Minisymposia Abstracts

Index

MS 1. Recent advances in matrix functions

Talk 1. **Computational issues related to the geometric mean of structured matrices**

In several applications it is required to compute the geometric mean of a set of positive definite matrices. In certain cases, like in the design of radar systems, the matrices are structured, say, they are Toeplitz, and one expects that the mean still keeps the same structure.
Unfortunately, the available definitions of geometric mean, like the Karcher mean, do not generally maintain the structure of the input matrices.
In this talk we introduce a definition of mean which preserves the structure, analyze its properties and present algorithms for its computation.

Dario A. Bini
Dipartimento di Matematica
Università di Pisa, Italy
bini@dm.unipi.it

Bruno Iannazzo
Dipartimento di Matematica e Informatica
Università di Perugia, Italy
bruno.iannazzo@dmi.unipg.it

Talk 2. **Efficient, communication-minimizing algorithms for the symmetric eigenvalue decomposition and the singular value decomposition**

We propose algorithms for computing the symmetric eigenvalue decomposition and the singular value decomposition (SVD) that minimize communication in the asymptotic sense while simultaneously having arithmetic operation costs within a factor 3 of that for the most efficient existing algorithms. The essential cost for the algorithms is in performing QR factorizations, of which we require no more than six for the symmetric eigenproblem and twelve for the SVD. We establish backward stability under mild assumptions, and numerical experiments indicate that our algorithms tend to yield decompositions with considerably smaller backward error and eigen/singular vectors closer to orthogonal than existing algorithms.

Yuji Nakatsukasa
School of Mathematics
The University of Manchester
yuji.nakatsukasa@manchester.ac.uk

Nicholas J. Higham
School of Mathematics
The University of Manchester
higham@maths.manchester.ac.uk

Talk 3. **The Padé approximation and the matrix sign function**

In the talk we focus on the properties of the Padé approximants of a certain hypergeometric function on which the Padé families of iterations for computing the matrix sign and sector functions are based. We have determined location of poles of the Padé approximants and we have proved that all coefficients of the power series expansions of the reciprocals of the denominators of the Padé approximants and of the power series expansions of the Padé approximants are positive. These properties are crucial in the the proof of the conjecture – stated by Laszkiewicz and Ziętak, and extending the result of Kenney and Laub – on a region of convergence of these Padé families of iterations.
The talk is based on the paper by O. Gomilko, F. Greco, K. Ziętak and the paper by O. Gomilko, D.B. Karp, M. Lin, K. Ziętak. In the talk we also consider a certain different kind of rational approximation to the sign function.

Krystyna Ziętak
Institute of Mathematics and Computer Science
Wrocław University of Technology
krystyna.zietak@pwr.wroc.pl

Talk 4. **A recursive blocked schur algorithm for computing the matrix square root**

The Schur algorithm for computing a matrix square root reduces the matrix to the Schur triangular form and then computes a square root of the triangular matrix. In this talk I will describe a recursive blocking technique in which the computation of the square root of the triangular matrix can be made rich in matrix multiplication. Numerical experiments making appropriate use of level 3 BLAS show significant speedups over the point algorithm, both in the square root phase and in the algorithm as a whole. The excellent numerical stability of the point algorithm is shown to be preserved by recursive blocking. Recursive blocking is also shown to be effective for multiplying triangular matrices.

Edvin Deadman
University of Manchester
NAG
edvin.deadman@nag.co.uk

Nicholas J. Higham
School of Mathematics
University of Manchester
higham@maths.manchester.ac.uk

Rui Ralha
Center of Mathematics
University of Minho, Portugal
r_ralha@math.uminho.pt

MS 2. Methods for Toeplitz matrices and their application

Talk 1. **Toeplitz operators with matrix-valued symbols and some (unexpected) applications**

We discuss the eigenvalue distribution in the Weyl sense of general matrix-sequences associated to a symbol. As a specific case we consider Toeplitz sequences generated by matrix-valued (non Hermitian) bounded functions. We show that the canonical distribution can be proved under mild assumptions on the spectral range of the given symbol. Finally some applications are introduced and discussed.

Stefano Serra Capizzano
Dipartimento di Fisica e Matematica
Università dell'Insubria - sede di Como, IT
s.serracapizzano@uninsubria.it

Talk 2. **Fast approximation to the Toeplitz matrix exponential**

The shift-invert Lanczos (or Arnoldi) method is employed to generate an orthonormal basis from the Krylov subspace corresponding to the real Toeplitz matrix and an initial vector. The vectors and recurrence coefficients produced by this method are exploited to approximate the Toeplitz matrix exponential. Toeplitz matrix inversion formula and rapid Toeplitz matrix-vector multiplications are utilized to lower the computational costs. For convergence analysis, a sufficient condition is established to guarantee that the error bound is independent of the norm of the matrix. Numerical results and applications to the computational finance are given to demonstrate the efficiency of the method.

Hai-Wei Sun
Faculty of Science and Technology
University of Macau, MO
hsun@umac.mo

Talk 3. **Matrix algebras sequences can be spectrally equivalent with ill-conditioned Toeplitz ones**
The construction of fast and efficient iterative procedure or effective multigrid schemes, requires the study of the spectrum of the matrix sequences $\{A_n\}_n$, where $\{A_n\}_n = \{P_n^{-1}(f)T_n(f)\}_n$. In this talk, we focus on the case where $T_n(f)$ is a Toeplitz matrix generated by a nonnegative real function f, and $P_n(f)$ denotes matrices belonging to tau or circulant algebras. Assuming that the symbol f has discrete roots of non integer order, we will show that under suitable assumptions the spectrum of the matrix sequence $\{A_n\}_n$ is bounded by constants far away from zero and infinity. Using the developed theory, we propose effective preconditioners and we give hints for optimal multigrid schemes.

Paris Vassalos
Dept. of Informatics
Athens University of Economics and Business
pvassal@aueb.gr

Dimitrios Noutsos
Dept. of Mathematics
University of Ioannina
dnoutsos@aueb.gr

Talk 4. **Aggregation-based multigrid methods for Toeplitz matrices**
Aggregation and smoothed aggregation based multigrid methods can be analyzed in the context of the convergence theory for Toeplitz and circulant matrices. As in the aggregation-based multigrid methods, for generating symbols with a single isolated zero at the origin aggregates are formed. The interpolation can then be improved by applying an additional operator. This improvement can be interpreted as the smoothing step in the original smoothed aggregation method. Depending on the original generating symbol, several smoothing steps can be necessary. Numerical examples show the efficiency of the aggregation based approach in the case of Toeplitz and circulant matrices.

Matthias Bolten
Department of Mathematics and Science
University of Wuppertal, DE
bolten@math.uni-wuppertal.de

Marco Donatelli
Dipartimento di Fisica e Matematica
Università dell'Insubria - sede di Como, IT
marco.donatelli@uninsubria.it

Thomas Huckle
Dept. of Informatics
Technische Universität München, DE
huckle@in.tum.de

MS 3. Matrix factorizations and applications

Talk 1. **Classes of matrices with bidiagonal factorization**
Matrices with a bidiagonal decomposition satisfying some sign restrictions are analyzed. They include all nonsingular totally positive matrices, their matrices opposite in sign and their inverses, as well as tridiagonal nonsingular H-matrices. Properties of these matrices are presented and the bidiagonal factorization can be used to perform computations with high relative accuracy.

Álvaro Barreras
Dept. of Applied Mathematics / IUMA
Universidad de Zaragoza
albarrer@unizar.es

Juan Manuel Peña
Dept. of Applied Mathematics / IUMA
Universidad de Zaragoza
jmpena@unizar.es

Talk 2. **Cholesky factorization for singular matrices**
Direct and iterative solution methods for linear least-squares problems have been studied in Numerical Linear Algebra. Part of the difficulty for solving least-squares problems is the fact that many methods solve the system by implicitly solving the normal equations $A^TAx = A^Tb$ with $A \in \mathbb{R}^{n\times m}$ and $b \in \mathbb{R}^n$. In this talk we consider this problem when A is a rank deficient matrix. Then, A^TA is a positive semidefinite matrix and its Cholesky factorization is not unique. So, we introduce a full rank Cholesky decomposition LL^T of the normal equations matrix without the need to form the normal matrix itself. We present two algorithms to compute the entries of L by rows (or by columns) with the corresponding error analysis. Numerical experiments illustrating the proposed algorithms are given.

Rafael Cantó
Dept. of Applied Mathematics
Universitat Politècnica de València
rcanto@mat.upv.es

Ana M. Urbano
Dept. of Applied Mathematics
Universitat Politècnica de València
amurbano@mat.upv.es

María J. Peláez
Dept. of Mathematics
Universidad Católica del Norte
mpelaez@ucn.cl

Talk 3. **Applications of the singular value decomposition to perturbation theory of eigenvalues of matrix polynomials**
In this talk, motivated by a problem posed by Wilkinson, we study the coefficient perturbations of a $n \times n$ matrix polynomial to $n \times n$ matrix polynomials which have a prescribed eigenvalue of specified algebraic multiplicity and index of annihilation. For an $n \times n$ matrix polynomial $P(\lambda)$ and a given scalar $\mu \in \mathbb{C}$, we introduce two weighted spectral norm distances, $\mathcal{E}_r(\mu)$ and $\mathcal{E}_{r,k}(\mu)$, from $P(\lambda)$ to the $n \times n$ matrix polynomials that have μ as an eigenvalue of algebraic multiplicity at least r and to those that have μ as an eigenvalue of algebraic multiplicity at least r and maximum Jordan chain length exactly k, respectively. Then we obtain a singular value characterization of $\mathcal{E}_{r,1}(\mu)$, and derive a lower bound for $\mathcal{E}_{r,k}(\mu)$ and an upper bound for $\mathcal{E}_r(\mu)$, constructing associated perturbations of $P(\lambda)$.

Panayiotis Psarrakos
Dept. of Mathematics
National Technical University of Athens
ppsarr@math.ntua.gr

Nikolaos Papathanasiou
Dept. of Mathematics
National Technical University of Athens
nipapath@mail.ntua.gr

Talk 4. **On reduced rank nonnegative matrix factorization for symmetric nonnegative matrices**
For a nonnegative matrix $V \in \mathbb{R}^{m,n}$, the *nonnegative matrix factorization* (NNMF) problem consists of finding nonnegative matrix factors $W \in \mathbb{R}^{m,r}$ and $H \in \mathbb{R}^{r,n}$ such that $V \approx WH$. We consider the algorithm provided by Lee and Seung which finds nonnegative W and H such that $\|V - WH\|_F$ is minimized. For the case $m = n$ and in which V is symmetric, we present results concerning when the best approximate

factorization results in the product WH being symmetric and on cases in which the best approximation cannot be a symmetric matrix. Results regarding other special cases as well as applications are also discussed.

Minerva Catral
Dept. of Mathematics
Xavier University
catralm@xavier.edu

Lixing Han
Dept. of Mathematics
University of Michigan-Flint
lxhan@umflint.edu

Michael Neumann
Dept. of Mathematics
University of Connecticut

Robert J. Plemmons
Dept. of Mathematics and Computer Science
Wake Forest University
plemmons@wfu.edu

MS 4. Algorithms on manifolds of low-rank matrices and tensors

Talk 1. **Low rank dynamics for computing extremal points of real and complex pseudospectra**
We consider the real ε-pseudospectrum of a square matrix, which is the set of eigenvalues of all real matrices that are ε-close to the given matrix, where closeness is measured in either the 2-norm or the Frobenius norm.
We characterize extremal points and compare the situation with that for the unstructured ε-pseudospectrum. We present differential equations for low rank (1 and 2) matrices for the computation of the extremal points of the pseudospectrum. Discretizations of the differential equations yield algorithms that are fast and well suited for sparse large matrices. Based on these low-rank differential equations, we further obtain an algorithm for drawing boundary sections of the structured pseudospectrum with respect to both considered norms.

Nicola Guglielmi
Dipartimento di Matematica
Università di L'Aquila, Italy
guglielm@univaq.it

Christian Lubich
Mathematisches Institut
Universität Tübingen
lubich@na.uni-tuebingen.de

Talk 2. **Parametric model order reduction using stabilized consistent interpolation on matrix manifolds**
A robust method for interpolating reduced-order linear operators on their matrix manifolds is presented. Robustness is achieved by enforcing consistency between the different sets of generalized coordinates underlying different instances of parametric reduced-order models (ROMs), and explicitly stabilizing the final outcome of the interpolation process. Consistency is achieved by transforming the ROMs before interpolation using a rotation operator obtained from the solution of a generalized orthogonal Procrustes problem. Stabilization is achieved using a novel real-time algorithm based on semidefinite programming. The overall method is illustrated with its on-line application to the parametric fluid-structure analysis of a wing-store configuration.

David Amsallem
Department of Aeronautics and Astronautics
Stanford University
amsallem@stanford.edu

Charbel Farhat
Department of Aeronautics and Astronautics
Department of Mechanical Engineering
Institute for Computational Methods in Engineering
Stanford University
cfarhat@stanford.edu

Talk 3. **Treatment of high-dimensional problems by low-rank manifolds of tensors**
Many problems in e.g. natural sciences, data mining and statistics are naturally posed as high-dimensional problems.Tensor product representations parametrize these problem on approximation manifolds, often fixed by a given maximal rank for the tensor approximation. A relatively new format is the HT/TT format as developed by Hackbusch (Leipzig) and Oseledets/Tyrtyshnikov (Moscow), which overcomes the shortcomings of older formats and gives a stable and often sparse opportunity to represent high-dimensional quantities, so that the treatment of e.g. high-dimensional partial differential equations is on the verge of realization. In this talk, a general framework to realize such tasks in data-sparse tensor formats is presented. For the HT/TT format, we present some theoretical as well as algorithmic results for the treatment of high-dimensional optimization tasks and high-dimensional evolution equations.

Thorsten Rohwedder
Institut für Mathematik
Technische Universität Berlin
rohwedde@math.tu-berlin.de

Talk 4. **Local convergence of alternating optimization of multivariate functions in the presence of scaling indeterminacies**
An easy and widely used approach to minimize functions with respect to certain tensor formats (such as CP, Tucker, TT or HT) is the alternating optimization algorithm, also called nonlinear Gauss–Seidel method. A prominent example is the PARAFAC-ALS algorithm. Due to the usual non-uniqueness of tensor representations, standard convergence results for nonlinear Gauss-Seidel are usually not directly applicable. In this talk we present a quite general approach to prove local convergence, based on a geometric viewpoint, which regards tensors of fixed rank as orbits of a Lie group generating equivalent representations.

André Uschmajew
Institut für Mathematik
Technische Universität (TU) Berlin
uschmajew@math.tu-berlin.de

MS 5. Advances in algebraic multigrid - New approaches and applications

Talk 1. **Algebraic collocation coarse approximation multigrid**
Most algebraic multigrid (AMG) methods define the coarse operators by applying the (Petrov-)Galerkin coarse approximation where the sparsity pattern and operator complexity of the multigrid hierarchy is dictated by the multigrid prolongation and restriction. Therefore, AMG algorithms usually must settle on some compromise between the quality of these operators and the aggressiveness of the coarsening, which affects their rate of convergence and operator complexity. In this paper we propose an algebraic generalization

of the *collocation coarse approximation* (CCA) approach of Wienands and Yavneh, where the choice of the sparsity pattern of the coarse operators is independent of the choice of the high-quality transfer operators. The new algorithm is based on the aggregation framework (smoothed and non-smoothed). Using a small set of low-energy eigenvectors, it computes the coarse grid operator by a weighted least squares process. Numerical experiments for two dimensional diffusion problems with sharply varying coefficients demonstrate the efficacy and potential of this multigrid algorithm.

Eran Treister
Department of Computer Science
Technion—Israel Institute of Technology, IL
eran@cs.technion.ac.il

Ran Zemach
Department of Computer Science
Technion—Israel Institute of Technology, IL
ran.zemach@gmail.com

Irad Yavneh
Department of Computer Science
Technion—Israel Institute of Technology, IL
irad@cs.technion.ac.il

Talk 2. **Energy-minimization interpolation for adaptive algebraic multigrid**

Adaptive algebraic multigrid (AMG) methods automatically detect the algebraically smooth error for a linear system and as such, are robust black box approaches for solving difficult problems. However, the two main families of methods, Bootstrap AMG (BAMG) and adaptive smoothed aggregation (αSA), suffer from drawbacks, such as noisy candidate vectors (BAMG) and potentially high operator complexity, especially for scalar problems, (αSA). This work is intended to address some of these drawbacks by combining elements of BAMG and αSA through an energy-minimization interpolation framework. While the approach is general, the challenging, motivating problem is a biquadratic discretization of anisotropic diffusion.

Jacob B. Schroder
Center for Applied Scientific Computing
Lawrence Livermore National Laboratory (LLNL), US
schroder2@llnl.gov

Robert D. Falgout
Center for Applied Scientific Computing
Lawrence Livermore National Laboratory (LLNL), US
falgout2@llnl.gov

Talk 3. **Algebraic multigrid (AMG) for complex network calculations**

Clustering, ranking, or measuring distance for vertices on scale-free graphs are all computational task of interest. Such calculations may be obtained by solving eigensystems or linear systems involving matrices whose sparsity structure is related to an underlying scale-free graph. For many large systems of interest, classical iterative solvers (such as conjugate gradient and Lanczos) converge with prohibitively slow rates, due to ill-conditioned matrices and small spectral gap ratios. Efficiently preconditioning these systems with multilevel methods is difficult due to the scale-free topology. For some large model problems and real-world networks, we investigate the performance of a few AMG-related coarsening approaches.

Geoffrey D. Sanders
Center for Applied Scientific Computing
Lawrence Livermore National Laboratory (LLNL), US
sanders29@llnl.gov

Van Emden Henson
Center for Applied Scientific Computing
Lawrence Livermore National Laboratory (LLNL), US
henson5@llnl.gov

Panayot S. Vassilevski
Center for Applied Scientific Computing
Lawrence Livermore National Laboratory (LLNL), US
vassilevski1@llnl.gov

Talk 4. **The polynomial of best uniform approximation to $1/x$ as smoother in two grid methods**

We discuss a simple convergence analysis of two level methods where the relaxation on the fine grid uses the polynomial of best approximation in the uniform norm to $1/x$ on a finite interval with positive endpoints. The construction of the latter polynomial is of interest by itself, and we have included a derivation of a three-term recurrence relation for computing this polynomial. We have also derived several inequalities related to the error of best approximation, monotonicity of the polynomial sequence, and positivity which we applied in the analysis of two-level methods.

Ludmil T. Zikatanov
Department of Mathematics
The Pennsylvania State University, US
ludmil@psu.edu

Johannes Kraus
Johann Radon Institute for Computational and Applied Mathematics (RICAM), AT
johannes.kraus@oeaw.ac.at

Panayot S. Vassilevski
Center for Applied Scientific Computing
Lawrence Livermore National Laboratory (LLNL), US
vassilevski1@llnl.gov

MS 6. Recent advances in fast iterative solvers - Part I of II

Talk 1. **Challenges in analysis of Krylov subspace methods**

The current state-of-the art of iterative solvers is the outcome of the tremendous algorithmic development over the last few decades and of investigations of *how* to solve given problems. In this contribution we focus on Krylov subspace methods and more on the dual question *why* things do or do not work. In particular, we will pose and discuss open questions such as what the spectral information tells us about the behaviour of Krylov subspace methods, to which extent we can relax the accuracy of local operations in inexact Krylov subspace methods without causing an unwanted delay, how important is considering of rounding errors in various algorithmic techniques, whether it is useful to view Krylov subspace methods as *matching moment model reduction*, and how the algebraic error can be included into locally efficient and fully computable a-posteriori error bounds for adaptive PDE solvers.

Zdeněk Strakoš
Charles University in Prague and Academy of Science of the Czech Republic
strakos@karlin.mff.cuni.cz

Jörg Liesen
Institute of Mathematics
Technical University of Berlin
liesen@math.tu-berlin.de

Talk 2. **Updating preconditioners for parameterized systems**

Parameterized linear systems arise in a range of applications, such as model reduction, acoustics, and inverse problems based on parametric level sets. Computing new preconditioners for

many small changes in parameter(s) would be very expensive. However, using one or only a few preconditioners for all systems leads to an excessive total number of iterations. We show strategies to efficiently compute effective multiplicative updates to preconditioners. This has the advantage that, for a slight increase in overhead, the update is more or less independent of the original preconditioner used.

Eric de Sturler
Department of Mathematics
Virginia Tech
sturler@vt.edu
Sarah Wyatt
Department of Mathematics
Virginia Tech
sawyatt@vt.edu
Serkan Gugercin
Department of Mathematics
Virginia Tech
gugercin@math.vt.edu

Talk 3. **Efficient preconditioning techniques for two-phase flow simulations**

In this talk we present efficient preconditioning strategies, suitable for the iterative solution of algebraic systems, arising in numerical simulations of two-phase flow problems, modelled by the Cahn-Hilliard equation.

In this work, we decompose the original Cahn-Hilliard equation, which is nonlinear and of fourth-order, into a system of two second-order equations for the so-called 'concentration' and 'chemical potential'. The so-obtained nonlinear system is discretized using the finite element method and solved by two variants of the inexact Newton method. The major focus of the work is to construct a preconditioner for the correcponding Jacobian, which is of block two-by-two form. The proposed preconditioning techniques are based on approximate factorization of the discrete Jacobian and utilise to a full extent the properties of the underlying matrices.

We propose a preconditioning method that reduces the problem of solving the non-symmetric discrete Cahn-Hilliard system to the problem of solving systems with symmetric positive definite matrices, where off-the-shelf multilevel and multigrid algorithms are directly applicable. The resulting iterative method exhibits optimal convergence and computational complexity properties. The efficiency of the resulting preconditioning method is illustrated via various numerical experiments, including large scale examples of both 2D and 3D problems.

The preconditioning techniques are more generally applicable for any algebraic system of the same structure as, e.g., when solving complex symmetric linear systems.

M. Neytcheva
Institute for Information Technology
Uppsala University
maya.neytcheva@it.uu.se
Owe Axelsson
Institute of Geonics
Academy of Sciences of the Czech Republic, Ostrava
owe.axelsson@it.uu.se
Petia Boyanova
Institute for Information Technology
Uppsala University
petia.boyanova@it.uu.se
Martin Kronbichler
Institute for Information Technology
Uppsala University
martin.kronbichler@it.uu.se
Xunxun Wu
Institute for Information Technology
Uppsala University
Xunxun.Wu.1786@student.uu.se

Talk 4. **Preconditioners in liquid crystal modelling**

Liquid crystal displays are ubiquitous in modern life, being used extensively in monitors, televisions, gaming devices, watches, telephones etc. Appropriate models feature characteristic length and time scales varying by many orders of magnitude, which provides difficult numerical challenges to those trying to simulate real-life dynamic industrial situations. The efficient solution of the resulting linear algebra sub-problems is of crucial importance for the overall effectiveness of the algorithms used. In this talk we will present some examples of saddle-point systems which arise in liquid crystal modelling and discuss their efficient solution using appropriate preconditioned iterative methods.

