methods For Toeplitz Systems
  - Highlighting and Note-Taking Iterative Methods For Toeplitz Systems
  - Interactive Elements Iterative Methods For Toeplitz Systems
8. Staying Engaged with Iterative Methods For Toeplitz Systems
  - Joining Online Reading Communities
  - Participating in Virtual Book Clubs
  - Following Authors and Publishers Iterative Methods For Toeplitz Systems
9. Balancing eBooks and Physical Books Iterative Methods For Toeplitz Systems
  - Benefits of a Digital Library
  - Creating a Diverse Reading Collection Iterative Methods For Toeplitz Systems
10. Overcoming Reading Challenges
  - Dealing with Digital Eye Strain
  - Minimizing Distractions
  - Managing Screen Time
11. Cultivating a Reading Routine Iterative Methods For Toeplitz Systems
  - Setting Reading Goals Iterative Methods For Toeplitz Systems
  - Carving Out Dedicated Reading Time
12. Sourcing Reliable Information of Iterative Methods For Toeplitz Systems
  - Fact-Checking eBook Content of Iterative Methods For Toeplitz Systems
  - Distinguishing Credible Sources
13. Promoting Lifelong Learning

- Utilizing eBooks for Skill Development
  - Exploring Educational eBooks
14. Embracing eBook Trends
- Integration of Multimedia Elements
  - Interactive and Gamified eBooks

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