Alison Ramage
Dept of Mathematics and Statistics
University of Strathclyde
Glasgow, Scotland
A.Ramage@strath.ac.uk
Chris Newton
Next Generation Displays Group
Hewlett-Packard Laboratories
Bristol, England
chris.newton@hp.com

MS 7. Application of statistics to numerical linear algebra algorithms - Part I of II

Talk 1. **Fast linear system solvers based on randomization techniques**

We illustrate how dense linear algebra calculations can be enhanced by randomizing general or symmetric indefinite systems. This approach, based on a multiplicative preconditioning of the initial matrix, revisits the work from [Parker, 1995]. It enables us to avoid pivoting and then to reduce significantly the amount of communication. This can be performed at a very affordable computational price while providing a satisfying accuracy. We describe solvers based on randomization that take advantage of the latest generation of multicore or hybrid multicore/GPU machines and we compare their Gflop/s performance with solvers from standard parallel libraries.

Marc Baboulin
Inria Saclay Île-de-France
University Paris-Sud, France
marc.baboulin@inria.fr
Dulceneia Becker
University of Tennessee, USA
dbecker7@eecs.utk.edu
Jack Dongarra
University of Tennessee, USA
dongarra@eecs.utk.edu
Stanimire Tomov
University of Tennessee, USA
tomov@eecs.utk.edu

Talk 2. **Numerical issues in randomized algorithms**

Randomized algorithms are starting to find their way into a wide variety of applications that give rise to massive data sets. These algorithms downsize the enormous matrices by picking and

choosing only particular columns or rows, thereby producing potentially huge savings in storage and computing speed. Although randomized algorithms can be fast and efficient, not much is known about their numerical properties. We will discuss the numerical sensitivity and stability of randomized algorithms, as well as the error due to randomization, and the effect of the coherence of the matrix. Algorithms under consideration include matrix multiplication, least squares solvers, and low-rank approximations.

Ilse Ipsen
Department of Mathematics
North Carolina State University, USA
ipsen@ncsu.edu

Talk 3. **Near-optimal column based matrix reconstruction**
We consider low-rank reconstruction of a matrix using a subset of its columns and we present asymptotically optimal algorithms for both spectral norm and Frobenius norm reconstruction. The main tools we introduce to obtain our results are: (i) the use of fast approximate SVD-like decompositions for column-based matrix reconstruction, and (ii) two deterministic algorithms for selecting rows from matrices with orthonormal columns, building upon the sparse representation theorem for decompositions of the identity that appeared in [Batson, Spielman, Srivastava, 2011].

Christos Boutsidis
Mathematical Sciences Department
IBM T. J. Watson Research Center, USA
cboutsi@us.ibm.com

Petros Drineas
Computer Science Department
Rensselaer Polytechnic Institute, USA
drinep@cs.rpi.edu

Malik Magdon-Ismail
Computer Science Department
Rensselaer Polytechnic Institute, USA
magdon@cs.rpi.edu

Talk 4. **Numerical experiments with statistical condition estimation**
In this talk we present the results of some numerical experiments illustrating the use of statistical condition estimation (SCE). After a brief review of SCE, the use of the technique is demonstrated on a few topics of general interest including the estimation of the condition of large sparse linear systems.

Alan J. Laub
Department of Mathematics
University of California Los Angeles, USA
laub@ucla.edu

MS 8. Rational Krylov methods: analysis and applications - Part I of II

Talk 1. **Solving Sylvester equations through rational Galerkin projections**
Recently (B. Beckermann, An error analysis for rational Galerkin projection applied to the Sylvester equation, SIAM J. Num. Anal. 49 (2012), 2430-2450), we suggested a new error analysis for the residual of Galerkin projection onto rational Krylov spaces applied to a Sylvester equation with a rank 1 right-hand side. In this talk we will consider more generally small rank right-hand sides, where block Krylov methods and tangential interpolation problems play an important role.

Bernhard Beckermann
Dept. of Mathematics
University of Lille
bbecker@math.univ-lille1.fr

Talk 2. **Stability-corrected spectral Lanczos decomposition algorithm for wave propagation in unbounded domains**
Applying Krylov subspace methods to exterior wave field problems has become an active topic of recent research. In this paper, we introduce a new Lanczos-based solution method via stability-corrected operator exponents, allowing us to construct structure-preserving reduced-order models (ROMs) respecting the delicate spectral properties of the original scattering problem. The ROMs are unconditionally stable and are based on a renormalized Lanczos algorithm, which enables us to efficiently compute the solution in the frequency and time domain. We illustrate the performance of our method through a number of numerical examples in which we simulate 2D electromagnetic wave propagation in unbounded domains.

Rob Remis
Faculty of Electrical Engineering, Mathematics and Computer Science
Delft University of Technology
R.F.Remis@tudelft.nl

Vladimir Druskin
Schlumberger-Doll Research
Druskin1@slb.com

Talk 3. **Generalized rational Krylov decompositions**
The notion of an orthogonal rational Arnoldi decomposition, as introduced by Axel Ruhe, is a natural generalization of the well-known (polynomial) Arnoldi decomposition. Generalized rational Krylov decompositions are obtained by removing the orthogonality assumption. Such decompositions are interesting linear algebra objects by themselves and we will study some of their algebraic properties, as well as the rational Krylov methods that can be associated with them.

Stefan Güttel
Mathematical Institute
University of Oxford
Stefan.Guettel@maths.ox.ac.uk

Talk 4. **Interpolatory model reduction strategies for nonlinear parametric inversion**
We will show how reduced order models can significantly reduce the cost of general inverse problems approached through parametric level set methods. Our method drastically reduces the solution of forward problems in diffuse optimal tomography (DOT) by using interpolatory, i.e. rational Krylov based, parametric model reduction. In the DOT setting, these surrogate models can approximate both the cost functional and associated Jacobian with little loss of accuracy and significantly reduced cost.

Serkan Gugercin
Dept. of Mathematics
Virginia Tech.
gugercin@math.vt.edu

Christopher A. Beattie
Dept. of Mathematics
Virginia Tech.
beattie@vt.edu

Saifon Chaturantabut
Dept. of Mathematics
Virginia Tech.
saifonc@math.vt.edu

Eric de Sturler
Dept. of Mathematics
Virginia Tech.
sturler@vt.edu

Misha E. Kilmer
Dept. of Mathematics
Tufts University
misha.kilmer@tufts.edu

MS 9. New trends in tridiagonal matrices - Part I of II

Talk 1. **Direct and inverse problems on pseudo-Jacobi matrices**

A theorem of Friedland and Melkman states the unique recovery of a non-negative Jacobi matrix from the spectra of its upper and lower principal submatrices obtained by deleting the kth row and column. Here this result is revisited and generalized. Other related problems are also investigated, including existence and uniqueness theorems.

Natália Bebiano
Department of Mathematics
University of Coimbra
3001-454 Coimbra
Portugal
bebiano@mat.uc.pt

Susana Furtado
Faculty of Economics
University of Porto
4200-464 Porto
Portugal
sbf@fep.up.pt

J. da Providência
Department of Physics
University of Coimbra
3004-516 Coimbra
Portugal
providencia@teor.fis.uc.pt

Talk 2. **Schwartz's matrices and generalized Hurwitz polynomials**

We present solutions of direct and inverse spectral problems for a kind of Schwarz's matrices (tridiagonal matrices with only one nonzero main-diagonal entry). We study dependence of spectra of such matrices on the signs of their off-main-diagonal entries. We show that for certain distributions of those signs, the characteristic polynomial of the correspondent Schwarz's matrix is a generalized Hurwitz polynomial. Recall that a real polynomial $p(z) = p_0(z^2) + zp_1(z^2)$, where p_0 and p_1 are the even and odd parts of p, respectively, is generalized Hurwitz if and only if the zeroes of p_0 and p_1 are real, simple and interlacing.

Mikhail Tyaglov
Institut für Mathematik
Technische Universität Berlin
Sekretariat MA 4-5
Straße des 17. Juni 136
10623 Berlin
Germany
tyaglov@math.tu-berlin.de

Talk 3. **On the Moore-Penrose inverse of singular, symmetric and periodic Jacobi M-matrices**

We aim here at determining the Moore–Penrose inverse, $\mathsf{J}^\dagger$ of any singular, symmetric and periodic Jacobi M–matrix J, both throughout direct computations or considering it as a perturbation of a singular, symmetric and nonperiodic Jacobi M–matrix. We tackle the problem by applying methods from the operator theory on finite networks, since the off–diagonal entries of J can be identified with the conductance function of a weighted n–cycle. Then, J appears as a positive–semidefinite Schrödinger operator on the cycle and hence, $\mathsf{J}^\dagger$ is nothing else that the corresponding Green operator.
We also consider the problem of characterizing when $\mathsf{J}^\dagger$ is itself an M-matrix.

Andrés M. Encinas
Departament de Matemàtica Aplicada III
Universitat Politècnica de Catalunya
08034 Barcelona
Spain
andres.marcos.encinas@upc.edu

Enrique Bendito
Departament de Matemàtica Aplicada III
Universitat Politècnica de Catalunya
08034 Barcelona
Spain
enrique.bendito@upc.edu

Ángeles Carmona
Departament de Matemàtica Aplicada III
Universitat Politècnica de Catalunya
08034 Barcelona
Spain
angeles.carmona@upc.edu

Margarida Mitjana
Departament de Matemàtica Aplicada I
Universitat Politècnica de Catalunya
08034 Barcelona
Spain
margarida.mitjana@upc.edu

Talk 4. **The commutant of the tridiagonal pattern**

We consider patterns that allow real commutativity with an irreducible tridiagonal n-by-n pattern. All are combinatorially symmetric. All also allow a complex symmetric commuting pair, but only some allow a real symmetric commuting pair. We also show that any matrix that commutes with an irreducible tridiagonal matrix satisfies certain ratio equations. Generalizations to matrices with tree patterns are also considered.

Charles R. Johnson
Department of Mathematics
College of William and Mary
PO Box 8795
Williamsburg, VA 23187
USA
crjohnso@math.wm.edu

MS 10. Numerical algorithms for switching systems: from theory to applications

Talk 1. **Observer design for hybrid systems**

The state estimation problem has been the subject of intensive study for many years by both the computer science community in the discrete domain and the control community in the continuous domain, but only scantly investigated in the hybrid system domain.
In this talk, we present a design methodology for dynamical observers of hybrid systems with linear continuous-time dynamics, which reconstruct the complete state from the knowledge of the inputs and outputs of a hybrid plant.
We demonstrate the methodology by building a hybrid observer for an industrial automotive control problem: on-line identification of the actual engaged gear.

Maria Domenica Di Benedetto
University of L'Aquila
mariadomenica.dibenedetto@univaq.it

Talk 2. **About polynomial instability for linear switched systems**
In this talk we present recent results on the characterization of marginal instability for linear switched systems. Our main contribution consists in pointing out a resonance phenomenon associated with marginal instability. In particular we derive an upper bound of the norm of the state at time t, which is polynomial in t and whose degree is computed from the resonance structure of the system. We also derive analogous results for discrete-time linear switched systems.

Paolo Mason
Laboratoire des Signaux et Systèmes
CNRS
Paolo.Mason@lss.supelec.fr
Yacine Chitour
Laboratoire des Signaux et Systèmes
Université Paris Sud
Yacine.Chitour@lss.supelec.fr
Mario Sigalotti
CMAP, INRIA Saclay
Mario.Sigalotti@inria.fr

Talk 3. **Stability and stabilization of positive switched systems: state of the art and open problems**
A positive switched system (PSS) consists of a family of positive state-space models and a switching law, specifying when and how the switching among the various models takes place. This class of systems has some interesting practical applications: PSS's have been adopted for describing networks employing TCP and other congestion control applications, for modeling consensus and synchronization problems, and, quite recently, for describing the viral mutation dynamics under drug treatment. In the talk we will provide a comprehensive picture of the conditions for stability and for stabilizability, and we will point out some open problems.

Maria Elena Valcher
Dept. of Information Engineering
University of Padova
meme@dei.unipd.it
Ettore Fornasini
Dept. of Information Engineering
University of Padova
fornasini@dei.unipd.it

Talk 4. **The joint spectral radius for semigroups generated by switched differential algebraic equations**
We introduce the joint spectral radius for matrix semigroups that are generated by switched linear ordinary differential equations with jumps. The jumps are modeled by projectors which are assumed to commute with the generators of the flow. This setup covers switched differential algebraic equations. It is shown that an exponential growth rate can only be defined if the discrete semigroup generated by the projections is product bounded. Assuming this is true we show that Barabanov norms may be defined in the irreducible case and that a converse Lyapunov theorem holds. Some further properties of the exponential growth rate are discussed.

Fabian Wirth
Dept. of Mathematics
University of Würzburg, Germany
wirth@mathematik.uni-wuerzburg.de
Stephan Trenn
Dept. of Mathematics
Technical University of Kaiserslautern, Germany
trenn@mathematik.uni-kl.de

MS 11. Recent advances in fast iterative solvers - Part II of II

Talk 1. **Combination preconditioning of saddle-point systems for positive definiteness**
There are by now many preconditioning techniques for saddle-point systems but also a growing number of applications where such are required. In this talks we will discuss preconditioners which preserve self-adjointness in non-standard inner products and the combination of such preconditioners as introduced by Martin Stoll and the first author in 2008.
Here we will show how two preconditioners which ensure self-adjointness in different inner products, but which are both indefinite may be combined to yield a positive definite self-adjoint preconditioned system in a third inner product which thus allows robust application of the Hestenes Steifel Conjugate Gradient method in that inner product.

Andrew J. Wathen
Mathematical Institute
Oxford University, UK
wathen@maths.ox.ac.uk
Jennifer Pestana
Mathematical Institute
Oxford University, UK
pestana@maths.ox.ac.uk

Talk 2. **Preconditioned iterative methods for nonsymmetric matrices and nonstandard inner products**
The convergence of a minimum residual method applied to a linear system with a nonnormal coefficient matrix is not well understood in general. This can make choosing an effective preconditioner difficult. In this talk we present a new GMRES convergence bound. We also show that the convergence of a nonstandard minimum residual method, applied to a preconditioned system, is bounded by a term that depends primarily on the eigenvalues of the preconditioned coefficient matrix, provided the preconditioner and coefficient matrix are self-adjoint with respect to nearby Hermitian sesquilinear forms. We relate this result to the convergence of standard methods.

Jennifer Pestana
Mathematical Institute
University of Oxford
pestana@maths.ox.ac.uk
Andrew J. Wathen
Mathematical Institute
University of Oxford
wathen@maths.ox.ac.uk

Talk 3. **Multi-preconditioned GMRES**
Standard Krylov subspace methods only allow the user to choose a single preconditioner. In many situations, however, there is no 'best' choice, but a number of possible candidates. In this talk we describe an extension of GMRES, multi-preconditioned GMRES, which allows the use of more than one preconditioner, and combines their properties in an optimal way. As well as describing some theoretical properties of the new algorithm we will present numerical results which highlight the utility of the approach.

Tyrone Rees
Numerical Analysis Group
Rutherford Appleton Laboratory
tyronere@cs.ubc.ca
Chen Greif
Dept. of Computer Science
University of British Columbia

greif@cs.ubc.ca
Daniel B. Szyld
Dept. of Mathematics
Temple University
szyld@temple.edu

Talk 4. **Bounds on the eigenvalues of indefinite matrices arising from interior-point methods**
Interior-point methods feature prominently in the solution of constrained optimization problems, and involve the need to solve a sequence of 3×3 block indefinite matrices that become increasingly ill-conditioned throughout the iteration. Most solution approaches are based on reducing the system size using a block Gaussian elimination procedure. In this talk we use energy estimates to obtain bounds on the eigenvalues of the original, augmented matrix, which indicate that the spectral structure of this matrix may be favorable compared to matrices obtained by performing a partial elimination of variables before solving the system.

Chen Greif
Department of Computer Science
The University of British Columbia
greif@cs.ubc.ca
Erin Moulding
Department of Mathematics
The University of British Columbia
moulding@math.ubc.ca
Dominique Orban
Mathematics and Industrial Engineering Department
Ecole Polytechnique de Montreal
dominique.orban@gerad.ca

MS 12. Application of statistics to numerical linear algebra algorithms - Part II of II

Talk 1. **Spectral graph theory, sampling matrix sums, and near-optimal SDD solvers**
We present a near-optimal solver for Symmetric Diagonally Dominant (SDD) linear systems. The solver is a great example of the power of statistical methods in linear algebra and in particular of sampling sums of positive semi-definite matrices. Crucial to the speed of the solver is the ability to perform fast sampling. In turn, key to fast sampling are low-stretch spanning trees, a central notion in spectral graph theory and combinatorial preconditioning. We will see that a low-stretch tree is essentially a 'spectral spine' of a graph Laplacian, allowing us to create a hierarchy of spectrally similar graphs which lends itself to the very fast multilevel solver.

Ioannis Koutis
Computer Science Department
University of Puerto Rico
ioannis.koutis@upr.edu
Gary Miller
Computer Science Department
Carnegie Mellon University, USA
glmiller@cs.cmu.edu
Richard Peng
Computer Science Department
Carnegie Mellon University, USA
yangp@cs.cmu.edu

Talk 2. **Implementation of a randomization algorithm for dense linear algebra libraries**
Randomization algorithms are an alternative to pivoting for factoring dense matrices to solve systems of linear equations. These techniques are more suitable to parallel architectures when compared to pivoting, requiring a reduced amount of communication and no synchronization during the factorization. The core kernel requires the multiplication of sparse matrices with a specific structure. The main issue in implementing such algorithms resides in the data dependency patterns, especially for the symmetric case. An implementation for the PLASMA library is described and traces are presented, together with performance data.

Dulceneia Becker
University of Tennessee, USA
dbecker7@eecs.utk.edu
Marc Baboulin
Inria Saclay Île-de-France
University Paris-Sud, France
marc.baboulin@inria.fr
Jack Dongarra
University of Tennessee, USA
dongarra@eecs.utk.edu

Talk 3. **Implementing randomized matrix algorithms in large-scale parallel environments**
Recent work from theoretical computer science on developing randomized matrix algorithms has recently led to the development of high-quality numerical implementations. Here, we describe our parallel iterative least-squares solver `LSRN`. The parallelizable normal random projection in the preconditioning phase leads to a very well-conditioned system. Hence, the number of iterations is fully predictable if we apply LSQR or the Chebyshev semi-iterative method to the preconditioned system. The latter method is particularly efficient for solving large-scale problems on clusters with high communication cost, e.g., on Amazon Elastic Compute Cloud clusters, that are increasingly common in large-scale data applications.

Michael W. Mahoney
Department of Mathematics
Stanford University, USA
mmahoney@theory.stanford.edu

Talk 4. **Random sampling preconditioners**
In the talk we study the use of preconditioners based on random sampling of rows for accelerating the solution of linear systems. We argue that the fusion of randomization with preconditioning is what enables fast and reliable algorithms.
We will discuss both dense and sparse matrices. For dense matrices, we will describe Blendenpik, a least-square solver for dense highly overdetermined systems that outperforms LAPACK by large factors, and scales significantly better than any QR-based solver. For sparse matrices, we relate random sampling preconditioners to fast SDD solvers, and generalize some of the techniques to finite element matrices.

Haim Avron
Mathematical Sciences Department
IBM T. J. Watson Research Center; USA
haimav@us.ibm.com
Sivan Toledo
Department of Computer Science
Tel-Aviv University, Israel
stoledo@tau.ac.il

MS 13. Rational Krylov methods: analysis and applications - Part II of II

Talk 1. **Rational Krylov methods for nonlinear matrix problems**

This talk is about the solution of non-linear eigenvalue problems and linear systems with a nonlinear parameter. Krylov and Rational Krylov methods are known to be efficient and reliable for the solution of such matrix problems with a linear parameter. The nonlinear function can be approximated by a polynomial. In earlier work, we suggested the use of Taylor expansions of the nonlinear function with an a priori undetermined degree. This led to the Taylor Arnoldi method that is an Arnoldi method applied to an infinite dimensional Companion linearization. When an interpolating polynomial is used instead of Taylor series, there is a similar connection with the rational Krylov subspace method applied on a linearization. The Krylov subspaces enjoy similar properties as the linear case such as moment matching and the convergence looks similar to convergence for a linear problem. We present several choices of polynomials and also discuss ideas for future work.

Karl Meerbergen
Department of Computer Science
KULeuven
Karl.Meerbergen@cs.kuleuven.be
Roel Van Beeumen
Department of Computer Science
KULeuven
Roel.VanBeeumen@cs.kuleuven.be
Wim Michiels
Department of Computer Science
KULeuven
Wim.Michiels@cs.kuleuven.be

Talk 2. **Block Gauss and anti-Gauss quadrature rules with application to networks**
The symmetric and nonsymmetric block Lanczos processes can be applied to compute Gauss quadrature rules for functionals with matrix-valued measures. We show that estimates of upper and lower bounds for these functionals can be computed inexpensively by evaluating pairs of block Gauss and anti-Gauss rules. An application to network analysis is described.

Lothar Reichel
Dept. of Mathematics
Kent State University
reichel@math.kent.edu
David Martin
Dept. of Mathematics
Kent State University
dmarti49@kent.edu

Talk 3. **On optimality of rational Krylov based low-rank approximations of large-scale matrix equations**
In this talk, we will discuss projection-based approximations for the solution of Lyapunov equations of the form

$$AXE^T + EXA^T + BB^T = 0,$$

with $A = A^T, E = E^T \in \mathbb{R}^{n\times n}$ and $B \in \mathbb{R}^{n\times m}$. Recently, a relation between minimizing the objective function

$$f : \mathcal{M} \to \mathbb{R},\ X \mapsto \operatorname{tr}\left(XAXE + BB^T\right)$$

on the manifold $\mathcal{M}$ of symmetric positive semi-definite matrices of rank k and the $\mathcal{L}-$norm defined by the operator

$$\mathcal{L} := -E \otimes A - A \otimes E$$

together with the inner product $\langle u, v\rangle_{\mathcal{L}} = \langle u, \mathcal{L}v\rangle$ has been shown. While so far this minimization problem was solved by means of a Riemannian optimization approach, here we will discuss an interpolation-based method which leads to the same results but relies on projecting the original Lyapunov equation onto a rational Krylov subspace. It will turn out that this can be achieved by the iterative rational Krylov algorithm (IRKA). Besides a generalization for the case of $A \neq A^T$, we will also discuss an extension for more general equations of the form

$$AXE + FXB + CD = 0,$$

with $A, F \in \mathbb{R}^{n\times n}$, $B, E \in \mathbb{R}^{m\times m}$, $C \in \mathbb{R}^{n\times p}$ and $D \in \mathbb{R}^{p\times m}$.

Tobias Breiten
Computational Methods in Systems and Control Theory
Max Planck Institute for Dynamics of Complex Technical Systems
breiten@mpi-magdeburg.mpg.de
Peter Benner
Computational Methods in Systems and Control Theory
Max Planck Institute for Dynamics of Complex Technical Systems
benner@mpi-magdeburg.mpg.de

Talk 4. **Inverse problems for large-scale dynamical systems in the H2-optimal model reduction framework**
In this work we investigate the Rational Krylov subspace (RKS) projection method with application to the inverse problems. We derive a representation for the reduced Jacobian as the product of a time-dependent and a stationary part. Then we show that the RKS satisfying the Meier-Luenberger necessary H_2 optimality condition not only minimizes the approximation error but completely annuls its influence on the inversion result (even if the subspace is not optimal globally). More precisely, the approximation error belongs to the (left) null-space of the reduced Jacobian. We compare inversion on such subspaces using other nearly optimal RKS's based on Zolotarev problem and adaptive pole selection algorithm.

Mikhail Zaslavsky
Schlumberger-Doll Research
mzaslavsky@slb.com
Vladimir Druskin
Schlumberger-Doll Research
druskin1@slb.com
Valeria Simoncini
Department of Mathematics
University of Bologna, Italy
valeria.simoncini@unibo.it

MS 14. New trends in tridiagonal matrices - Part II of II

Talk 1. **On generalized Jacobi matrices which are symmetric in Krein spaces**
I will give some motivations to introduce generalized Jacobi matrices of a special type. Then, some direct and inverse problems for these matrices will be presented.

Maxim Derevyagin
Institut für Mathematik
Technische Universität Berlin
Sekretariat MA 4-5
Straße des 17. Juni 136
10623 Berlin
Germany
derevyag@math.tu-berlin.de

Talk 2. **On the characteristic function for Jacobi matrices**
For a certain class of infinite Jacobi matrices with a discrete spectrum it is introduced a characteristic function as an analytic

function on a suitable complex domain. It is shown that the zero set of the characteristic function actually coincides with the point spectrum. As an illustration several explicitly solvable examples are discussed.

Pavel Štovíček
Department of Mathematics
Faculty of Nuclear Sciences and Physical Engineering
Czech Technical University
Trojanova 13
120 00 Prague
Czech Republic
stovipav@kmlinux.fjfi.cvut.cz

Talk 3. **Tridiagonal matrices in comb filters**
In the present talk we use some known and new results on tridiagonal matrices to compute the minimum mean square error for a decision feedback equalizer when the filter is a comb filter. We also apply those mathematical results on tridiagonal matrices to a problem in linear estimation with comb filters.

Jesús Gutiérrez-Gutiérrez
CEIT and Tecnun
Universidad de Navarra
Paseo de Manuel Lardizabal, no. 13
20018 Donostia - San Sebastián
Spain
jgutierrez@ceit.es

Talk 4. **The nullity theorem: forecasting structures in the inverses of sparse matrices**
The Nullity Theorem for matrices was formulated by Markham and Fiedler in 1986. At first sight, this theorem and its five-line proof appear trivial. Examples show, however, that it is powerful tool in computations with sparse and structured rank matrices. It is, e.g., a straightforward consequence of this theorem that the inverse of a tridiagonal is semiseparable, the inverse of a band matrix is higher order semiseparable, without even posing constraints of irreducibility.
We will reconsider the nullity theorem and extend it to predicting structures in LU and QR-factorizations.

Raf Vandebril
K.U. Leuven
Departement Computerwetenschappen (Postbus 02402)
Celestijnenlaan 200A
3001 Heverlee
Belgium
raf.vandebril@cs.kuleuven.be

MS 15. Application of compressed sensing in Bio-Medicine

Talk 1. **Evaluation of compressed sensing impact in cardiac signals processing and transmission**
Sensor networks are a field which benefits significantly from compressed sensing (CS), as, for instance, quality of service, or battery lifetime are directly improved by the subsequent reduction of traffic. Networks transmitting biomedical data, and within those, cardiac data, have particular advantages. ECG and PPG are the most studied 1D signals in the biomedical field, and where CS implementation has been more studied. One study scenario is using the sparsity of wavelet decomposition of these signals, and Iterative Shrinkage/Thresholding algorithms. Focus is given in accuracy and computation overhead, the most critical constraints of cardiac data processing. Networking implications are quantified, for different types of real network models, as well as the impact in signals quality, and on the extracted information (heart rate, oxygen saturation, pulse wave velocity).

Eduardo Pinheiro
Instituto de Telecomunicaes
Instituto Superior Tcnico, Lisboa, Portugal
eduardo.pinheiro@lx.it.pt

Talk 2. **Compressive sensing in drug discovery**
The design of new drugs is often based on certain interactions between a small molecule (the drug) and a protein. Often a high affinity between the small molecule and the protein is desirable. The affinity can be estimated by using statistical thermodynamics. In order to provide statistical data, high-performance computing machines are used to explore the conformational space of the molecular system. The corresponding algorithms are based on simplified physical models (force fields) for the interaction between the drug molecule and the protein. These models mostly do not take quantum effects into account. The talk will present new ideas to better include quantum chemical information, it will provide some important application areas of molecular simulation in drug discovery, and it gives some hints about using compressive sensing in this field.

Marcus Weber
Zuse Institute Berlin (ZIB), Germany
weber@zib.de

Talk 3. **Reconstruction of bacterial communities using sparse representation**
Determining the identities and frequencies of species present in a sample is a central problem in metagenomics, with scientific, environmental and clinical implications. A popular approach to the problem is sequencing the Ribosomal 16s RNA gene in the sample using universal primers, and using variation in the gene's sequence between different species to identify the species present in the sample. We present a novel framework for community reconstruction, based on sparse representation; while millions of microorganisms are present on earth, with known 16s sequences stored in a database, only a small minority (typically a few hundreds) are likely to be present in any given sample. We discuss the statistical framework, algorithms used and results in terms of accuracy and species resolution.

Or Zuk
Broad Institute, Cambridge, USA
orzuk@broadinstitute.org

Talk 4. **Sensing genome via factorization**
Since the last decade the matrix factorization and dimension reduction methods have been used for mining in genomics and proteomics. Also most recently the norm one optimization is emerging as a useful approach for this purpose. We propose a hybrid algorithm which uses the utility of SVD along with efficiency and robustness of norm one minimization for overcoming the shortcomings of each of these mentioned approaches.

Amir Niknejad
College of Mount Saint Vincent, New York, USA
amir.niknejad@mountsaintvincent.edu

MS 16. Preconditioning of non-normal linear systems arising in scattering problems

Talk 1. **Approximate deflation preconditioning methods for penetrable scattering problems**
In this talk I consider the Lippmann-Schwinger (LS) integral equation for inhomogeneous acoustic scattering. I demonstrate

that spectral properties of the LS equations suggest that deflation based preconditioning might be effective in accelerating the convergence of a restarted GMRES method. Much of the convergence results on deflation based preconditioning are based on using exact invariant subspaces. I will present an analytical framework for convergence theory of general approximate deflation that is widely applicable. Furthermore, numerical illustrations of the spectral properties also reveal that a significant portion of the spectrum is approximated well on coarse grids. To exploit this, I develop a novel restarted GMRES method with adaptive preconditioning based on spectral approximations on multiple grids.

Josef Sifuentes
Courant Institute of Mathematical Sciences
New York University
sifuentes@cims.nyu.edu
Mark Embree
Department of Computational and Applied Mathematics
Rice University
embree@rice.edu

Talk 2. **Direct approximate factoring of the inverse**
To precondition a large and sparse linear system, two direct methods for approximate factoring of the inverse are devised. The algorithms are fully parallelizable and appear to be more robust than the iterative methods suggested for the task. A method to compute one of the matrix subspaces optimally is derived. These approaches generalize the approximate inverse preconditioning techniques in several natural ways.

Marko Huhtanen
Department of Electrical and Information Engineering
University of Oulu
Marko.Huhtanen@aalto.fi
Mikko Byckling
CERFACS
Mikko.Byckling@cerfacs.fr

Talk 3. **Regularization of singular integral operators as a preconditioning strategy**
In this talk we consider the singular integral equation arising in electromagnetic scattering on inhomogeneous objects in free space. To understand the apparent poor convergence of iterative methods, such as GMRES, we analyze the spectrum of both the integral operator and the system matrix. It turns out that the convergence is slowed down by dense spectral clusters, whose origin and location may be traced to the nontrivial essential spectrum of the integral operator. We propose a multiplicative regularizer which reduces the extent of these clusters and in conjunction with the deflation of largest-magnitude eigenvalues makes for a good preconditioner.

Neil Budko
Numerical Analysis, Delft Institute of Applied Mathematics
Delft University of Technology
n.v.budko@tudelft.nl
Grigorios Zouros
School of Electrical and Computer Engineering
National Technical University of Athens
zouros@mail.ntua.gr

Talk 4. **High-order shifted Laplace preconditioners for wave equations**
Shifted Laplace preconditioners techniques have been introduced by Erlangga, Vuik and Oosterlee (Applied Numerical Mathematics, 2004) for solving PDEs problems related to wave-like equations. The aim of this talk is to propose a generalization of shifted Laplace preconditioning methods by using operator representation combined with complex Padé approximants. We will show that the resulting high-order shifted Laplace preconditioners are highly efficient and robust for two- and three-dimensional scattering problems that exhibit complex geometrical features (e.g. resonant structures). Furthermore, the convergence is proved to be weakly frequency dependent.

Xavier Antoine
Institut Elie Cartan de Nancy
University of Lorraine
xavier.antoine@iecn.u-nancy.fr
Christophe Geuzaine
Institut Montefiore
University of Liège
cgeuzaine@ulg.ac.be
Ibrahim Zangré
Institut Elie Cartan de Nancy
University of Lorraine
ibrahim.zangre@iecn.u-nancy.fr

MS 17. Markov Chains

Talk 1. **Markov Chain properties in terms of column sums of the transition matrix**
Questions are posed regarding the influence that the column sums of the transition probabilities of a stochastic matrix (with row sums all one) have on the stationary distribution, the mean first passage times and the Kemeny constant of the associated irreducible discrete time Markov chain. Some new relationships, including some inequalities, and partial answers to the questions, are given using a special generalized matrix inverse that has not previously been considered in the literature on Markov chains.

Jeffrey J. Hunter
School of Computing and Mathematical Sciences
Auckland University of Technology, Auckland, New Zealand
jeffrey.hunter@aut.ac.nz

Talk 2. **Hamiltonian cycle problem and Markov chains**
We consider the famous Hamiltonian cycle problem (HCP) embedded in a Markov decision process (MDP). More specifically, we consider the HCP as an optimization problem over the space of either stationary policies, or of occupational measures induced by these stationary policies. This approach has led to a number of alternative formulations and algorithmic approaches involving researchers from a number of countries. These formulations exploit properties of a range of matrices that usually accompany investigations of Markov chains. It will be shown that when these matrices are induced by the given graph some of the graph's underlying structures can be detected in their matrix analytic properties.

Jerzy Filar
School of Computer Science, Engineering and Mathematics
Flinders University, Bedford Park, SA, Australia
jerzy.filar@flinders.edu.au

Talk 3. **Inequalities for functions of transition matrices**
Consider an irreducible finite-state Markov chain on N states. It is known that the N by N matrix vanishing on the diagonal and which is equal to the mean first passage matrix elsewhere, is invertible. We prove that if N is greater than two, the diagonal entries of the inverse are negative, and obtain some related inequalities. Analogous results for a closely related matrix are derived as well. Joint with Michael Neumann and Olga Pryporova.

Iddo Ben-Ari
Department of Mathematics
University of Connecticut, Storrs, CT, United States of America
iddo.ben-ari@uconn.ecdu

Talk 4. **Compartmental systems and computation of their stationary probability vectors**
To compute stationary probability vectors of Markov chains whose transition matrices are cyclic of index p may be a difficult task if p becomes large. A class of iterative aggregation/disaggregation methods (IAD) is proposed to overcome the difficulty. It is shown that the rate of convergence of the proposed IAD processes is governed by the maximal modulus of the eigenvalues laying out of the peripheral spectrum of the smoothing matrix. The examined generators of Markov chains come from compartmental systems and cause that the transition matrices under consideration may depend upon the appropriate stationary probability vectors. The nonlinearity represents further difficulties in computation.

Ivo Marek
School of Civil Engineering
Czech Institute of Technology, Praha, Czech Republic
marek@mbox.ms.mff.cuni.cz

MS 18. Preconditioning for PDE-constrained optimization - Part I of II

Talk 1. **Structural spectral properties of symmetric saddle point problems**
Symmetric and indefinite block structured matrices often arise after the discretization of a large variety of application problems, where the block form stems from the presence of more than one partial differential equation (PDE) in the problem, or from the imposition of some constraints, usually associated with PDEs. Structure-aware preconditioning strategies have emerged as winning devises for efficiently and optimally solving the associated large linear systems. In some relevant applications, the coefficient matrix shows a particular spectral symmetry around the origin, which should be taken into account when selecting both the iterative system solver and the most appropriate preconditioner. In this talk we analyze in detail this symmetry, and discuss its consequences in the solution of three model problems in optimal control, distributed time-harmonic parabolic control and distributed time-harmonic Stokes control.

Valeria Simoncini
Dipartimento di Matematica
Università di Bologna, Italy
valeria.simoncini@unibo.it
Wolfgang Krendl
Doctoral Program Computational Mathematics
Johannes Kepler University, Linz, Austria
wolfgang.krendl@dk-compmath.jku.at
Walter Zulehner
Institute of Computational Mathematics
Johannes Kepler University, 4040 Linz, Austria
zulehner@numa.uni-linz.ac.at

Talk 2. **Preconditioned iterative methods for Stokes and Navier-Stokes control problems**
The development of iterative solvers for PDE-constrained optimization problems is a subject of considerable recent interest in numerical analysis. In this talk, we consider the numerical solution of two such problems, namely those of Stokes control and Navier-Stokes control. We describe the role of saddle point theory, mass matrix and Schur complement approximation, multigrid routines, and commutator arguments, in the construction of solvers for these problems. We also discuss issues involved with regularization terms, and, in the case of Navier-Stokes control, the outer iteration employed. We display numerical results that demonstrate the effectiveness of our solvers.

John Pearson
Mathematical Institute
University of Oxford
john.pearson@maths.ox.ac.uk

Talk 3. **Preconditioners for elliptic optimal control problems with inequality constraints**
In this talk we consider optimal control problems with an elliptic boundary value problem as state equation. Based on recent results for distributed elliptic optimal control problems without inequality constraints we present and discuss preconditioners for the optimality system in the presence of additional control constraints or state constraints. The focus is on the performance of these preconditioners within a Krylov subspace method with respect to model and discretization parameters.
A possible extension of the presented approach to optimal control problems with other state equations, like the steady-state Stokes equations, is discussed.

Walter Zulehner
Institute of Computational Mathematics
Johannes Kepler University, Linz, Austria
zulehner@num.uni-linz.ac.at
Markus Kollmann
Doctoral Program Computational Mathematics
Johannes Kepler University, Linz, Austria
markus.kollmann@dk-compmath.jku.at

Talk 4. **Nearly optimal block preconditioners for block two-by-two linear systems**
For a class of block two-by-two systems of linear equations, we construct block preconditioning matrices and discuss the eigen-properties of the corresponding preconditioned matrices. The block preconditioners can be employed to accelerate the convergence rates of Krylov subspace iteration methods such as MINRES and GMRES. Numerical experiments show that the block preconditioners are feasible and effective when used in solving the block two-by-two linear systems arising from the finite-element discretizations of a class of PDE-constrained optimization problems.

Zhong-Zhi Bai
Institute of Computational Mathematics
Academy of Mathematics and Systems Science
Chinese Academy of Sciences
P. O. Box 2719, Beijing 100190, China
bzz@lsec.cc.ac.cn

MS 19. Matrices and graphs - Part I of II

Talk 1. **(0,1) matrices and the analysis of social networks**
In the sociology literature, an $m \times n$ $(0,1)$ matrix is called an actor–event matrix. In many examples, the matrix A is uniquely determined by AA^T, A^TA, and the fact that A is $(0,1)$. In this talk, we present a result on pairs of actor–event matrices that are distinct but 'close', and yield the same AA^T and A^TA. Specifically, using techniques from combinatorial matrix theory, we characterise all pairs of $(0,1)$ matrices A_1, A_2 such that $A_1A_1^T = A_2A_2^T$, $A_1^TA_1 = A_2^TA_2$, and the $(0,1,-1)$ matrix $A_1 - A_2$ has at most one 1 and one -1 in each row and column.

Steve Kirkland
Hamilton Institute
National University of Ireland Maynooth
stephen.kirkland@nuim.ie

Talk 2. **Necessary and sufficient conditions for a Hamiltonian graph**
A graph is singular if the zero eigenvalue is in the spectrum of its 0-1 adjacency matrix **A**. If an eigenvector belonging to the zero eigenspace of **A** has no zero entries, then the singular graph is said to be a core graph. A (κ, τ)-regular set is a subset of the vertices inducing a κ-regular subgraph such that every vertex not in the subset has τ neighbours in it. We consider the case when $\kappa = \tau$ which relates to the eigenvalue zero under certain conditions. We show that if a regular graph has a (κ, κ)-regular set, then it is a core graph. By considering the walk matrix, we develop an algorithm to extract (κ, κ)-regular sets and formulate a necessary and sufficient condition for a graph to be Hamiltonian.

Irene Sciriha
Dept of Mathematics, Faculty of Science
Univ. of Malta
irene.sciriha-aquilina@um.edu.mt

Domingos Moreira Cardoso
Departamento de Matemtica
Univ. de Aveiro
dcardoso@ua.pt

Talk 3. **On the eigenvalues of symmetric matrices associated with graphs**
Let G be a weighted graph of order n. It is known that $\lambda_1 \geq d_1$ and $\lambda_2 \geq d_3$ where λ_i and d_i are the i^{th} largest Laplacian eigenvalue and degree of G, respectively. For λ_3 and smaller eigenvalues we show that it is possible to construct a weighted graph G of any order n such that $\lambda_j < d_n$.
To obtain these results we show that for every $k \geq 2$ and $n \geq k + 1$ there exists a weighted graph of order n whose adjacency matrix has exactly k negative eigenvalues.
This is done by obtaining some beautiful properties of the Schur complements of the adjacency matrix.

Miriam Farber
Department of Mathematics
Technion
miriamfarber@yahoo.com

Talk 4. **An extension of the polytope of doubly stochastic matrices**
We consider a class of matrices whose row and column sum vectors are majorized by given vectors b and c, and whose entries lie in the interval $[0, 1]$. This class generalizes the class of doubly stochastic matrices. We investigate the corresponding polytope $\Omega(b|c)$ of such matrices. Main results include a generalization of the Birkhoff - von Neumann theorem and a characterization of the faces, including edges, of $\Omega(b|c)$.

Richard A. Brualdi
Department of Mathematics
University of Wisconsin-Madison
brualdi@math.wisc.edu

Geir Dahl
Center of Mathematics for Applications
Departments of Mathematics and Informatics
University of Oslo
geird@math.uio.no

MS 20. Tensor based methods for high dimensional problems in scientific computing - Part I of II

Talk 1. **Optimal a priori Tensor Decomposition for the Solution of High Dimensional Problems**
Tensor-based methods are receiving a growing attention for their use in high dimensional applications in scientific computing where functions of multiple parameters have to be approximated. These methods are based on the construction of tensor decompositions that provide approximate representations of functions on adapted low dimensional reduced bases. Here, we propose algorithms that are able to directly construct an approximation of optimal tensor decompositions with respect to a desired metric, without a priori information on the solution. Connections with optimal model reduction will be discussed.

Anthony Nouy
LUNAM Université, GeM, UMR CNRS 6183, Ecole Centrale de Nantes, Universit de Nantes, FR
anthony.nouy@ec-nantes.fr

Talk 2. **Application of the Proper Generalized Decomposition (PGD) to 3D cracked plates and estimation of the discretization error**
We present a new numerical approach to solve cracked plates in an efficient way by obtaining a single solution in which the Poisson's ratio ν and the plate thickness B are non-fixed parameters. With a single analysis, it is possible to obtain a numerical solution for a cracked plate problem that can be particularized for any ν and B by simple post-processing, thus providing an efficient tool for the numerical analysis of these problems. The method makes use of the Proper Generalized Decomposition (PGD). In this method, the sought displacement field $\mathbf{u}(x, y, z, \nu, B)$ is written as a series expansion of function products. The formulation proposed here uses a 2D discretization for the plane XY and a 1D discretization in the Z-direction. In addition, independent functions of ν and B are included in the tentative solution to be converged. An iterative process is then carried out by which the necessary terms of the series expansion are added in order to attain the required accuracy. We have also implemented a recovery type error estimator to evaluate the discretization error in energy norm both in the XY plane (2D problem) and along the Z-direction (1D problem). The combination of both errors provides the local error distribution that can be used to drive the *h*-adaptive refinement.

Eugenio Giner
Centro Investigación Tecnología de Vehículos - CITV, U. Politècnica València, ES
eginerm@mcm.upv.es

Chady Ghnatios
EADS Chair at École Centrale de Nantes, FR
chady.ghnatios@ec-nantes.fr

Brice Bognet
EADS Chair at École Centrale de Nantes, FR
brice.bognet@ec-nantes.fr

Adrien Leygue
EADS Chair at École Centrale de Nantes, FR
adrien.leygue@ec-nantes.fr

Juan José Ródenas
Centro Investigación Tecnología de Vehículos - CITV, U. Politècnica València, ES
jjrodena@mcm.upv.es

F. Javier Fuenmayor
Centro Investigación Tecnología de Vehículos - CITV, U. Politècnica València, ES
ffuenmay@mcm.upv.es

Francisco Chinesta

EADS Chair at École Centrale de Nantes, FR
francisco.chinesta@ec-nantes.fr

Talk 3. **A tensor calculus approach for Bézier shape deformation**

The goal of our research is to obtain a computationally efficient deformation of a parametric curve. This research is applied to engineering applications as, for example, mobile robotics and liquid composite moulding. A new technique was developed to modify a Bézier curve by minimizing the changes of its shape. This shape modification is computed through a field of vectors, applying them on particular points of the Bézier curve (Bézier Shape Deformation, BSD). In these kinds of applications the computational cost is a critical issue because the parametric curve must be modified in real time. Therefore, the original BSD algorithm has been reformulated using algebra of tensors to reduce the computational time (Tensor-Bézier Shape Deformation, T-BSD). While BSD grows exponentially, T-BSD grows linearly. As a consequence, the Bézier curve is modified with the lowest computational cost.

Lucía Hilario
Departamento de Ciencias Físicas, Matemáticas y de la Computación, Universidad CEU Cardenal Herrera, ES
luciah@uch.ceu.es

Nicolás Montés
Departamento de Ingeniería de la Edificación y Producción Industrial, Universidad CEU Cardenal Herrera ,ES
nicolas.montes@uch.ceu.es

Marta C. Mora
Departamento de Ingeniería Mecánica y Construcción, Universitat Jaume I , ES
mmora@emc.uji.es

Antonio Falcó
Departamento de Economía Financiera y Contabilidad, Universidad de Alicante, ES
Antonio.Falco@ua.es

Talk 4. **Tensor approximation methods for parameter identification**

In this talk we present methods for parameter identification—here the coefficient fields of partial differential equations—based on Bayesian procedures. As is well known, Bayes's theorem for random variables (RVs) of finite variance is an orthogonal projection onto a space of functions generated by the observations. Both the quantity to be identified as well as the space to project onto are described as functions of known RVs. All this takes place in high-dimensional tensor product spaces. To limit the numerical effort, we use low-rank tensor approximations for the forward as well as the inverse problem.

Hermann G. Matthies
Institute of Scientific Computing
TU Braunschweig
wire@tu-bs.de

Alexander Litvinenko
Institute of Scientific Computing
TU Braunschweig
wire@tu-bs.de

Bojana Rosić
Institute of Scientific Computing
TU Braunschweig
wire@tu-bs.de

Oliver Pajonk
Institute of Scientific Computing
TU Braunschweig
wire@tu-bs.de

MS 21. Reducing communication in linear algebra - Part I of II

Talk 1. **Communication-optimal parallel algorithm for Strassen's matrix multiplication**

Parallel matrix multiplication is one of the most studied fundamental problems in distributed and high performance computing. We obtain a new parallel algorithm that is based on Strassen's fast matrix multiplication and minimizes communication. The algorithm outperforms all other parallel matrix multiplication algorithms, classical and Strassen-based, both asymptotically and in practice.

A critical bottleneck in parallelization of Strassen's algorithm is the communication between the processors. Ballard, Demmel, Holtz, and Schwartz (SPAA'11) provide lower bounds on these communication costs, using expansion properties of the underlying computation graph. Our algorithm matches these lower bounds, and so is communication-optimal. It has perfect strong scaling within the maximum possible range. Our parallelization approach generalizes to other fast matrix multiplication algorithms.

Oded Schwartz
Computer Science Division
UC Berkeley
odedsc@eecs.berkeley.edu

Grey Ballard
Computer Science Division
UC Berkeley
ballard@cs.berkeley.edu

James Demmel
Computer Science Division
UC Berkeley
demmel@cs.berkeley.edu

Olga Holtz
Math Department
UC Berkeley and TU Berlin
oholtz@eecs.berkeley.edu

Benjamin Lipshitz
Computer Science Division
UC Berkeley
lipshitz@berkeley.edu

Talk 2. **A communication-avoiding symmetric-indefinite factorization**

We describe a communication-avoiding symmetric indefinite factorization. The factorization works in two phases. In the first phase, we factor $A = LTL^T$ where L is unit lower triangular and T is banded with bandwidth $\Theta(\sqrt{M})$ where M is the size of the cache. This phase uses a block version of Aasen's algorithm. In the second phase, we factor T; this can be done efficiently using Kaufman's retraction algorithm, or LU with partial pivoting, or successive band reduction. We show that the algorithm is asymptotically optimal in terms of communication, is work efficient ($n^3/3 + o(n^3)$ flops), and is backward stable.

Sivan Toledo
School of Computer Science
Tel-Aviv University
stoledo@tau.ac.il

Grey Ballard
Computer Science Division
UC Berkeley
ballard@cs.berkeley.edu

James Demmel
Computer Science Division
UC Berkeley
demmel@cs.berkeley.edu

Alex Druinsky
School of Computer Science
Tel-Aviv University
alexdrui@post.tau.ac.il
Inon Peled
School of Computer Science
Tel-Aviv University
inon.peled@gmail.com
Oded Schwartz
Computer Science Division
UC Berkeley
odedsc@eecs.berkeley.edu

Talk 3. **LU factorisation with panel rank revealing pivoting and its communication avoiding version**
We present the LU decomposition with panel rank revealing pivoting (LU_PRRP), an LU factorization algorithm based on strong rank revealing QR panel factorization. LU_PRRP is more stable than Gaussian elimination with partial pivoting (GEPP). Our extensive numerical experiments show that the new factorization scheme is as numerically stable as GEPP in practice, but it is more resistant to pathological cases and easily solves the Wilkinson matrix and the Foster matrix.
We also present CALU_PRRP, a communication avoiding version of LU_PRRP that minimizes communication. CALU_PRRP is more stable than CALU, the communication avoiding version of GEPP.

Amal Khabou
Laboratoire de Recherche en Informatique Universite Paris-Sud 11,
INRIA Saclay- Ile de France
amal.khabou@inria.fr
James W. Demmel
Computer Science Division and Mathematics Department, UC Berkeley,
CA 94720-1776, USA
demmel@cs.berkeley.edu
Laura Grigori
INRIA Saclay - Ile de France, Laboratoire e Recherche en Informatique
Universite Paris-Sud 11, France
laura.grigori@inria.fr
Ming Gu
Mathematics Department, UC Berkeley, CA 94720-1776, USA
mgu@math.berkeley.edu

Talk 4. **2.5D algorithms for parallel dense linear algebra**
We give a '2.5D' parallelization scheme for dense linear algebra computations. Our scheme exploits any extra available memory adaptively. The scheme generalizes previous work on 2D and 3D algorithms in matrix multiplication. Further, we extend 2.5D algorithms to LU, Cholesky, and Cholesky-QR factorizations, triangular solve, and the all-pairs-shortest-path problem. These new algorithms perform asymptotically less communication than any previous counterparts. 2.5D algorithms are also practical and map well to torus networks. We benchmark 2.5D matrix multiplication and LU factorization on 65,536 cores of a Blue Gene/P supercomputer. Our results demonstrate that memory replication improves strong scalability and overall efficiency significantly.

Edgar Solomonik
Dept. of Compiter Science
University of California, Berkeley
solomon@cs.berkeley.edu
James Demmel
Dept. of Compiter Science and Mathematics
University of California, Berkeley
demmel@cs.berkeley.edu

MS 22. Linear algebra for inverse problems - Part I of II

Talk 1. **Block-extrapolation methods for linear matrix ill-posed problems**
In this talk, we consider large-scale linear discrete ill-posed problems where the right-hand side contains noise. In many applications such as in image restoration the coefficient matrix is given as a sum of Kronecker products of matrices and then Tikhonov regularization problem leads to a generalized linear matrix equation. We define some block extrapolation methods and show how they could be used in combination with the singular value decomposition (SVD) to solve these problems. In particular, the proposed methods will be applied in image restoration. Some theoretical results and numerical tests in image restoration are also given.

Khalide Jbilou
LMPA, Université du Littoral,
50, rue F. Buisson, BP 699,
62228 CALAIS-Cedex, FRANCE
jbilou@lmpa.univ-littoral.fr

Talk 2. **Convergence properties of GMRES and RRGMES method for ill posed problems**
Range restricted iterative methods (RRGMRES) based on the Arnoldi process are attractive for the solution of large nonsymmetric linear discrete ill-posed problems with error-contaminated data (right-hand side).
GMRES is one of the most widely used iterative methods for the solution of linear system of equations, with a large real or complex nonsingular matrix. Convergence properties of GMRES are discussed by many authors.
We present some theoretical results for GMRES and RRGMRES and we give some numerical tests.

Hassane Sadok
LMPA, Université du Littoral,
50, rue F. Buisson, BP 699,
62228 CALAIS-Cedex, FRANCE
sadok@lmpa.univ-littoral.fr
Lothar Reichel
Department of Mathematical Sciences
Kent State University
reichel@math.kent.edu

Talk 3. **Inverse problems for regularization matrices**
Discrete ill-posed problems are difficult to solve, because their solution is very sensitive to errors in the data and to round-off errors introduced during the solution process. Tikhonov regularization replaces the given discrete ill-posed problem by a nearby penalized least-squares problem whose solution is less sensitive to perturbations. The penalization term is defined by a regularization matrix, whose choice may affect the quality of the computed solution significantly. We describe several inverse matrix problems whose solution yields regularization matrices adapted to the desired solution. Numerical examples illustrate the performance of the regularization matrices determined.

Silvia Noschese
Dipartimento di Matematica "Guido Castelnuovo"
SAPIENZA Università di Roma
noschese@mat.uniroma1.it
Lothar Reichel
Department of Mathematical Sciences
Kent State University
reichel@math.kent.edu

Talk 4. **Meshless regularization for the numerical**

computation of the solution of steady Burgers-type equations

In this talk, we introduce a meshless method approximation for the numerical solution of the Burgers-type steady equations. The numerical approximation to the exact solution is obtained from the exact values of the analytical solution on a finite set of scattered data points in the interior of the domain. The exact values are in fact unkown and contamained by a noise. Regularization techniques are needed to obtain the numerical approximation as the smoothing thin plate splines. This strategy leads to a nonlinear system which may be solved by using the Tikhonov regularization method. The estimation of the regularization parameter is obtained by using the classical GCV or the L-curve criteria. We present some theoretical results and we give some numerical tests.

Abderrahman Bouhamidi
LMPA, Université du Littoral,
50, rue F. Buisson, BP 699,
62228 CALAIS-Cedex, FRANCE
bouhamidi@lmpa.univ-littoral.fr

Mustapha Hached
LMPA, Université du Littoral,
50, rue F. Buisson, BP 699,
62228 CALAIS-Cedex, FRANCE
hached@lmpa.univ-littoral.fr

Khalide Jbilou
LMPA, Université du Littoral,
50, rue F. Buisson, BP 699,
62228 CALAIS-Cedex, FRANCE
jbilou@lmpa.univ-littoral.fr

MS 23. Modern matrix methods for large scale data and networks

Talk 1. **Nonlinear eigenproblems in data analysis and graph partitioning**
It turns out that many problems in data analysis and beyond have natural formulations as nonlinear eigenproblems. In this talk I present our recent line of research in this area. This incluces the efficient computation of nonlinear eigenvectors via a generalization of the inverse power method and a general result showing that a certain class of NP-hard combinatorial problems such as balanced graph cuts or the (constrained) maximum density subgraph have tight relaxations as nonlinear eigenproblems.

Matthias Hein
Faculty of Mathematics and Computer Science
Saarland University
hein@cs.uni-sb.de

Talk 2. **LSRN: a parallel iterative solver for strongly over- or under-determined systems**
We develop a parallel iterative least squares solver named LSRN that is based on random normal projection. It computes the unique minimum-length solution to $\min_{x\in\mathbb{R}^n} \|Ax-b\|_2$, where $A \in \mathbb{R}^{m\times n}$ can be rank-deficient with $m \gg n$ or $m \ll n$. A can be a dense matrix, a sparse matrix, or a linear operator, and LSRN speeds up automatically on sparse matrices and fast operators. The preconditioning phase consists of a random normal projection, which is embarrassingly parallel, and a singular value decomposition of size $\lceil \gamma \min(m,n) \rceil \times \min(m,n)$, where γ is moderately larger than 1, e.g., $\gamma = 2$. We show that the preconditioned system is well-conditioned with a strong concentration result on the extreme singular values. Hence the number of iterations is fully predictable if we apply LSQR or the Chebyshev semi-iterative method to the preconditioned system. The latter method is particularly efficient for solving large-scale problems on clusters with high communication cost. LSRN is also capable of handling certain types of Tikhonov regularization. Numerical results show that LSRN outperforms LAPACK's DGELSD on large-scale dense problems and MATLAB's backslash (SuiteSparseQR) on sparse problems on a shared memory machine, and LSRN scales well on Amazon Elastic Compute Cloud (EC2) clusters.

Xiangrui Meng
Institute for Computational and Mathematical Engineering
Stanford University
mengxr@stanford.edu

M. A. Saunders
Institute for Computational and Mathematical Engineering
Stanford University
saunders@stanford.edu

M. W. Mahoney
Stanford University
mmahoney@cs.stanford.edu

Talk 3. **Solving large dense linear systems with covariance matrices**
Gaussian processes are a fundamental tool in spatial/temporal statistics, and they have broad applications to fields such as nuclear engineering and climate science. The maximum likelihood approach for fitting a Gaussian model requires the manipulation of the covariance matrix through inversion, logarithmic action and trace computation, all of which pose significant challenges for large dense matrices. We consider a reformulation of the maximum likelihood through a stochastic approximation framework, which narrows down the several linear algebra challenges to solving a linear system with the covariance matrix for multiple right-hand sides. In this talk I will present an iterative technique integrating the designs of the solver, the preconditioner and the matrix-vector multiplications, which lead to a scalable method for solving the maximum likelihood problem in data analysis.

Jie Chen
Mathematics and Computer Science Division
Argonne National Laboratory
jiechen@mcs.anl.gov

Talk 4. **Fast coordinate descent methods with variable selection for non-negative matrix factorization**
Non-negative Matrix Factorization (NMF) is a dimension reduction method for non-negative matrices, and has proven to be useful in many areas, such as text mining, bioinformatics and image processing. In this talk, I will present a new coordinate descent algorithm for solving the least squares NMF problem. The algorithm uses a variable selection scheme that employs the gradient of the objective function. This new method is considerably faster in practice, especially when the solution is sparse, as is often the case in real applications. In these cases, our method benefits by selecting important variables to update more often, thus resulting in higher speed. As an example, on a text dataset RCV1, our method is 7 times faster than FastHals, which is a cyclic coordinate descent algorithm, and more than 15 times faster when the sparsity is increased by adding an L1 penalty. We also develop new coordinate descent methods when error in NMF is measured by KL- divergence by applying the Newton method to solve the one-variable sub-problems.

Experiments indicate that our algorithm for minimizing the KL-divergence is faster than the Lee & Seung multiplicative rule by a factor of 10 on the CBCL image dataset.

Inderjit S. Dhillon
Department of Computer Science
The University of Texas at Austin
inderjit@cs.utexas.edu
Cho-Jui Hsieh
Department of Computer Science
The University of Texas at Austin
cjhsieh@cs.utexas.edu

MS 24. Novel and synergetic algorithms for multicore and multinode architecture

Talk 1. **Novel and synergetic linear algebra algorithms on multicore and multinode architecture**
The advent of parallel computers from multiple CPUs to, more recently, multiple processor cores within a single CPU has continued to spur innovative linear algebra algorithms. This minisymposium aims to present a number of works that not only exhibit new algorithmic ideas suitable for these modern computer architectures, but also present interesting synergies among themselves in several levels. This talk gives an overview on how a set of such algorithms work together and sets the stage for the details to follow in each of the subsequent presentations.

Ping Tak Peter Tang
Intel Corporation
Peter.Tang@intel.com

Talk 2. **Towards hybrid factorization methods for solving large sparse systems**
The availability of large-scale computing platforms comprised of thousands of multicore processors motivates the need for highly scalable sparse linear system solvers. In this talk I will review some recent work by researchers at Purdue University, University of Lugano, and Intel Corporation on the combined use of direct and iterative methods for solving very large linear systems of equations. We will present recent progress in the area of parallel direct solvers and present a new parallel solver that combines the desirable characteristics of direct methods (robustness) and iterative solvers (computational efficiency), while alleviating their drawbacks (high memory requirements, lack of robustness).

Olaf Schenk
Institute of Computational Science
University of Lugano
olaf.schenk@usi.ch
Ahmed Sameh
Dept. of Computer Science
Purdue University
sameh@cs.purdue.edu

Talk 3. **Eigensolver-based reordering and parallel traceMIN**
The eigenvector corresponding to the second smallest eigenvalue of the Laplacian of a graph, known as the Fiedler vector, has a number of applications in areas that include matrix reordering, graph partitioning, protein analysis, data mining, machine learning, and web search. The computation of the Fiedler vector has been regarded as an expensive process as it involves solving a large eigenvalue problem. We present an efficient parallel algorithm for computing the Fiedler vector of large graphs based on the Trace Minimization algorithm. We compare the parallel performance of our method against one of the best implementations of a sequential multilevel scheme, designed specifically for computing the Fiedler vector – routine MC73 of the Harwell Subroutine Library (HSL). In addition, we present results showing how such reordering: (i) enhances data locality for sparse matrix-vector multiplication on parallel architectures, as well as (ii) helps in extracting effective and scalable preconditioners.

Murat Manguoğlu
Department of Computer Engineering
Middle East Technical University, 06800 Ankara, Turkey
manguoglu@ceng.metu.edu.tr
Faisal Saied
Department of Computer Science
Purdue University, West Lafayette, 47906 IN, USA
fsaied@purdue.edu, sameh@cs.purdue.edu
Ahmed H. Sameh
Department of Computer Science
Purdue University, West Lafayette, 47906 IN, USA
fsaied@purdue.edu, sameh@cs.purdue.edu

Talk 4. **FEAST a density matrix based eigensolver**
The FEAST algorithm takes its inspiration from the density matrix representation and contour integration technique in quantum mechanics. It combines simplicity and efficiency and offers many important capabilities for achieving high performance, robustness, accuracy, and scalability for solving large sparse eigenvalue problems on parallel architectures. Starting from a random set of vectors, FEAST's main computational tasks consist of solving a few complex-valued independent linear systems with multiple right-hand sides, and one reduced eigenvalue problem orders of magnitude smaller than the original one. Accuracy can be systematically improved through an iterative process that usually converges in two to three iterations. In this talk, FEAST will first be presented as an outer-layer interface to any linear system solvers either shared-memory or distributed such as PSPIKE. In addition, it will be shown that a single FEAST iteration provides the best suitable eigen-subspace which can be used for initiating the TraceMIN algorithm.

Eric Polizzi
Department of Electrical and Computer Engineering
University of Massachusetts, Amherst, USA
polizzi@ecs.umass.edu

MS 25. Direction preserving and filtering methods for solving sparse linear systems

Talk 1. **Algebraic two-level domain decomposition methods**
We consider the solving of linear systems arising from porous media flow simulations with high heterogeneities. The parallel solver is a Schwarz domain decomposition method. The unknowns are partitioned with a criterion based on the entries of the input matrix. This leads to substantial gains compared to a partition based only on the adjacency graph of the matrix. From the information generated during the solving of the first linear system, it is possible to build a coarse space for a two-level domain decomposition algorithm. We compare two coarse spaces: a classical approach and a new one adapted to parallel implementation.

Frédéric Nataf
Laboratory J.L. Lions
University of Paris 6
nataf@ann.jussieu.fr
Pascal Havé
IFP

Rueil Malmaison
pascal.have@ifpen.fr
Roland Masson
Laboratoire J.A. Dieudonné
University of Nice
roland.masson@unice.fr
Mikolaj Szydlarski
INRIA
France
mikolaj.szydlarski@inria.fr
Tao Zhao
Laboratory J.L. Lions
University of Paris 6
zhaot.cn@gmail.com

Talk 2. **Filtering solvers**
In this talk, we give an overview on filtering solvers. This comprises frequency filtering and the smoothing correction scheme, the tangential frequency filtering (TFFD) by Wagner, the two frequency decomposition by Buzdin et al. We then discuss the adaptive filtering method. The adaptive test vector iterative method allows the combination of the tangential frequency decomposition and other iterative methods such as multi-grid. We further discuss the Filtering Algebraic Multigrid (FAMG) method. Interface problems as well as problems with stochastically distributed properties are considered. Realistic numerical experiments confirm the efficiency of the presented algorithms.

Gabriel Wittum
G-CSC, Frankfurt
wittum@techsim.org

Talk 3. **Bootstrap algebraic multigrid**
By the time of its development Algebraic Multigrid (AMG) was thought of as a black box solver for systems of linear equations. Yet, the classical formulation of AMG turned out to lack the robustness to overcome challenges encountered in many of today's computational simulations which lead to the development of adaptive techniques in AMG methods.
We present in this talk a Bootstrap approach to adaptive AMG introducing the so-called "Least Squares Interpolation" (LSI) which allows to define interpolation operators solely based on prototypes of algebraically smooth error. Furthermore, we introduce a "Bootstrap Setup" which enables us to compute accurate LSI operators using a multigrid approach in the setup to efficiently compute the required prototypes of algebraically smooth error.
We demonstrate the potential of the Bootstrap AMG approach in the application to a variety of problems, each illustrating a certain aspect of the method.

Karsten Kahl
Dept. of Mathematics and Natural Sciences
University of Wuppertal
kkahl@math.uni-wuppertal.de
James Brannick
Dept. of Mathematics
Pennsylvania State University
brannick@psu.edu

Talk 4. **Block filtering decomposition**
We describe a preconditioning technique that is suitable for matrices arising from the discretization of a system of PDEs on unstructured grids. The preconditioner satisfies a filtering property, which ensures that the input matrix is identical with the preconditioner on a given filtering vector. This vector is chosen to alleviate the effect of low frequency modes on convergence. We present a general approach that allows to ensure that the filtering condition is satisfied in a matrix decomposition. The input matrix can have an arbitrary sparse structure, and can be reordered using nested dissection to allow a parallel implementation.

Laura Grigori
INRIA Saclay
University of Paris 11, France
Laura.Grigori@inria.fr
Frédéric Nataf
Dept. of Applied Mathematics
University of Paris 6, France
nataf@ann.jussieu.fr
Riadh Fezzanni
INRIA Saclay
University of Paris 11, France
riadh.fezzani@inria.fr

MS 26. Advances in Krylov subspace methods

Talk 1. **The new challenges to Krylov subspace methods**
Solution methods based on preconditioned Krylov subspace methods have reached a certain level of maturity and research in this area is now mostly concerned with issues related to preconditioning. This state of equilibrium is currently being challenged by the emerging computational architectures. For example, general purpose GPUs put a high cost on inner products on which Krylov methods rely heavily. At the same time the many-core environment will make standard Krylov method unreliable due to the potentially high number of possible hardware failures when tens or hundreds of thousands of cores are deployed. In this talk we will explore these challenges and see what options are available to face them.

Yousef Saad
Dept. of Computer Science and Engineering
University of Minnesota, Twin Cities, US
saad@cs.umn.edu

Talk 2. **Random shadow vectors in IDR(s): an explanation of its GMRES-like convergence**
The IDR(s) method [Sonneveld and van Gijzen, SISC 31, 1035-1062 (2008)], is a family of short-term recurrent Krylov subspace solvers for large sparse, not necessarily symmetric linear systems. For increasing s, the convergence behaviour shows an increasing similarity with full GMRES. The residuals of IDR(s) are, roughly speaking, orthogonalized with respect to s shadow vectors. Usually these are randomly chosen. Each iteration step can be related to a Galerkin approximation in a corresponding Krylov subspace. In this talk we describe why the quality of this Galerkin approximation comes close to the optimal (GMRES), if s is large enough.

Peter Sonneveld
Delft Institute of Applied Mathematics
Delft University of Technology, NL
p.sonneveld@tudelft.nl

Talk 3. **Truncated and inexact Krylov subspace methods for parabolic control problems**
We study the use of inexact and truncated Krylov subspace methods for the solution of linear systems arising in the discretized solution of optimal control of a parabolic partial differential equation. An all-at-once temporal discretization and a reduced Hessian approach are used. The solutions of the two linear systems involved in this reduced Hessian can be approximated, and in fact they can be less and less exact as the

iterations progress. The option we propose is the use of the parareal-in-time algorithm for approximating the solution of these two linear systems. Truncated methods can be used without much delay in convergence, but with important savings in storage. Spectral bounds are provided and numerical experiments are presented, illustrating the potential of the proposed methods.

Daniel B. Szyld
Dept. of Mathematics
Temple University, US
szyld@temple.edu
Xiuhong Du
Dept. of Mathematics
Alfred University, US
du@alfred.edu
Marcus Sarkis
Dept. of Mathematics
Worcester Polytechnic Institute, US
msarkis@wpi.edu
Christian E. Schaerer
Dept. of Computer Science
National University of Asuncion, PY
cschaer@pol.una.py

Talk 4. **Convergence of iterative solution algorithms for least-squares problems**
We consider the iterative solution of linear least-squares problems. We ask the following questions: which quantities should be used to monitor convergence, and how can these quantities be estimated at every iteration of commonly used algorithms? We argue that the backward error, appropriately scaled, is an excellent measure of convergence. We show how certain projections of the residual vector can be used to bound or estimate it. We present theoretical results and numerical experiments on the convergence of the backward error and its estimates in the algorithms LSQR of Paige and Saunders and LSMR of Fong and Saunders.

David Titley-Peloquin
Mathematical Institute
University of Oxford, UK
David.Titley-Peloquin@maths.ox.ac.uk
Serge Gratton
ENSEEIHT, FR
serge.gratton@enseeiht.fr
Pavel Jiranek
CERFACS, FR
pavel.jiranek@gmail.com

MS 27. Preconditioning for PDE-constrained optimization - Part II of II

Talk 1. **On linear systems arising in Trust-region methods**
Trust-region methods are widely used for the numerical solution of nonlinear constrained and unconstrained optimization problems. Similar as line-search methods, they take turns in minimizing local models of the objective. In contrast to line-search methods, however, trust-region approaches do not require nor promote the positive definiteness of the local Hessian approximations.
In this presentation, we address issues arising in the context of the preconditioned approximate solution of these local models. The talk will highlight connections between algorithmic optimization and linear algebra.

Susann Mach
Dept. of Mathematics
University of Technology Chemnitz
susann.mach@mathematik.tu-chemnitz.de
Roland Herzog
Dept. of Mathematics
University of Technology Chemnitz
roland.herzog@mathematik.tu-chemnitz.de

Talk 2. **Preconditioning for PDE-constrained optimization using proper orthogonal decomposition**
The main effort of solving a PDE constrained optimization problem is devoted to solving the corresponding large scale linear system, which is usually sparse and ill conditioned. As a result, a suitable Krylov subspace solver is favourable, if a proper preconditioner is embedded.Other than the commonly used block preconditioners, we exploit knowledge of proper orthogonal decomposition (POD) for preconditioning and achieve some interesting features. Numerical results on nonlinear test problems are proposed.

Ekkehard Sachs
Department of Mathematics University of Trier 54286 Trier, Germany
sachs@uni-trier.de
Xuancan Ye
Department of Mathematics University of Trier 54286 Trier, Germany
yexuancan@uni-trier.de

Talk 3. **Preconditioning for Allen-Cahn variational inequalities with non-local constraints**
The solution of Allen-Cahn variational inequalities with mass constraints is of interest in many applications. This problem can be solved in its scalar and vector-valued form as a PDE-constrained optimization problem. At the heart of this method lies the solution of linear systems in saddle point form. In this talk we propose the use of Krylov-subspace solvers and suitable preconditioners for the saddle point systems. Numerical results illustrate the competitiveness of this approach.

Luise Blank
Dept. of Mathematics
University of Regensburg
Germany
luise.blank@mathematik.uni-r.de
Martin Stoll
Max Planck Institute for Dynamics of Complex Technical Systems
Magdeburg, Germany
stollm@mpi-magdeburg.mpg.de
Lavinia Sarbu

Talk 4. **A one-shot approach to time-dependent PDE control**
In this talk, we motivate, derive and test effective preconditioners to be used with the MINRES algorithm for solving a number of saddle point systems, which arise in PDE constrained optimization problems. We consider the distributed control and boundary control problems subject to partial differential equations such as the heat equation or Stokes equations. Crucial to the effectiveness of our preconditioners in each case is an effective approximation of the Schur complement of the matrix system. In each case, we state the problem being solved, propose the preconditioning approach, and provide numerical results which demonstrate that our solvers are effective for a wide range of regularization parameter values, as well as mesh sizes and time-steps.

Martin Stoll
Computational Methods in Systems and Control Theory
Max Planck Institute for Dynamics of Complex Technical Systems
Sandtorstr. 1, 39106 Magdeburg Germany

stollm@mpi-magdeburg.mpg.de
Andy Wathen
Numerical Analysis Group
Mathematical Institute, 24–29 St Giles', Oxford, OX1 3LB, United Kingdom
wathen@maths.ox.ac.uk
John Pearson
Numerical Analysis Group
Mathematical Institute, 24–29 St Giles', Oxford, OX1 3LB, United Kingdom
pearson@maths.ox.ac.uk

MS 28. Matrices and graphs - Part II of II

Talk 1. **Parameters related to maximum nullity, zero forcing number, and tree-width of a graph**
Tree-width, and variants that restrict the allowable tree decompositions, play an important role in the study of graph algorithms and have application to computer science. The zero forcing number is used to study the maximum nullity/minimum rank of the family of symmetric matrices described by a graph. Relationships between these parameters and several Colin de Verdière type parameters, and numerous variations (including the minor monotone floors and ceilings of some of these parameters) are discussed.

Leslie Hogben
Department of Mathematics
Iowa State University
hogben@aimath.org
Francesco Barioli
Department of Mathematics
University of Tennessee at Chattanooga
francesco-barioli@utc.edu
Wayne Barrett
Department of Mathematics
Brigham Young University
wayne@math.byu.edu
Shaun M. Fallat
Department of Mathematics and Statistics
University of Regina
sfallat@math.uregina.ca
H. Tracy Hall
Department of Mathematics
Brigham Young University
H.Tracy@gmail.com
Bryan Shader
Department of Mathematics
University of Wyoming
bshader@uwyo.edu
P. van den Driessche
Department of Mathematics and Statistics
University of Victoria
pvdd@math.uvic.ca
Hein van der Holst
Department of Mathematics and Statistics
Georgia State University
hvanderholst@gsu.edu

Talk 2. **Colin de Verdière numbers of chordal and split graphs**

I will discuss the Colin de Verdière number of a chordal graph, showing that it always takes one of two possible values. For the important subcase of split graphs, I will present a complete distinction between the two cases. Finally, I will show how to deduce from the result on chordal graphs an improvement of factor 2 to Colin de Verdière's well-known tree-width upper bound for the eponymous number. This work was done while the author was at Technion.

Felix Goldberg
Hamilton Institute
National University of Ireland Maynooth
felix.goldberg@gmail.com
Abraham Berman
Department of Mathematics
Technion
berman@techunix.technion.ac.il

Talk 3. **Kochen-Specker sets and the rank-1 quantum chromatic number**
The quantum chromatic number of a graph G is sandwiched between its chromatic number and its clique number, which are well known NP-hard quantities. We restrict our attention to the rank-1 quantum chromatic number $\chi_q^{(1)}(G)$, which upper bounds the quantum chromatic number, but is defined under stronger constraints. We study its relation with the chromatic number $\chi(G)$ and the minimum dimension of orthogonal representations $\xi(G)$. It is known that $\xi(G) \leq \chi_q^{(1)}(G) \leq \chi(G)$. We answer three open questions about these relations: we give a necessary and sufficient condition to have $\xi(G) = \chi_q^{(1)}(G)$, we exhibit a class of graphs such that $\xi(G) < \chi_q^{(1)}(G)$, and we give a necessary and sufficient condition to have $\chi_q^{(1)}(G) < \chi(G)$. Our main tools are Kochen-Specker sets, collections of vectors with a traditionally important role in the study of noncontextuality of physical theories, and more recently in the quantification of quantum zero-error capacities. Finally, as a corollary of our results and a result by Avis, Hasegawa, Kikuchi, and Sasaki on the quantum chromatic number, we give a family of Kochen-Specker sets of growing dimension.

Simone Severini
Department of Computer Science and Department of Physics & Astronomy, University College London
simoseve@gmail.com
Giannicola Scarpa
Centrum Wiskunde & Informatica (CWI)
g.scarpa@cwi.nl

Talk 4. **On the null vectors of graphs**
Eigenvalues and eigenvectors associated with graphs have been important areas of research for many years. My plan for this talk it to revisit a basic, yet important, result by Fiedler on the inertia of acyclic matrices and discuss its impact on some previous related work and highlight some interesting new implications on certain null vectors associated with a graph.

Shaun M. Fallat
Department of Mathematics and Statistics
University of Regina
sfallat@math.uregina.ca

MS 29. Tensor based methods for high dimensional problems in scientific computing - Part II of II

Talk 1. **A greedy algorithm for the convergence of a Laplacian operators in the blind deconvolution problem**
In this talk we present new results on the a greedy algorithm to study the convergence of the Fractional Blind Deconvolution in a Hilbert Space. We will show the theoretical results and the application to the artistic Restoration.

Pantaleón David Romero Sánchez
Departamento de Ciencias Físicas, Matemáticas y de la Computación

Universidad CEU-Cardenal Herrera
pantaleon.romero@uch.ceu.es
Vicente F. Candela
Departamento de Matemática Aplicada
Universidad de Valencia
candela@uv.es

Talk 2. **Algorithms for approximate inverse of operators for preconditioning systems of equations in tensor tormat**
We here propose and analyze greedy algorithms for the approximation of the inverse of an operator in tensor format. Algorithms are based on successive best approximations with respect to non usual norms that makes possible the decomposition of the inverse operator without any a priori information. This approximate inverse is then used for preconditioning iterative solvers and PGD algorithms for the solution of high dimensional PDEs in tensor format. The efficiency of the proposed preconditioner is illustrated on numerical examples, where it is compared to other preconditioners.

Loic Giraldi
LUNAM Université, GeM, UMR CNRS 6183, Ecole Centrale de Nantes, Université de Nantes, FR
loic.giraldi@ec-nantes.fr
Anthony Nouy
LUNAM Université, GeM, UMR CNRS 6183, Ecole Centrale de Nantes, Université de Nantes, FR
anthony.nouy@ec-nantes.fr
Gregory Legrain
LUNAM Université, GeM, UMR CNRS 6183, Ecole Centrale de Nantes, Université de Nantes, FR
gregory.legrain@ec-nantes.fr

Talk 3. **Geometric structures in tensor representations**
In this talk we discuss about the geometric structures associated with tensor representations based in subspaces. We introduce a generalization of the hierarchical Tucker format. Then we give a Banach manifold structure to the set of tensors in generalized hierarchical Tucker format with fixed hierarchical rank. It allows to extend the dynamical low-rank tensor approximation framework to tensor Banach spaces.

Antonio Falcó
Dept. de Economía Financiera y Contabilidad
Universidad de Alicante, ES
antonio.falco@ua.es
Wolfgang Hackbusch
Max-Planck-Institut *Mathematik in den Naturwissenschaften*
Leipzig, DE
wh@mis.mpg.de
Anthony Nouy
LUNAM Université, GeM, UMR CNRS 6183, Ecole Centrale de Nantes, Université de Nantes, FR
anthony.nouy@ec-nantes.fr

MS 30. Reducing communication in linear algebra - Part II of II

Talk 1. **Communication-avoiding sparse matrix-matrix multiplication**
Sparse matrix-matrix multiplication is a key primitive for many high performance graph algorithms as well as some linear solvers, such as algebraic multigrid. There is a significant gap between communication costs of existing algorithms and known lower bounds. We present new 1D and 2.5D algorithms that perform less communication than existing algorithms. These algorithms have different memory requirements, and they scale differently with increasing matrix density and processor count. We also report on our performance results on large-scale experiments and our recent progress in obtaining tighter lower bounds.

Aydın Buluç
Computational Research Division
Lawrence Berkeley National Laboratory
abuluc@lbl.gov
Grey Ballard
Computer Science Division
UC Berkeley
ballard@cs.berkeley.edu
James Demmel
Computer Science Division
UC Berkeley
demmel@cs.berkeley.edu
Laura Grigori
INRIA Saclay - Ile de France, Laboratoire e Recherche en Informatique
Universite Paris-Sud 11, France
laura.grigori@inria.fr
Oded Schwartz
Computer Science Division
UC Berkeley
odedsc@eecs.berkeley.edu

Talk 2. **Improving the stability of communication-avoiding Krylov subspace methods**
Krylov Subspace Methods (KSMs) are commonly used for solving linear systems, eigenvalue problems, and singular value problems. Standard KSMs are communication-bound on modern computer architectures, due to required sparse matrix-vector multiplication and projection operations in each iteration. This motivated s-step KSMs, which can use blocking strategies to increase temporal locality, allowing an $O(s)$ reduction in communication cost. Despite attractive performance benefits, these variants are often considered impractical, as increased error in finite precision can negatively affect stability. We discuss practical techniques for alleviating these problems in s-step methods while still achieving an asymptotic reduction in communication cost.

Erin Carson
Dept. of Computer Science
University of California, Berkeley
ecc2z@eecs.berkeley.edu
Nicholas Knight
Dept. of Computer Science
University of California, Berkeley
knight@cs.berkeley.edu
James Demmel
Dept. of Computer Science, Mathematics
University of California, Berkeley
demmel@cs.berkeley.edu

Talk 3. **Hiding global synchronization latencies in Krylov methods for systems of linear equations**
In Krylov methods, global synchronization due to reduction operations for dot-products is becoming a bottleneck on parallel machines. We adapt GMRES and CG such that this global communication latency is completely overlapped by other local work. This requires the global communication to be performed in a non-blocking or asynchronous way. To maintain stability even at the strong scaling limit, different Krylov bases, like Newton and Chebychev bases, can be used. Our performance model predicts large benefits for future exascale machines as well as for current-scale applications such as solving the coarsest level of a multigrid hierarchy in parallel.

Pieter Ghysels
Dept. of Math and Computer Science
University of Antwerp, BE
pieter.ghysels@ua.ac.be
Wim Vanroose
Dept. of Math and Computer Science
University of Antwerp, BE
pieter.ghysels@ua.ac.be

Talk 4. **Avoiding communication with hierarchical matrices**
We show how to reorganize the construction of a Krylov basis $[x, Ax, \ldots, A^s x]$ to asymptotically reduce data movement, when A is a hierarchical matrix. Our approach extends the blocking covers algorithm of Leiserson, Rao, and Toledo, and requires that off-diagonal blocks of A are low-rank. This approach enables communication-avoiding s-step Krylov subspace methods with hierarchical preconditioners. We also discuss extensions to multigrid and fast multipole methods.

Nick Knight
Dept. of Electrical Engineering and Computer Science
University of California, Berkeley
knight@cs.berkeley.edu
Erin Carson
Dept. of Electrical Engineering and Computer Science
University of California, Berkeley
ecc2z@cs.berkeley.edu
James Demmel
Dept. of Electrical Engineering and Computer Science
University of California, Berkeley
demmel@cs.berkeley.edu

MS 31. Linear algebra for inverse problems - Part II of II

Talk 1. **Implicit filtering methods for inverse problems**
In this talk we consider a nonlinear least squares framework to solve separable nonlinear ill-posed inverse problems. It is shown that with proper constraints and well chosen regularization parameters, it is possible to obtain an objective function that is fairly well behaved. Although uncertainties in the data and inaccuracies of linear solvers make it unlikely to obtain a smooth and convex objective function, it is shown that implicit filtering optimization methods can be used to avoid becoming trapped in local minima. An application to blind deconvolution is used for illustration.

James G. Nagy
Dept. of Mathematics and Computer Science
Emory University
nagy@mathcs.emory.edu
Anastasia Cornelio
Dept. of Mathematics
University of Modena and Reggio Emilia
anastasia.cornelio@unimore.it
Elena Loli Piccolomini
Department of Mathematics
University of Bologna
elena.loli@unibo.it

Talk 2. **Iterative reconstruction methods for adaptive optics**
The image quality of large ground based astronomical telescopes suffers from turbulences in the atmosphere. Adaptive Optics is a hardware-based technique that corrects the influence of the turbulence. To this end, wavefront measurements from the incoming wavefront of several guide stars are used for the reconstruction of the turbulent layers in the atmosphere. The reconstructed atmosphere is then used to compute the surface of several deformable mirrors such that, in the reflected light, the influence of the turbulence is removed. The reconstruction of the turbulence in the atmosphere is related to a limited angle tomography problem and therefore severely ill posed. For the new class of extremely large telescopes, the numerical task is to invert a linear system with a dimension of approximately 60.000×10.000 every millisecond.
We present iterative methods, based on Kaczmarz and cg, for the reconstruction of the layers. The methods will be evaluated in different function spaces. In particular, we will include the modeling of specific effects that are related to the use of laser guide stars. We will also demonstrate that our method are able to compute the correcting shape of the deformable mirrors within the available time frame.

Ronny Ramlau
Industrial Mathematics Institute
Kepler University Linz, Austria
ronny.ramlau@jku.at

Talk 3. **Approximated nonstationary iterated Tikhonov with application to image deblurring**
In this talk we present new iterative regularization methods, based on the approximation of nonstationary iterated Tikhonov. In particular we investigate the image deblurring problem, where the blurring matrix is not easily invertible with a low computational cost, while an approximation with such property is available. This is for instance the case of block Toeplitz matrices with Toeplitz blocks that can be well approximated by block circulant matrices with circulant blocks matrices which can be diagonalized by two dimensional fast Fourier transforms. Matrices arising from the imposition of other boundary conditions can be considered as well.
A detailed analysis is proposed in the stationary case and we discuss relations with preconditioned Landweber method and other known methods. A large numerical experimentation with different boundary conditions, blurring phenomena and noise level is presented.

Marco Donatelli
Dept. of Scienza e Alta Tecnologia
University of Insubria
marco.donatelli@uninsubria.it
Martin Hanke
Institute of Mathematics
University of Mainz
hanke@mathematik.uni-mainz.de

Talk 4. **On the Richardson-Lucy method for image restoration**
Image deconvolution problems with a symmetric point-spread function arise in many areas of science and engineering. These problems often are solved by the Richardson- Lucy method, a nonlinear iterative method. In this talk we first show a convergence result for the Richardson-Lucy method. The proof sheds light on why the method may converge slowly. Subsequently, we describe an iterative active set method that imposes the same constraints on the computed solution as the Richardson- Lucy method. Computed examples show the latter method to yield better restorations than the Richardson- Lucy method with less computational effort.

Fiorella Sgallari
Dept. of Mathematics- CIRAM
University of Bologna,Bologna, Italy
fiorella.sgallari@unibo.it
M. Kazim Khan

Dept. of Mathematical Sciences,
Kent State University, Kent, OHIO, USA
kazim@math.kent.edu

Serena Morigi
Dept. of Mathematics- CIRAM
University of Bologna,Bologna, Italy
serena.morigi@unibo.it

Lothar Reichel
Dept. of Mathematical Sciences,
Kent State University, Kent, OHIO, USA
reichel@math.kent.edu

MS 32. Orderings in sparse matrix computation

Talk 1. **Orderings and solvers for "non-uniform sparse matrices"**
Sparse matrices from non-PDE problems come in rich varieties. We specifically address sparse matrices that have a non-uniform distribution of nonzeros per row (power-law graphs are a popular example that lead to these), which may be called "non-uniform sparse matrices." We examine the appropriateness of traditional orderings to solve various problems for these types of matrices. For example, instead of RCM reordering for ILU(k), it is natural and indeed better to use an ordering by increasing degree. By studying why such orderings are effective, we are lead to "incomplete" versions of minimum degree ordering, i.e., the ordering operates like minimum degree, but the maximum degree is capped by a parameter, just as fill-in level in ILU(k) is capped. Lee, Raghavan, and Ng proposed such a technique for pivoting in 2006. In our studies, tie-breaking and the complementary strategies of reducing the number of fill-ins and the aggregate size of fill-ins are important issues. Sparse matrices from PDEs have well-defined model problems; to further study non-uniform sparse matrices, we propose models (structure and values) derived from realistic applications.

Edmond Chow
School of Computational Science and Engineering
College of Computing
Georgia Institute of Technology
echow@cc.gatech.edu

Oguz Kaya
School of Computational Science and Engineering
College of Computing
Georgia Institute of Technology
oguzkaya@gatech.edu

Talk 2. **On hypergraph partitioning based ordering methods for sparse matrix factorization**
We discuss the use of hypergraph-based methods for orderings of sparse matrices in Cholesky, LU and QR factorizations. For the Cholesky factorization case, we investigate a recent result on pattern-wise decomposition of sparse matrices, generalize the result and develop effective ordering algorithms. The generalized results help us formulate the ordering problem in LU as we do in the Cholesky case, without ever symmetrizing the given matrix. For the QR factorization case, the use of hypergraph models is fairly standard; the method does not symmetrize the given matrix. We present comparisons with the most common alternatives in all three cases.

Bora Uçar
CNRS and ENS Lyon
France
bora.ucar@ens-lyon.fr

Iain S. Duff
RAL Oxon, OX11 0QX, England and
CERFACS, Toulouse, France
iain.duff@stfc.ac.uk

Johannes Langguth
ENS Lyon
France
Johannes.Langguth@ens-lyon.fr

Talk 3. **Orderings governed by numerical factorization**
We study the solution of sparse least-squares problems using an augmented system approach:

$$\begin{pmatrix} I & A \\ A^T & 0 \end{pmatrix} \begin{pmatrix} r \\ x \end{pmatrix} = \begin{pmatrix} b \\ 0 \end{pmatrix}$$

If the null space approach for constrained optimization is used, a crucial aspect is the selection of the basis rows from the overdetermined matrix A. We discuss the effect of this showing that the concept of condition number and conditioning needs to be rethought in this case. We illustrate our discussion with runs using a basis selection routine from HSL that involves a sparse factorization with rook pivoting and a subsequent solution of the augmented system using iterative methods.

Iain S. Duff
Rutherford Appleton Laboratory
iain.duff@stfc.ac.uk

Mario Arioli
Rutherford Appleton Laboratory
mario.arioli@stfc.ac.uk

Talk 4. **Reordering sparse Cholesky factorization: minimum fill vs. minimum FLOP count**
Given a sparse positive definite matrix A, we discuss the problem of finding a permutation matrix P such that the number of floating point operations for computing the Cholesky factorization $PAP^T = LL^T$ is minimum. Two theoretical results are presented: First, we outline a reduction from MAXCUT in order to give an NP-hardness result. Second, we discuss the relationship of minimizing FLOPs and the minimum fill problem. Using an explicit construction we show that orderings which minimize the operation count may be non-optimal in terms of the fill and vice versa.

Robert Luce
Dept. of Mathematics
Technical University of Berlin
luce@math.tu-berlin.de

Esmond G. Ng
Lawrence Berkeley National Laboratory
EGNg@lbl.gov

MS 33. Moving from multicore to manycore in applied linear algebra

Talk 1. **Parallel preconditioners and multigrid methods for sparse systems on GPUs**
Large-scale numerical simulation relies on both efficient parallel solution schemes and platform-optimized parallel implementations. Due to the paradigm shift towards multicore and manycore technologies, both aspects have become more intricate. In this talk we address fine-grained parallel preconditioning techniques and multigrid solvers that are compliant with SIMD-like parallelism of graphics processing units. By means of multi-coloring reordering combined with the power(q)-pattern method for incomplete LU decompositions with fill-ins we show how scalable parallelism can be introduced to the triangular solution phase of smoothers and preconditioners. Performance results demonstrate efficiency and

scalability of our approach on recent GPUs and on multicore-CPUs.

Jan-Philipp Weiss
Engineering Mathematics and Computing Lab (EMCL)
Karlsruhe Institute of Technology (KIT), Germany
jan-philipp.weiss@kit.edu

Dimitar Lukarski
Engineering Mathematics and Computing Lab (EMCL)
Karlsruhe Institute of Technology (KIT), Germany
dimitar.lukarski@kit.edu

Vincent Heuveline
Engineering Mathematics and Computing Lab (EMCL)
Karlsruhe Institute of Technology (KIT), Germany
vincent.heuveline@kit.edu

Talk 2. **Towards a GPU-accelerated direct sparse solver**
We present a detailed study about the acceleration of a direct method to solve sparse linear systems using GPU-based computing. Particularly, we describe a variant for the factorization stage of the multifrontal method which combines CPU and GPU computations. Additionally, the developed routine is included in the CSparse library to cover the whole solver. We evaluate the proposal and compare it with an ad-hoc multicore implementation and the implementation included in MUMPS library (combined with Goto BLAS) The results obtained show that this is a promising research line to accelerate this kind of sparse matrix solvers on cheap hardware platforms.

Pablo Ezzatti
Instituto de Computación
Univ. de la República, Montevideo, Uruguay.
pezzatti@fing.edu.uy

Alejandro Zinemanas
Instituto de Computación
Univ. de la República, Montevideo, Uruguay.
azinemanas@gmail.com

Talk 3. **Exploiting the flexibility of `libflame` for novel multi-core and many-core architectures**
The `libflame` library is a modern, high-performance dense linear algebra library that is extensible, easy to use, and available under an open source license, and offers competitive (and in many cases superior) real-world performance when compared to traditional libraries like LAPACK. It can optionally exploit multiple cores by casting an algorithm as an algorithm-by-blocks which can generate a directed acyclic graph (DAG) that is then scheduled to cores via a runtime system called SuperMatrix. In this talk we demonstrate its flexibility for running efficiently dense linear algebra codes on general-purpose architectures, including single core, multi-core and GPU-based architectures. In addition, we adapt our runtime to support a novel, highly efficient HPC architecture: the Texas Instrument's C6678 multi-core DSP.

Francisco D. Igual
Dept. de Ingeniería y Ciencia de los Computadores
University Jaume I de Castellón
figual@icc.uji.es

Murtaza Ali
Texas Instruments
mali@ti.com

Robert A. van de Geijn
The University of Texas at Austin
rvdg@cs.utexas.edu

Talk 4. **High-performance genome studies**
In the context of the genome-wide association study (GWAS), one has to solve long sequences of generalized least-squares problems; such a problem presents two limiting factors: execution time –often in the range of days or weeks– and data management –in the order of Terabytes–. We present algorithms that obviate both issues. By taking advantage of domain-specific knowledge, exploiting parallelism provided by multicores and GPU, and handling data effciently, our algorithms attain unequalled high performance. When compared to GenABEL, one of the most widely used libraries for GWAS, we obtain speedups up to a factor of 50.

Lucas Beyer
Aachen Institute for Advanced Study in Computational Engineering Science (AICES)
RWTH Aachen
lucas.beyer@rwth-aachen.de

Diego Fabregat-Traver
AICES
RWTH Aachen
fabregat@aices.rwth-aachen.de

Paolo Bientinesi
AICES
RWTH Aachen
pauldj@aices.rwth-aachen.de

MS 34. Least squares methods and applications

Talk 1. **Block Gram–Schmidt algorithms with reorthogonalization**
The talk discusses reorthogonalized block classical Gram–Schmidt algorithms for factoring a matrix A into $A = QR$ where Q is left orthogonal (has orthonormal columns) and R is upper triangular. These algorithms are useful in developing BLAS–3 versions of orthogonal factorization in the implementation of Krylov space methods and in modifying an existing orthogonal decomposition.
In previous work, we have made assumptions about the diagonal blocks of R to insure that a block classical Gram–Schmidt algorithm with reorthogonalization will produce a backward stable decomposition with a near left orthogonal Q. The context of this talk is where these diagonal blocks violate those assumptions and are allowed to be singular or very ill-conditioned. A strategy for using rank–revealing decompositions to deal with that contingency is given that insures a similar result to the case where the assumptions about the blocks of R hold. The algorithm is considered in the context of block downdating.

Jesse Barlow
Department of Computer Science and Engineering
Penn State University
University Park, PA 16802, USA
barlow@cse.psu.edu

Talk 2. **A numerical method for a mixed discrete bilinear least squares problem**
For CPU utilization control in distributed real-time embedded systems, we recently proposed a new scheme to make synchronous rate and frequency adjustment to enforce the utilization set point. In this scheme, we need to solve a mixed discrete bilinear least squares problem, in which one unknown vector is subject to a box constraint and the other unknown vector's each entry has to be taken from a discrete set of numbers. In this talk we propose an alternating iterative method to solve this problem.
This is joint work with Xi Chen and Xue Liu.

Xiao-Wen Chang

School of Computer Science
McGill University
Montreal, Quebec H3A 1Y1, Canada
chang@cs.mcgill.ca

Talk 3. **On condition numbers for constrained linear least squares problems**

Condition numbers are important in numerical linear algebra, which can tell us the posterior error bounds for the computed solution. Classical condition numbers are normwise, but they ignore the input data sparsity and/or scaling. Componentwise analysis have been introduced, which gives a powerful tool to study the perturbations on input and output data regarding the sparsity and scaling. In this paper under componentwise perturbation analysis we will study the condition numbers for constrained linear least squares problems. The obtained expressions of the condition numbers avoid the explicit forming of Kronecker products, which can be estimated by power methods efficiently. Numerical examples show that our condition numbers can give better error bounds.

Huaian Diao
School of Mathematics and Statistics
Northeast Normal University
Chang Chun 130024
P.R. China
hadiao@gmail.com

Yimin Wei
School of Mathematical Sciences
Fudan University
Shanghai, 200433
P.R. China
ymwei@fudan.edu.cn

Talk 4. **SOR inner-iteration GMRES for underdetermined least squares problems**

Successive over-relaxation (SOR) inner iterations are proposed for preconditioning the generalized minimal residual method (GMRES) for underdetermined least squares problems. The right-preconditioned GMRES (AB-GMRES) may fail to converge for inconsistent problems. Instead, the left-preconditioned GMRES method (BA-GMRES) works since we can transform an inconsistent system to a consistent one. Numerical experiments show that BA-GMRES with SOR for the normal equation works efficiently. Moreover, we show conditions under which BA-GMRES determines a minimum-norm least squares solution without breakdown and present numerical results.

Keiichi Morikuni
The Department of Informatics
The School of Multidisciplinary Science
The Graduate University for Advanced Studies
2-1-2 Hitotsubashi, Chiyoda-ku
Tokyo 101-8430
Japan
morikuni@nii.ac.jp

Ken Hayami
The Department of Informatics
The School of Multidisciplinary Science
The Graduate University for Advanced Studies
2-1-2 Hitotsubashi, Chiyoda-ku
Tokyo 101-8430
Japan
hayami@nii.ac.jp

MS 35. Nonlinear eigenvalue problems

Talk 1. **Computable error bounds for nonlinear eigenvalue problems allowing for a minimax characterization**

For a nonlinear eigenvalue problem

$$T(\lambda)x = 0$$

allowing for a variational characterization of its eigenvalues we discuss computable error bounds of Krylov–Bogoliubov and of Kato–Temple type.

Heinrich Voss
Institute of Numerical Simulation
Hamburg University of Technology
voss@tuhh.de

Kemal Yildiztekin
Institute of Numerical Simulation
Hamburg University of Technology
kemal.yildiztekin@tuhh.de

Talk 2. **A restarting technique for the infinite Arnoldi method**

Different adaptions of the Arnoldi method are often used to compute partial Schur factorizations. We propose here a technique to compute a partial Schur factorization of a nonlinear eigenvalue problem (NEP). The technique is inspired by the algorithm in *[E. Jarlebring, K. Meerbergen, W. Michiels, A linear eigenvalue algorithm for the nonlinear eigenvalue problem, 2012]*, now called the *infinite Arnoldi method*, for which we design an appropriate restarting technique. The technique is based on a characterization of the invariant pairs of the NEP, which turn out to be equivalent to the invariant pairs of an operator. We characterize the structure of the invariant pairs of the operator and show how one can carry out a modification of the infinite Arnoldi method by respecting this structure. This also allows us to naturally add the feature known as locking. We nest this algorithm with an outer iteration, where the infinite Arnoldi method for a particular type of structured functions is appropriately restarted. The restarting exploits the structure and is inspired by the well-known implicitly restarted Arnoldi method for standard eigenvalue problems.

Elias Jarlebring
CSC / Numerical analysis
KTH - Royal institute of technology
eliasj@kth.se

Karl Meerbergen
Dept. of Comp. Science
K.U.Leuven
Karl.Meerbergen@cs.kuleuven.be

Wim Michiels
Dept. of Comp. Science
K.U.Leuven
Wim.Michiels@cs.kuleuven.be

Talk 3. **Robust successive computation of eigenpairs for nonlinear eigenvalue problems**

The successive computation of several eigenpairs of a nonlinear eigenvalue problem requires a means to prevent our algorithm from repeatedly converging to the same eigenpair. For linear eigenproblems, this is usually accomplished by restricting the problem to the subspace orthogonal to all previously computed eigenvectors. In the nonlinear case, though, this strategy is harmful as it may cause eigenpairs to be missed due to possible linear dependencies among the eigenvectors. In this talk, we present a modified orthogonalization scheme based on the concept of minimal invariant pairs, which does not bear this danger.

Cedric Effenberger
Mathematics Institute of Computational Science and Engineering
Swiss Federal Institute of Technology Lausanne
cedric.effenberger@sam.math.ethz.ch

Talk 4. **Triangularization of matrix polynomials**
Using similarity transformations that preserve the structure of the companion matrix, we show that any matrix polynomial $P(\lambda)$ over the complex numbers can be triangularized in the sense that there always exists a triangular matrix polynomial $T(\lambda)$ having the same degree and elementary divisors (finite and infinite) as $P(\lambda)$. Although the result is theoretical the approach is constructive and hints on possible numerical algorithms.

Leo Taslaman
School of Mathematics
University of Manchester
leo.taslaman@maths.man.ac.uk
Yuji Nakatsukasa
School of Mathematics
University of Manchester
yuji.nakatsukasa@manchester.ac.uk
Françoise Tisseur
School of Mathematics
University of Manchester
Francoise.Tisseur@manchester.ac.uk

MS 36. Hybrid solvers for sparse linear equations

Talk 1. **The augmented block-Cimmino distributed method**
In row projection methods, such as Block-Cimmino, near linear dependency between partitions implies small eigenvalues in the spectrum of the iteration matrix. In this work we try to break this near linear dependency by augmenting the matrix to enforce orthogonality between partitions. We formulate a linear system in a super-space, where the extra equations that are introduced for consistency are obtained by projections and can be handled implicitly. In the ideal case the resulting iteration matrix has all eigenvalues almost equal to one. We investigate the numerical components of this approach and ways to reduce the number of super-space variables.

Mohamed Zenadi
ENSEEIHT-IRIT
mzenadi@enseeiht.fr
Iain Duff
CERFACS and Rutherford Appleton Laboratory
iain.duff@stfc.ac.uk
Ronan Guivarch
ENSEEIHT-IRIT
ronan.guivarch@enseeiht.fr
Daniel Ruiz
ENSEEIHT-IRIT
ruiz@enseeiht.fr

Talk 2. **On a parallel hierarchical algebraic domain decomposition method for a large scale sparse linear solver**
The emerging petaflop computers have processing nodes based on multi- /many-core chips. To fully utilize such parallel architectures, a natural approach is to exploit medium-grain parallelism through multi-threading within a node and coarse-grain parallelism using message-passing (MPI) between nodes. For a hybrid direct/iterative solver, this can be implemented by using a parallel sparse direct solver within a node on local subproblems. The available multi-threaded sparse direct solvers can be used to take advantage of the multicore architecture of the nodes. The MPI paradigm is then used to implement the iterative scheme for the interfaces between the subproblems. In this talk, we will present such a parallel implementation and illustrate its performance scalability on a set of academic and industrial test problems. In addition, we will propose a model to compute the subsequent computational and memory costs, depending on the ratio of computation performed in the direct solver. We apply this model to several classes of problems and illustrate the possible trade-offs in terms of computational and memory complexity.

Luc Giraud
Inria, joint Inria-CERFACS lab.
luc.giraud@inria.fr
Emmanuel Agullo
Inria
Emmanuel.Agullo@inria.fr
Abdou Guermouche
Bordeaux University
abdou.guermouche@labri.fr
Jean Roman
Inria
jean.roman@inria.fr

Talk 3. **A two-level Schwarz method for systems with high contrasts**
Two-level Schwarz methods are popular domain decomposition methods. They are based on direct solves in each subdomain as well as in a specified coarse space. Used as a preconditioner for the Conjugate Gradient algorithm they lead to efficient hybrid solvers.
Heterogeneous coefficients in the PDEs are a known challenge for robustness in domain decomposition, specially if the heterogeneities are across interfaces. We introduce a new coarse space for which the Schwarz method is robust even in this case. It relies on solving local generalized eigenvalue problems in the overlaps between subdomains which isolate exactly the terms responsible for slow convergence.

Nicole Spillane
Laboratoire Jacques-Louis Lions
Université Pierre et Marie Curie
spillane@ann.jussieu.fr
Victorita Dolean
Laboratoire J.-A. Dieudonné
Université de Nice-Sophia Antipolis
dolean@unice.fr
Patrice Hauret
Centre de technologie
MFP Michelin
patrice.hauret@fr.michelin.com
Frédéric Nataf
Laboratoire Jacques-Louis Lions
Université Pierre et Marie Curie
nataf@ann.jussieu.fr
Clemens Pechstein
Institute of Computational Mathematics
Johannes Kepler University
clemens.pechstein@numa.uni-linz.ac.at
Robert Scheichl
Department of Mathematical Sciences
University of Bath
r.scheichl@bath.ac.uk

Talk 4. **A 3-level parallel hybrid preconditioner for sparse linear systems**
We describe ShyLU, a hybrid direct-iterative preconditioner and solver for general sparse linear systems. We use a Schur complement approach where subproblems are solved using a direct solver while the Schur complement is solved iteratively.

We employ a block decomposition, which is formed in a fully automatic way using state-of-the-art partitioning and ordering algorithms in the Zoltan and Scotch software packages. The method can be viewed as a two-level scheme. We show results that demonstrate the robustness and effectiveness of ShyLU for problems from a variety of applications. We have found it is particularly effective on circuit simulation problems where many iterative methods fail. We also show results from a hybrid MPI + threads version of ShyLU. The Schur complement strategy in ShyLU works well for moderate amount of parallelism. For very large problems on very large parallel systems, we introduce a third level based on domain decomposition to improve scalability. We study how ShyLU behaves as a subdomain solver. This strategy looks promising for peta- and exa-scale systems, which usually have a hierarchical structure.

Erik G. Boman
Sandia National Labs
egboman@sandia.gov

Siva Rajamanickam
Sandia National Labs
srajama@sandia.gov

Michael A. Heroux
Sandia National Labs
maherou@sandia.gov

Radu Popescu
EPFL, Switzerland
radu.popescu@epfl.ch

MS 37. Optimization methods for tensor decomposition

Talk 1. **Efficient algorithms for tensor decompositions**
The canonical polyadic and rank-$(L_r, L_r, 1)$ block term decomposition (CPD and BTD, respectively) are two closely related tensor decompositions. The CPD is an important tool in psychometrics, chemometrics, neuroscience and data mining, while the rank-$(L_r, L_r, 1)$ BTD is an emerging decomposition in signal processing and, recently, blind source separation. We present a decomposition that generalizes these two and develop algorithms for its computation. Among these algorithms are alternating least squares schemes, several general unconstrained optimization techniques, as well as matrix-free nonlinear least squares methods. In the latter we exploit the structure of the Jacobian's Gramian by means of efficient expressions for its matrix-vector product. Combined with an effective preconditioner, numerical experiments confirm that these methods are among the most efficient and robust currently available for computing the CPD, rank-$(L_r, L_r, 1)$ BTD and their generalized decomposition.

Laurent Sorber
Dept. of Computer Science KU Leuven
Laurent.Sorber@cs.kuleuven.be

Marc Van Barel
Dept. of Computer Science KU Leuven
Marc.VanBarel@cs.kuleuven.be

Lieven De Lathauwer
Group Science, Engineering and Technology, KU Leuven Campus Kortrijk
& Dept. of Electrical Engineering (ESAT), KU Leuven
Lieven.DeLathauwer@kuleuven-kortrijk.be

Talk 2. **Symmetric tensor decomposition via a power method for the generalized tensor eigenproblem**
We present an approach for approximate (least-squares) decomposition of a symmetric positive-definite tensor of dimension n into a given number p of symmetric rank-1 terms. This is accomplished in two parts. The first part is to transform the decomposition problem into a "generalized tensor eigenproblem" (GTEP) for tensors of dimension np. The GTEP is of independent interest and, for example, subsumes the previously defined Z-eigenpairs and H-eigenpairs. The second part is to extend a previously developed power method for Z-eigenpairs to solve the GTEP. We discuss the concepts underlying these techniques and provide numerical examples.

Jackson R. Mayo
Sandia National Laboratories
jmayo@sandia.gov

Tamara G. Kolda
Sandia National Laboratories
jmayo@sandia.gov

Talk 3. **All-at-once optimization for coupled matrix and tensor factorizations**
Joint analysis of data from multiple sources can enhance knowledge discovery. The task of fusing data, however, is challenging since data may be incomplete and heterogeneous, i.e., data consists of matrices and higher-order tensors. We formulate this problem as a coupled matrix and tensor factorization problem where heterogeneous data are modeled by fitting outer-product models to higher-order tensors and matrices in a coupled manner. Unlike traditional approaches using alternating algorithms, we use a gradient-based all-at-once optimization approach. Using numerical experiments, we demonstrate that the all-at-once approach is often more accurate than the alternating approach and discuss the advantages of coupled analysis in terms of missing data recovery.

Evrim Acar
University of Copenhagen
evrim@life.ku.dk

Tamara G. Kolda
Sandia National Laboratories
tgkolda@sandia.gov

Daniel M. Dunlavy
Sandia National Laboratories
dmdunla@sandia.gov

Rasmus Bro
University of Copenhagen
rb@life.ku.dk

Talk 4. **An algebraic multigrid optimization method for low-rank canonical tensor decomposition**
A new algorithm based on algebraic multigrid is presented for computing the rank-R canonical decomposition of a tensor for small R. Standard alternating least squares (ALS) is used as the relaxation method. Transfer operators and coarse-level tensors are constructed in an adaptive setup phase that combines multiplicative correction and bootstrap algebraic multigrid. An accurate solution is computed by an additive solve phase based on the full approximation scheme. Numerical tests show that for certain test problems, our multilevel method significantly outperforms standalone ALS when a high level of accuracy is required.

Killian Miller
University of Waterloo
k7miller@uwaterloo.ca

Hans De Sterck
University of Waterloo
hdesterck@uwaterloo.ca

MS 38. Generalized inverses and applications - Part I

of II

Talk 1. **The group inverse of additively modified matrices**
Let $A \in \mathbb{C}^{n\times n}$. We recall that the group inverse of A, is the unique matrix $A^{\#} \in \mathbb{C}^{n\times n}$, if it exists, which satisfies the equations: $A^{\#}AA^{\#} = A^{\#}$; $AA^{\#}A = A$; $AA^{\#} = A^{\#}A$. If A is nonsingular then $A^{\#} = A^{-1}$. It is well known that the group inverse of A exists if $\mathrm{rank}(A) = \mathrm{rank}(A^2)$. Alternatively, $A^{\#}$ exists if $A + I - AA^{-}$ is nonsingular, independently of the choice of A^{-}, where A^{-} denotes an inner inverse of A, i.e. $AA^{-}A = A$. Let $B \in \mathbb{C}^{n\times r}$, $C \in \mathbb{C}^{r\times n}$, and $r < n$. If A and $I - CA^{-1}B$ are nonsingular, then to adapt the inverse of the modified matrix $A - BC$ we can apply the Sherman-Morrison-Woodbury formula: $(A - BC)^{-1} = A^{-1} + A^{-1}B(I - CA^{-1}B)^{-1}CA^{-1}$; and, hence, we need to compute the inverse of $I - CA^{-1}B$, which has size $r < n$. This talk will be focused on the group inverse of additively modified matrices, $(A - BC)^{\#}$, when it exists. Extensions of the previous formula will be considered. An application to the perturbation of the group inverse of $A = I - T$, where T is the transition matrix of a Markov chain will be given. The research is partially supported by Project MTM2010-18057, "Ministerio de Ciencia e Innovación" of Spain.

Nieves Castro González
Departamento de Matemática
Universidad Politécnica de Madrid, Spain
nieves@fi.upm.es

Talk 2. **The Moore-Penrose inverse of a linear combination of commuting generalized and hypergeneralized projectors**
We present new results concerning the representation of the Moore-Penrose inverse of a linear combination of generalized and hypergeneralized projectors and give the form for the Moore-Penrose inverse, i.e., the group inverse of $c_1A + c_2B$, where A, B are two commuting generalized or hypergeneralized projectors and $c_1; c_2 \in \mathbb{C}\backslash\{0\}$ and $c_1^3 + c_2^3 \neq 0$. Furthermore, we show that under that conditions the invertibility of $c_1A + c_2B$ is independent of the choice of the scalars $c_1; c_2$. Also, we present some results relating different matrix partial orderings and the invertibility of a linear combination of EP matrices.

Dragana S. Cvetković-Ilić
Faculty of Mathematics and Sciences
University of Niš, Serbia
gagamaka@ptt.rs

Talk 3. **Generalized inverses of operators on Hilbert C^*-modules**
We present new results on the theory and applications of generalized inverses of operators between Hilbert C^*-modules.

Dragan S. Djordjevic
Faculty of Sciences and Mathematics
University of Niš, Serbia
dragan@pmf.ni.ac.rs

Talk 4. **Some results on the reverse order law**
We presented some necessary and sufficient conditions concerning the reverse order laws for the group inverses of elements in rings and rings with involution. In particular, assuming that a and b are Moore-Penrose invertible or group invertible elements, we study equivalent conditions which are related to the reverse order law for the group inverse of the product ab. Also, some equivalent condition which ensure that the product ab is EP element are consider too. Several conditions for $(ab)^{\#} = b^{\#}(a^{\#}abb^{\#})^{\#}a^{\#}$ to hold in rings are investigate. We extend the recent results to more general settings, giving some new conditions and providing simpler proofs to already existing conditions.

D. Mosić
Faculty of Sciences and Mathematics
University of Niš, Serbia
sknme@ptt.rs

MS 39. Challenges for the solution and preconditioning of multiple linear systems - Part I of II

Talk 1. **Preconditioners for sequences of shifted linear systems**

Sequences of shifted linear systems with the same right-hand side can be solved with multi-shift Krylov methods at almost the same cost as for solving the unshifted system. This is possible due to the fact that the Krylov subspaces for the shifted and the unshifted problems are the same. The main drawback of multi-shift Krylov methods is that they cannot be combined with an arbitrary preconditioner since in general the Krylov subspaces for the preconditioned shifted problems will be different. In the talk we will discuss this problem in detail and also explain how to construct preconditioners that can be combined with multi-shift Krylov methods.

Martin B. van Gijzen
Delft Institute of Applied Mathematics
Delft University of Technology, the Netherlands
M.B.vanGijzen@TUDelft.nl

Daniel B. Szyld
Department of Mathematics
Temple University, Philadelphia, Pa., USA
szyld@temple.edu

Talk 2. **Solving sequences of linear systems with application to model reduction**
To obtain efficient solutions for sequences of linear systems arising in interpolatory model order reduction (both parametric and nonparametric), we recycle Krylov subspaces from one system (or pair of systems) in a sequence to the next. We first introduce a generalization of BiCG. Here we show that even for non-Hermitian matrices one can build bi-orthogonal bases (for the associated two Krylov subspaces) using a short-term recurrence. We then adapt and apply Recycling BiCG and Recycling BiCGSTAB to model reduction algorithms. For a model reduction problem we demonstrate that solving the problem without recycling leads to (about) a 50% increase in runtime.

Kapil Ahuja
Max Planck Institute for Dynamics of Complex Technical Systems
Magdeburg, Germany
kahuja@vt.edu

Eric de Sturler
Dept. of Mathematics
Virginia Tech, Blacksburg, Va., USA
sturler@vt.edu

Serkan Gugercin
Dept. of Mathematics
Virginia Tech, Blacksburg, Va., USA
gugercin@vt.edu

Peter Benner
Max Planck Institute for Dynamics of Complex Technical Systems
Magdeburg, Germany
benner@mpi-magdeburg.mpg.de

Talk 3. **Krylov subspace recycling for families of shifted linear systems**
We address the solution of a sequence of families of linear systems. For each family, there is a base coefficient matrix A_i, and the coefficient matrices for all systems in the family differ from A_i by a multiple of the identity, e.g.,

$$A_i x_i = b_i \quad \text{and} \quad (A_i + \sigma_i^{(\ell)} I) x_i^{(\ell)} = b_i \quad \text{for} \quad \ell = 1 \ldots L_i,$$

where L_i is the number of shifts at step i. We propose a new method which solves the base system using GMRES with subspace recycling while constructing approximate corrections to the solutions of the shifted systems. At convergence of the base system solution, GMRES with subspace recycling is applied to further improve the solutions of the shifted systems to tolerance. We present analysis of this method and numerical results involving systems arising in lattice quantum chromodynamics.

Kirk M. Soodhalter
Department of Mathematics
Temple University, Philadelphia, Pa., USA
ksoodha@temple.edu

Daniel B. Szyld
Department of Mathematics
Temple University, Philadelphia, Pa., USA
szyld@temple.edu

Fei Xue
Department of Mathematics
Temple University, Philadelphia, Pa., USA
fxue@temple.edu

Talk 4. **Krylov subspace recycling for faster model reduction algorithms**
The numerical solution of shifted linear system with multiple right-hand sides is a recurring task in many computational problems related to model reduction. Shifts and right-hand sides may be known in advance or may became available only after the previous linear system has been solved. We will survey some model reduction algorithms where these tasks occur and will demonstrate that Krylov subspace recycling may significantly accelerate the computation of reduced-order models in these situations.

Peter Benner
Max Planck Institute for Dynamics of Complex Technical Systems
Magdeburg, Germany
benner@mpi-magdeburg.mpg.de

Lihong Feng
Max Planck Institute for Dynamics of Complex Technical Systems
Magdeburg, Germany
feng@mpi-magdeburg.mpg.de

MS 40. Different perspectives on conditioning and numerical stability - Part I of II

Talk 1. **Highly accurate numerical linear algebra via rank revealing decompositions**
High accuracy algorithms are those that produce relative forward errors of order the unit roundoff of the computer even for matrices that are very ill-conditioned in a traditional sense. This type of algorithms only exist for certain structured matrices. A wide class of these matrices are the matrices for which it is possible to compute accurate rank revealing decompositions (RRDs), i.e., factorizations XDY where D is diagonal and non-singular, and X and Y are well conditioned. This class comprise many important structured matrices, like Vandermonde, Cauchy, graded matrices and many others. Originally, high accuracy algorithms acting on the factors of RRDs (instead of acting directly on the matrix) were designed for computing Singular Value Decompositions (1999), then for computing eigenvalues/eigenvectors of symmetric matrices (2003, 2009), and very recently for computing solutions of linear systems (2011) and least square problems (2012). The purpose of this talk is to present a unified description of all these algorithms and to pose some open problems in this area.

Froilán M. Dopico
ICMAT and Department of Mathematics
Universidad Carlos III de Madrid (Spain)
dopico@math.uc3m.es

Talk 2. **Stability of numerical algorithms with quasiseparable matrices**
Quasiseparable matrices are encountered in PDEs, computations with polynomials (interpolation, root finding etc.), design of digital filters and other areas of applied mathematics. There have been major interest in fast algorithms with quasiseparable matrices in the last decade. Many linear complexity algorithms have been developed including QR factorization, system solver, QR iterations and others. However, their numerical stability has not received equal attention of the scientific community. In our talk we will present first results of error analysis of QR decomposition and system solvers. We will also present a generalization of Parlett's dqds algorithm and discuss perspectives of using quasiseparable matrices for stable evaluation of polynomials' roots.

Pavel Zhlobich
School of Mathematics
University of Edinburgh
P.Zhlobich@ed.ac.uk

Froilán Dopico
Departamento de Matemáticas
Universidad Carlos III de Madrid
dopico@math.uc3m.es

Vadim Olshevsky
Department of Mathematics
University of Connecticut
olshevsky@uconn.edu

Talk 3. **Gram-Schmidt orthogonalization with standard and non-standard inner product: rounding error analysis**
In this contribution we consider the most important schemes used for orthogonalization with respect to the standard and non-standard inner product and review the main results on their behavior in finite precision arithmetic. Although all the schemes are mathematically equivalent, their numerical behavior can be significantly different. We treat separately the particular case of the standard inner product and show that similar results hold also for the case when the inner product is induced by a positive diagonal matrix. We will show that in the case of general inner product the orthogonality between computed vectors besides the linear independence of initial vectors depends also on the condition number of the matrix that induces the non-standard inner product. Finally we discuss the extension of this theory to some bilinear forms used in the context of various structure-preserving transformations.

Miroslav Rozložník
Institute of Computer Science, Czech Academy of Sciences
Prague, Czech Republic
miro@cs.cas.cz

Jiří Kopal

Institute of Novel Technologies and Applied Informatics
Technical University of Liberec, Czech Republic
jiri.kopal@tul.cz

Alicja Smoktunowicz
Faculty of Mathematics and Information Science
Warsaw University of Technology, Poland
A.Smoktunowicz@mini.pw.edu.pl

Miroslav Tůma
Institute of Computer Science, Czech Academy of Sciences
Prague, Czech Republic
tuma@cs.cas.cz

Talk 4. **Backward stability of iterations for computing the polar decomposition**

Among the many iterations available for computing the polar decomposition the most practically useful are the scaled Newton iteration and the recently proposed dynamically weighted Halley iteration. Effective ways to scale these and other iterations are known, but their numerical stability is much less well understood. In this work we show that a general iteration $X_{k+1} = f(X_k)$ for computing the unitary polar factor is backward stable under two conditions. The first condition requires that the iteration is implemented in a mixed backward–forward stable manner and the second requires that the mapping f does not significantly decrease the size of any singular value relative to the largest singular value. Using this result we show that the dynamically weighted Halley iteration is backward stable when it is implemented using Householder QR factorization with column pivoting and either row pivoting or row sorting. We also prove the backward stability of the scaled Newton iteration under the assumption that matrix inverses are computed in a mixed backward–forward stable fashion; our proof is much shorter than a previous one of Kiełbasiński and Ziętak. We also use our analysis to explain the instability of the inverse Newton iteration and to show that the Newton–Schulz iteration is only conditionally stable. This work shows that by carefully blending perturbation analysis with rounding error analysis it is possible to produce a general result that can prove the backward stability or predict or explain the instability (as the case may be) of a wide range of practically interesting iterations for the polar decomposition.

Nicholas J. Higham
School of Mathematics
University of Manchester
Nicholas.J.Higham@manchester.ac.uk

Yuji Nakatsukasa
School of Mathematics
University of Manchester
yuji.nakatsukasa@manchester.ac.uk

MS 41. Recent advances in model reduction - Part I of II

Talk 1. **The Loewner framework in data-driven model reduction**

In this talk we will survey recent advances in model reduction concentrating on the method of model reduction directly from data using the Loewner framework. In addition we will show how the Loewner framework can be extended to handle reduction of systems depending on parameters.

A.C. Antoulas
Rice University
aca@rice.edu

Talk 2. **Robust computational approaches to $\mathcal{H}_2$-optimal model reduction**

We present an approach to model reduction for MIMO linear dynamical systems that is numerically stable, nonintrusive, and computationally tractable even for very large order systems. Our strategy is a hybrid of the Iterative Rational Krylov Algorithm (IRKA) and a trust-region method with logarithmic barrier that guarantees stability. The method produces a monotonically improving (with respect to $\mathcal{H}_2$ error) sequence of stable reduced order models that is rapidly and globally convergent. The effectiveness of the algorithm is illustrated through numerical examples drawn from a variety of challenging dynamical systems that arise in practical settings.

Christopher Beattie
Dept. of Mathematics
Virginia Polytechnic Institute and State University
beattie@vt.edu

Serkan Gugercin
Dept. of Mathematics
Virginia Polytechnic Institute and State University
gugercin@math.vt.edu

Talk 3. **Reduced order modeling via frames**

In this talk we present a new concept that arises in the discretization of PDEs. Instead of using bases (like hierarchical finite elements) to represent the solution in a certain function space, we use frames, which consist of a set of standard basis functions enriched by specific functions that allow to address specific solution behavior like singularities, boundary layers or small amplitude, high frequency oscillations. We then determined sparse solutions represented in these frames, by solving the under-determined problems to compute sparse solutions. We show that by doing this in a multilevel approach we can achieve much smaller models than with classical adaptive FEM.

Volker Mehrmann
Inst. f. Mathematik
TU Berlin
mehrmann@math.tu-berlin.de

Sadegh Jokar
Inst. f. Mathematik TU Berlin
jokar@math.tu-berlin.de

Sarosh Quraischi
Inst. f. Mathematik TU Berlin
sarosh.quraishi@gmail.com

Talk 4. **Semidefinite Hankel-type model reduction based on frequency response matching**

In this talk a model reduction method for linear time-invariant systems is discussed. It is based on frequency response matching and semidefinite programming techniques. The method is related to Hankel model reduction. It can be claimed that the presented method is a scalable approach to Hankel model reduction. Numerical simulations show that the accuracy of the method is comparable to the well-known techniques, such as balanced truncation and Hankel model reduction. The developed method can be applied to various problems. In this talk we are going to briefly discuss two: parameterized model reduction and reduction in the nu-gap metric.

Aivar Sootla
Dept. of Automatic Control
Lund University
aivar.sootla@control.lth.se

Anders Rantzer
Dept. of Automatic Control

Lund University
anders.rantzer@control.lth.se
Kin Cheong Sou
KTH School of Electrical Engineering, Automatic Control,
kin.cheong.sou@ee.kth.se

MS 42. Structured solution of nonlinear matrix equations and applications - Part I of II

Talk 1. **Structured solution of large-scale algebraic Riccati and nonlinear matrix equations**

We consider the solution of large-scale algebraic Riccati and nonlinear matrix equations (AREs, NMEs). For discrete-time AREs, the structure-preserving doubling algorithm will be adapted for the corresponding sparsity and low-ranked structures. For continuous-time AREs, the Cayley transform is applied before doubling. Similar methodology is applied to large-scale nonsymmetric AREs and NMEs. With n being the dimension of the equations, the resulting algorithms are of $O(n)$ complexity. Numerical results will be presented. As an example, a DARE with 3.19 billion unknowns was solved using MATLAB on a MacBook Pro to machine accuracy within 1,100 seconds.

Eric King-wah Chu
School of Mathematical Sciences
Building 28, Monash University, VIC 3800, Australia
eric.chu@monash.edu
Tiexiang Li
Dept. of Mathematics
Southeast University, Nanjing 211189, People's Republic of China
txli@seu.edu.cn
Wen-Wei Lin
Dept. of Applied Mathematics
National Chiao Tung University, Hsinchu 300, Taiwan
wwlin@math.nctu.edu.tw
Peter Chang-Yi Weng
School of Mathematical Sciences
Building 28, Monash University, VIC 3800, Australia
peter.weng@monash.edu

Talk 2. **Accurate solutions of nonlinear matrix equations in queueing models**

In this talk, we discuss numerical issues arising in finite precision implementations of iterative methods for solving nonlinear matrix equations arising in queueing models. Exploring the structure of the problem, we shall present some numerically more stable implementations. A rounding error analysis together with numerical examples are given to demonstrate the higher accuracy achieved by the refined implementations.

Qiang Ye
Dept. of Mathematics
University of Kentucky, Lexington KY 40506-0027, U.S.
qiang.ye@uky.edu

Talk 3. **A numerical approach for solving nonlinear matrix equations in economic dynamics**

Modern economic theory views the economy as a dynamical system. The dynamics includes changes over time of market behavior such as consumption, investment, labor supply, and technology innovation. To make analytical analysis, the naive approach is to set up the Euler equation and subsequently solve it by finding the policy functions. Indeed, this is a process of solving the nonlinear matrix equation. In this work, we propose a Newton iterative scheme on approximating the unknown policy functions. Applications to the neoclassical growth model with leisure choice are used to demonstrate the working of the idea.

Matthew M. Lin
Dept. of Mathematics
National Chung Cheng University
mlin@math.ccu.edu.tw
Moody T. Chu
Dept. of Applied Mathematics
North Carolina State University
chu@math.ncsu.edu
Chun-Hung Kuo
Dept. of Economics
North Carolina State University
ckuo2@unity.ncsu.edu

Talk 4. **A structure-preserving doubling algorithm for quadratic eigenvalue problems arising from time-delay systems**

We propose a structure-preserving doubling algorithm for a quadratic eigenvalue problem arising from the stability analysis of time-delay systems. We are particularly interested in the eigenvalues on the unit circle, which are difficult to estimate. The convergence and backward error of the algorithm are analyzed and three numerical examples are presented. Our experience shows that our algorithm is efficient in comparison to the few existing approaches for small to medium size problem.

Tiexiang Li
Dept. of Mathematics
Southeast University, Nanjing 211189, People's Republic of China
txli@seu.edu.cn
Eric King-wah Chu
School of Mathematical Sciences
Building 28, Monash University 3800, Australia
eric.chu@monash.edu
Wen-Wei Lin
Dept. of Applied Mathematics
National Chiao Tung University, Hsinchu 300, Taiwan
wwlin@math.nctu.edu.tw

MS 43. Challenges for the solution and preconditioning of multiple linear systems - Part II of II

Talk 1. **Low-rank techniques for parameter-dependent linear systems and eigenvalue problems**

Motivated by the need for quantifying the impact of uncertainties in engineering applications, recently a number of new approaches for solving parameter-dependent and stochastic PDEs have been developed. In particular, this includes sparse grid Galerkin and collocation methods, as well as low-rank techniques. Depending on the regularity of the parameter dependence, these methods are able to deal with potentially many parameters. The aim of this talk to provide a survey of recent work on low-rank techniques for solving linear systems arising from the spatial discretization of parameter-dependent PDEs. The extension of these techniques to general parameter-dependent eigenvalue problems is nontrivial and will also be briefly discussed.

Christine Tobler
MATHICSE-ANCHP
EPF Lausanne, Switzerland
daniel.kresser@epfl.ch
Daniel Kressner
MATHICSE-ANCHP
EPF Lausanne, Switzerland
christine.tobler@sam.math.ethz.ch

Talk 2. **Recycling Krylov subspace information in sequences of linear systems**

Many problems in numerical simulations in physics require the solution of long sequences of slowly changing linear systems. One problem that is of interest to us arises in Lattice QCD simulations, e.g., while computing masses of elementary particles. In each time step, we have to solve a linear system with a Dirac operator which changes slightly from time step to time step. Based on the work of M. Parks, E. de Sturler etal. (Recycling Krylov subspaces for sequences of linear systems, SIAM J. on Scientific Computing, $28(2006)$, $1651-1674$) we will show how the cost of solving subsequent systems is reduced by recycling selected subspaces generated for previous systems. Furthermore, we have investigated how the algorithm behaves when we use the solution of the previous system as an initial guess and also, when we use different kinds of extrapolations of the previous solutions as an initial guess. We will show these results and the effectiveness of the algorithm in comparison to the algorithm that solves each system separately.

Nemanja Božović
Fachbereich C, Mathematik und Naturwissenschaften
Bergische Universität Wuppertal
bozovic@math.uni-wuppertal.de

Talk 3. **Efficiently updating preconditioners in quantum Monte Carlo simulations**

In the quantum Monte Carlo method for computing properties of materials, we need to solve a very long sequence of linear systems arising from importance sampling. Each system in the sequence is a so-called Slater matrix, and the matrices change by one row (or a few rows) at a time corresponding to small moves by particles. We will combine a method for incremental matrix reordering with multilevel preconditioning to develop effective preconditioners that can be recycled efficiently.

Arielle Grim McNally
Department of Mathematics
Virginia Tech, Blacksburg, Va., USA
arielle5@vt.edu

Eric de Sturler
Department of Mathematics
Virginia Tech, Blacksburg, Va., USA
sturler@vt.edu

Kapil Ahuja
Max Planck Institute for Dynamics of Complex Technical Systems
Magdeburg, Germany
kahuja@vt.edu

Li Ming
Department of Mathematics
Virginia Tech, Blacksburg, Va., USA
liming@vt.edu

Talk 4. **A domain decomposition preconditioned recycling GMRES for stochastic parabolic PDE**

We discuss an implicit space-time approach for solving stochastic parabolic PDEs. We first decouple the space-time discretized stochastic equation into some uncoupled deterministic systems by using a Karhunen-Loeve expansion and double orthogonal polynomials. And then a domain decomposition method is combined with recycling GMRES to solve the large number of systems with similar structures. We report experiments obtained on a parallel computer with a large number of processors. This is a joint work with Cui Cong.

Xiao-Chuan Cai
Department of Computer Science
University of Colorado at Boulder
Boulder, Co., USA
cai@cs.colorado.edu

MS 44. Different perspectives on conditioning and numerical stability - Part II of II

Talk 1. **Accuracy and sensitivity of Monte Carlo matrix multiplication algorithms**

Randomized matrix multiplication algorithms were designed to approximate very large matrix products for which a deterministic algorithm is prohibitively expensive. For an algorithm introduced by Drineas, Kannan, and Mahoney, we analyze the error resulting from randomization and derive a bound that improves existing results. In addition, we formulate a measure for the sensitivity of the algorithm to perturbations in the input and present a bound for this measure. We also compare the sensitivity of the randomized algorithm to the sensitivity of the deterministic algorithm.

John T. Holodnak
Dept. of Mathematics
North Carolina State University
Raleigh, NC 27695, USA.
jtholodn@ncsu.edu

Ilse C. F. Ipsen
Dept. of Mathematics
North Carolina State University
Raleigh, NC 27695, USA.
ipsen@ncsu.edu

Talk 2. **Hyperdeterminant and the condition number of a multilinear system**

The condition number of a problem is the reciprocal of its normalized distance to the nearest ill-posed instance in that class of problems. We shall see that in solving a system of multilinear equations, the set of ill-posed problems is given by the set of coefficient tensors with vanishing hyperdeterminant. The parallel with matrices goes further: the hyperdeterminant of a tensor is zero iff it has a zero singular value; and in the case of a symmetric tensor, iff it has a zero eigenvalue. Moreover, the criterion is invariant under Gaussian elimination or Householder/Givens transformations applied to 'all k sides' of the tensor viewed as a k-dimensional hypermatrix.

Lek-Heng Lim
Department of Statistics
University of Chicago
lekheng@galton.uchicago.edu

Talk 3. **Condition numbers and backward errors in functional setting**

In this talk we present a functional perturbation results, i.e., a functional normwise backward error, for the PDE eigenvalue problems. Inspired by the work of Arioli et al. for linear systems arising from the finite element discretization of boundary value problems we extend the ideas of the functional *Compatibility Theorem* and condition numbers to eigenvalue problems in their variational formulation. Moreover, we discuss a new *spacewise backward error* for PDEs using the componentwise error analysis, i.e., by performing the error analysis using the so-called hypernorms of order k.

Agnieszka Miedlar
Institute of Mathematics
Technical University of Berlin
miedlar@math.tu-berlin.de

Mario Arioli
STFC Rutherford Appleton Laboratory
mario.arioli@stfc.ac.uk

Talk 4. **Orthogonality and stability in large-sparse-matrix iterative algorithms**

Many iterative algorithms for large sparse matrix problems are based on orthogonality, but this can rapidly be lost using vector orthogonalization (subtracting multiples of earlier vectors from the latest vector to produce the next orthogonal vector). Yet these are among the best algorithms we have, and include the Lanczos process, CG, Golub and Kahan bidiagonalization, and MGS-GMRES.
Here we describe a form of orthogonal matrix that arises from any sequence of supposedly orthogonal vectors. We illustrate some of its properties, including a beautiful measure of orthogonality of the original set of vectors. We will show how this leads to new concepts of conditioning and stability for these algorithms.

Chris Paige
School of Computer Science
McGill University
paige@cs.mcgill.ca

Wolfgang Wülling
W2 Actuarial & Math Services Ltd.
wolfgang.wuelling@web.de

MS 45. Recent advances in model reduction - Part II of II

Talk 1. **Automating DEIM for nonlinear model reduction**
The discrete empirical interpolation method (DEIM) can provide spectacular dimension and complexity reduction for challenging systems large scale nonlinear ordinary differential equations. The DEIM replaces orthogonal projection of POD with an interpolatory projection of the nonlinear term that only requires the evaluation of a few selected components. However, the implementation at present is intrusive in the sense that a user must provide a scheme for evaluating the selected components of the nonlinear terms in order to integrate the reduced order system. We have utilized some of the techniques of automatic differentiation to fully automate this process. In particular, this approach will automatically generate a new code derived directly from the original C-code for the right hand side of a first order ODE.

D.C. Sorensen
Dept. of Computational and Applied Math.
Rice University
sorensen@rice.edu

Russell L. Carden
Dept. of Computational and Applied Math.
Rice University
Russell.L.Carden@rice.edu

Talk 2. **Model reduction for optimal control problems in field-flow fractionation**
We discuss the application of model order reduction to optimal control problems governed by coupled systems of the Stokes-Brinkmann and advection diffusion equations. Such problems arise in field-flow fractionation processes for the efficient and fast separation of particles of different size in microfluidic flows. Our approach is based on a combination of balanced truncation and tangential interpolation for model reduction of the semidiscretized optimality system. Numerical results demonstrate the properties of this approach.

Tatjana Stykel
Institut für Mathematik
Universität Augsburg
stykel@math.uni-augsburg.de

Carina Willbold
Institut für Mathematik
Universität Augsburg
willbold@math.uni-augsburg.de

Talk 3. **Numerical implementation of the iterative rational Krylov algorithm for optimal $\mathcal{H}_2$ model order reduction**
The Iterative Rational Krylov (IRKA) algorithm for model order reduction (Gugercin, Antoulas, Beattie 2008.) has recently attracted attention because of its effectiveness in real world applications, as well as because of its mathematical elegance. Our current work is focused on the development of efficient and numerically reliable mathematical software that implements the IRKA algorithm. The first step is, necessarily, a theoretical study of the algorithm. We analyze the convergence of fixed point iterations that run in the background of IRKA, in particular the morphology of the mapping $\sigma^{(k+1)} = \phi(\sigma^{(k)})$ (fixed points, periodic points and their classification). Other theoretical issues include perturbation theory to analyze stability of the shifts, revealing relevant condition numbers, Cauchy–like structure of certain key matrices, connection of the fixed point iterations and pole placement, proper stopping criterion that translates into a backward stability relation, etc.
Besides rich theory, IRKA also offers many numerical challenges. How to implement the algorithm efficiently using direct or iterative solvers for
$\mathbf{V}(\sigma) = ((\sigma_1\mathbf{I} - \mathbf{A})^{-1}\mathbf{b}, \ldots, (\sigma_r\mathbf{I} - \mathbf{A})^{-1}\mathbf{b})$,
$\mathbf{W}(\sigma) = ((\sigma_1\mathbf{I} - \mathbf{A}^T)^{-1}\mathbf{c}, \ldots, (\sigma_r\mathbf{I} - \mathbf{A}^T)^{-1}\mathbf{c})$, and how to deal with numerical rank deficiency? How to adapt iterative solvers in an inner loop that communicates with the outer fixed point iterations loop? When to stop? This requires estimates in the $\mathcal{H}_2$ space, and we show to combine them together with the usual stopping scheme for fixed point iterations. All these and many other questions (e.g. implementations on modern parallel architectures such as CPU/GPU) are analyzed during software development. We will give some answers and illustrate the performances of the software package.

Zlatko Drmač
Dept. of Mathematics
University of Zagreb
drmac@math.hr

Christopher Beattie
Dept. of Mathematics
Virginia Polytechnic Institute and State University
beattie@vt.edu

Serkan Gugercin
Dept. of Mathematics
Virginia Polytechnic Institute and State University
gugercin@mat.vt.edu

Talk 4. **Low rank deflative/iterative solutions of Lur'e equations**
The bottleneck of model reduction by passivity-preserving balanced truncation is the numerical solution of Lur'e equations. A typical approach is an a priori perturbation leading to an algebraic Riccati equation. This is however, from an analytical point of view, insufficiently understood and, from a numerical point of view, leads to an ill-conditioned problem. Hence we are following an alternative approach that is basically consisting of two steps:

a) 'Filter out' the 'critical part' of the Lur'e equations: This will lead us to an eigenproblem of moderate complexity, the outcome is an algebraic Riccati equation on some subspace.

b) Solve algebraic Riccati equation on the subspace.

We show that this method provides low rank approximative solutions of the Lur'e equations. Especially this makes the presented method feasible for large-scale model order reduction problems.

Timo Reis
Fachbereich Mathematik
Universität Hamburg
timo.reis@math.uni-hamburg.de

Federico Poloni
Institut für Mathematik
Technische Universität Berlin
poloni@math.tu-Berlin.de

MS 46. Structured solution of nonlinear matrix equations and applications - Part II of II

Talk 1. **Inertia and rank characterizations of the expressions $A - BXB^* - CYC^*$ and $A - BXC^* \pm CX^*B^*$**
In this talk we consider the admissible inertias and ranks of the expressions $A - BXB^* - CYC^*$ and $A - BXC^* \pm CX^*B^*$ with unknowns X and Y in the four cases when these expressions are: (i) complex self-adjoint, (ii) com- plex skew-adjoint, (iii) real symmetric, (iv) real skew symmetric. We also pro- vide a construction for X and Y to achieve the desired inertia/rank, that uses only unitary/orthogonal transformation thus leading to a numerically reliable construction. Consequently, necessary and sufficient solvability conditions for matrix equations

$$A - BXB^* - CYC^* = 0;$$

and

$$A - BXC^* \pm CX^*B^* = 0$$

are provided.

Delin Chu
Dept. of Mathematics
National University of Singapore, Singapore
matchudl@nus.edu.sg

Talk 2. **Structure-preserving Arnoldi-type algorithm for solving eigenvalue problems in leaky surface wave propagation**
We study the generalized eigenvalue problems (GEP) arising from modeling leaky surface waves propagation in a acoustic resonator with infinitely many periodically arranged interdigital transducers. The constitution equations are discretized by finite element method with mesh refinement along the electrode interface and corners. The associated GEP is then transformed to a T-palindromic quadratic eigenvalue problem so that the eigenpairs can be accurately and efficiently computed by using structure-preserving algorithm with a generalized T-skew-Hamiltonian implicity-restarted Arnoldi method. Our numerical results show that the eigenpairs produced by the proposed structure-preserving method not only preserve the reciprocal property but also possess high efficiency and accuracy.

Tsung-Ming Huang
Dept. of Mathematics
National Taiwan Normal University, Taipei 116, Taiwan
min@ntnu.edu.tw

Wen-Wei Lin
Dept. of Applied Mathematics
National Chiao Tung University, Hsinchu 300, Taiwan
wwlin@math.nctu.edu.tw

Chin-Tien Wu
Dept. of Applied Mathematics
National Chiao Tung University, Hsinchu 300, Taiwan
ctw@math.nctu.edu.tw

Talk 3. **Structure-preserving curve for symplectic pairs**
We study the stabilizing solution of the equation $X + A^*X^{-1}A = Q$, where Q is Hermitian positive definite. We construct a smooth curve, parameterized by $t \geq 1$, of symplectic pairs with a special structure, in which the curve passes through all iteration points generated by the known numerical methods, including the fixed-point iteration, structured preserving doubling algorithm and Newton's method, under specified conditions. We give a necessary and sufficient condition for the existence of this structured symplectic pairs and characterize the behavior of this curve. We also use this curve to measure the convergence rates of these numerical methods. Some numerical results are presented.

Yueh-Cheng Kuo
Dept. of Applied Mathematics
National University of Kaohsiung, Kaohsiung, 811, Taiwan
yckuo@nuk.edu.tw

Shih-Feng Shieh
Dept. of Mathematics
National Taiwan Normal University, Taipei, Taiwan
sfshieh@ntnu.edu.tw

Talk 4. **A doubling algorithm with shift for solving a nonsymmetric algebraic Riccati equation**
In this talk, we analyze a special instance of nonsymmetric algebraic matrix Riccati equation (NARE) arising from transport theory. Traditional approaches for finding the minimal nonnegative solution of NARE are based on the fixed point iteration and the speed of the convergence is linear. Recently, a structure-preserving doubling algorithm (SDA) with quadratic convergence is designed for improving the speed of convergence. Our contribution is to show that applied with a shifted technique, the SDA is guaranteed to converge quadratically with no breakdown. Also, we modify the conventional simple iteration algorithm to dramatically improve the speed of convergence.

Chun-Yueh Chiang
Center for General Education
National Formosa University
chiang@nfu.edu.tw

Matthew M. Lin
Department of Mathematics
National Chung Cheng University
mlin@math.ccu.edu.tw

MS 47. Generalized inverses and applications - Part II of II

Talk 1. **On a partial order defined on certain matrices**
For a given matrix $A \in \mathbb{C}^{m\times n}$, we recall that the weighted Moore-Penrose inverse with respect to two Hermitian positive definite matrices $M \in \mathbb{C}^{m\times m}$ and $N \in \mathbb{C}^{n\times n}$ is the unique solution $X \in \mathbb{C}^{n\times m}$ satisfying the equations: $AXA = A$, $XAX = X$, $(MAX)^* = MAX$, $(NXA)^* = NXA$. This matrix will be used to define a partial order on certain class of complex matrices. Some properties on predecessors and successors of a given matrix in that class will be established.
This paper has been partially supported by Universidad Nacional de La Pampa (Facultad de Ingeniería) of Argentina (grant Resol. N. 049/11) and by the Ministry of Education of Spain (Grant DGI MTM2010-18228).

Néstor Thome
Instituto Universitario de Matemática Multidisciplinar
Universitat Politècnica de València, Spain
njthome@mat.upv.es
Araceli Hernández
Facultad de Ingeniería
Universidad Nacional de La Pampa, General Pico, Argentina
aracelih@ing.unlpam.edu.ar
Marina Lattanzi
Facultad de Ciencias Exactas y Naturales
Universidad Nacional de La Pampa, Santa Rosa, Argentina
mblatt@exactas.unlpam.edu.ar
Fabián Urquiza
Facultad de Ingeniería
Universidad Nacional de La Pampa, General Pico, Argentina
urquizaf@ing.unlpam.edu.ar

Talk 2. **Generalized inverses and path products**
Let $M = [a_{ij}]$ be a lower triangular matrix over an arbitrary ring with unity 1, and set $a_i := a_{ii}$. We may split M as $M = D + N$, where $D = diag(a_1, \ldots, a_n)$ and $N = M - D$. The latter is strictly lower triangular and hence nilpotent. Associated with the matrix M, we will consider the weighted digraph $G = (V, E)$ where $V = \{S_i\}$ is a set of nodes (or sites) and $E = \{(S_i, S_j)\} \in V \times V$ is a collection of arcs such that $(S_i, S_j) \in E$ if $a_{ij} \neq 0$. We add a loop at site S_i if $a_i \neq 0$. We will relate the existence of the generalized inverse, namely von Neumann, group and the Moore-Penrose inverse, of a lower triangular matrix again gives a matrix of the same type by means of path products obtained in the graph associated to the matrix.

Pedro Patrício
Departamento de Matematica e Aplicacções
Universidade do Minho, Portugal
pedro@math.uminho.pt
R. Hartwig
Dept. of Mathematics
N.C.S.U. Raleigh, USA.
hartwig@math.ncsu.edu

Talk 3. **On structured condition numbers for a linear functional of Tikhonov regularized solution**
A structured componentwise and normwise perturbation analysis of Tikhonov regularization problems are presented. The structured matrices we consider include: Toeplitz, Hankel, Vandermonde, and Cauchy matrices. Structured normwise, mixed and componentwise condition numbers for these Tikhonov regularization problems are introduced and their expressions are derived. Such expressions for many other classes of matrices can be similarly derived. By means of the power method, the fast condition estimated algorithms are proposed. The condition numbers and perturbation bounds are examined on some numerical examples and compared with unstructured normwise, mixed and componentwise condition numbers. The numerical examples show that the structured mixed condition numbers give better perturbation bounds than others.

Yimin Wei
Department of Mathematics
Fudan University, P.R. China
ymwei@fudan.edu.cn
Huaian Diao
School of Mathematics and Statistics
Northeast Normal University, Chang Chun 130024, P.R. China.
hadiao@gmail.com

Talk 4. **Explicit characterization of the Drazin index**
Let $\mathbb{B}(X)$ be the set of bounded linear operators on a Banach space X, and $A \in \mathbb{B}(X)$ be Drazin invertible. An element $B \in \mathbb{B}(X)$ is said to be a stable perturbation of A if B is Drazin invertible and $I - A^{\pi} - B^{\pi}$ is invertible, where I is the identity operator on X, A^{π} and B^{π} are the spectral projectors of A and B respectively. Under the condition that B is a stable perturbation of A, a formula for the Drazin inverse B^{D} is derived. Based on this formula, a new approach is provided to the computation of the explicit Drazin indices of certain 2×2 operator matrices

Qingxiang Xu
Department of Mathematics
Shanghai Normal University, Shanghai, 200234, PR China
qingxu@online.sh.cn

MS 48. Parallelization of efficient algorithms

Talk 1. **A highly scalable error-controlled fast multipole method**
We present a linear scaling, error-controlled FMM implementation for long-range interactions of particle systems with open, 1D, 2D and 3D periodic boundary conditions. Similarly to other fast summation algorithms the FMM allows to reduce the total runtime significantly. This runtime advantage however comes with considerably increased memory requirements posing constraints to the overall particle system size. In this talk we focus on the reduced memory footprint as well as the communication pattern for trillions of particles. The current code is designed to lower the memory consumption to only 45Byte/particle already including a small 16.2% parallel overhead for 300k MPI ranks.

Ivo Kabadshow
Jülich Supercomputing Centre
Research Centre Jülich
i.kabadshow@fz-juelich.de
Holger Dachsel
Jülich Supercomputing Centre
Research Centre Jülich
h.dachsel@fz-juelich.de

Talk 2. **A parallel fast Coulomb solver based on nonequispaced Fourier transforms**
The fast calculation of long-range Coulomb interactions is a computational demanding problem in particle simulation. Therefore, several fast approximate algorithms have been developed, which reduce the quadratic arithmetic complexity of the plain summation to linear complexity (up to a logarithmic factor). This talk focuses on Fourier based methods with special attention to the application of the nonequispaced fast Fourier transform and its parallelization.
We present a massively parallel Coulomb solver software library for distributed memory architectures. The underlying fast algorithms for periodic and non-periodic boundary conditions will be explained and extensive performance evaluations will be presented.

Michael Pippig
Dept. of Mathematics
Chemnitz University of Technology
michael.pippig@mathematik.tu-chemnitz.de

Talk 3. **Generalized fast Fourier transforms via CUDA**
The fast Fourier transform (FFT) belongs to the algorithms with large impact on science and engineering. By appropriate approximations, this scheme has been generalized for arbitrary spatial sampling points. We discuss the computational costs in detail for this so called nonequispaced FFT and its variations.

Because of the evolution of programmable graphic processor units into highly parallel, multithreaded, manycore processors with enormous computational capacity and very high memory bandwith, we parallelized the nonequispaced FFT by means of the so called Compute Unified Device Architecture (CUDA) using the CUDA FFT library and a dedicated parallelization of the approximation scheme.

Susanne Kunis
Dept. of Mathematics
University of Osnabrück
susanne.kunis@uos.de

Talk 4. **Efficient regularization and parallelization for sparse grid regression**

Regression, (high-dimensional) function reconstruction from scattered data, is a common problem in data-driven tasks. Typically, meshfree methods are employed to circumvent the curse of dimensionality. To deal with regression by discretizing the feature space, sparse grids can be employed. Due to their primarily data-independent approach, sparse grids enable one to deal with massive amounts of data. Adaptive refinement then allows to adapt to the pecularities of the problem at hand.
To be able to deal with large, noisy datasets, efficient algorithms and parallelizations have to be employed, and the full potential of modern hardware architectures has to be exploited. This can be complicated having to deal with hierarchical basis functions on multiple levels. We present the special challenges posed to hierarchical and recursive sparse grid algorithms and discuss efficient solutions for regularization and parallelization.

Dirk Pflüger
Dept. of Informatics
Technische Universität München
pflueged@in.tum.de

Alexander Heinecke
Dept. of Informatics
Technische Universität München
heinecke@in.tum.de

MS 49. Analysis and computation on matrix manifold

Talk 1. **Best low multilinear rank approximation of symmetric tensors by Jacobi rotations**

We consider third-order symmetric tensors and seek their best low multilinear rank approximations. The proposed algorithm is based on Jacobi rotations and symmetry is preserved at each iteration. Examples are provided that illustrate the need of such algorithms. Our algorithm converges to stationary points of the objective function. The proof of convergence can be considered as an advantage of the algorithm over existing symmetry-preserving algorithms in the literature.

Pierre-Antoine Absil
Department of Mathematical Engineering, ICTEAM Institute
Université catholique de Louvain
absil@inma.ucl.ac.be

Mariya Ishteva
School of Computational Science and Engineering
Georgia Institute of Technology
mariya.ishteva@cc.gatech.edu

Paul Van Dooren
Department of Mathematical Engineering, ICTEAM Institute
Université catholique de Louvain
paul.vandooren@uclouvain.be

Talk 2. **Differential geometry for tensors with fixed hierarchical Tucker rank**

A number of authors have recently proposed several geometries for rank-structured matrix and tensor spaces, namely for matrices or tensors with fixed matrix, Tucker, and TT rank. In this talk we present a unifying approach for establishing a smooth, differential structure on the set of tensors with fixed hierarchical Tucker rank. Our approach describes this set as a smooth submanifold, globally embedded in the space of real tensors. The previous spaces are shown to be specific instances of a particular hierarchical Tucker tree (possibly with additional constraints on the frames). As numerical example we show how this geometry can be used to dynamically update a time-varying tensor. This approach compares favorable to point-wise SVD-based computations.

Bart Vandereycken
Mathematics Section, ANCHP
École Polytechnique Fédérale de Lausanne
bart.vandereycken@epfl.ch

André Uschmajew
Department of Mathematics
Technische Universität (TU) Berlin
uschmajew@math.tu-berlin.de

Talk 3. **Deterministic approaches to the Karcher mean of positive definite matrices**

We propose a deterministic approach to the Karcher mean of positive definite matrices via geometric power means. For a matrix geometric mean G, we construct one-parameter group G_t of geometric means varying continuously over $t \in [-1, 1] \setminus \{0\}$ and approaching the Karcher mean as $t \to 0$. Each of these means arises as unique positive definite solution of a non-linear matrix equation and has the distance less $\leq \sqrt{t/2}$ to the Karcher mean. This provides not only a structured and deterministic sequence of matrix means converging to the Karcher mean, but also a simple proof of the monotonicity of the Karcher mean, conjectured by Bhatia and Holbrook, and other new properties, which have recently been established by Lawson and Lim and also Bhatia and Karandikar using probabilistic methods on the metric structure of positive definite matrices equipped with the trace metric.

Yongdo Lim
Dept. of Mathematics
Kyungpook National University
ylim@knu.ac.kr

Talk 4. **The Karcher mean: first and second order optimization techniques on matrix manifolds**

In this talk, we present a collection of implementations for the Karcher mean, which is a specific instance of the matrix geometric mean. The Karcher mean is defined as the solution to an optimization problem on the manifold of positive definite matrices, where it exhibits an appealing analogy with the arithmetic mean. Generalization of classical optimization schemes results in Riemannian optimization, where the intrinsic properties of the manifold are maintained and exploited throughout the algorithm. We examine several optimization techniques, such as SD, CG, Trust Region, and BFGS, and compare the results with the ALM, BMP and CHEAP mean algorithms.

Ben Jeuris
Dept. of Computer Science
Katholieke Universiteit Leuven
ben.jeuris@cs.kuleuven.be

Raf Vandebril

Dept. of Computer Science
Katholieke Universiteit Leuven
raf.vandebril@cs.kuleuven.be

Bart Vandereycken
Mathematics Institute of Computational Science and Engineering
École Polytechnique Fédérale de Lausanne
bart.vandereycken@epfl.ch

MS 50. Advanced methods for large eigenvalue problems and their applications

Talk 1. **DQDS with aggressive early deflation for computing singular values**
The DQDS algorithm is the standard method for computing all the singular values of a bidiagonal matrix with high relative accuracy. Its efficient implementation is now available as a LAPACK subroutine DLASQ. In order to reduce the DQDS runtime, we incorporate into DQDS a technique called aggressive early deflation, which has been applied successfully to the Hessenberg QR algorithm. In addition, a shift-free version of our algorithm has a potential to be parallelized in a pipelined fashion. Our mixed forward-backward stability analysis proves that with our proposed deflation strategy, DQDS computes all the singular values to high relative accuracy.

Kensuke Aishima
Dept. of Mathematics of Informatics
University of Tokyo
Kensuke_Aishima@mist.i.u-tokyo.ac.jp

Yuji Nakatsukasa
School of Mathematics
University of Manchester
yuji.nakatsukasa@manchester.ac.uk

Ichitaro Yamazaki
Dept. of Computer Science
University of Tennessee
ic.yamazaki@gmail.com

Talk 2. **A scalable parallel method for large-scale nonlinear eigenvalue problems**
In this presentation, we present parallel software for nonlinear eigenvalue problems that has interfaces for PETSc. The software implements an eigensolver based on contour integral. It finds a partial set of eigenpairs of large sparse nonlinear eigenvalue problems and has high scalability. We demonstrate parallel performance of the implemented method through numerical experiments arising from several practical applications.

Kazuma Yamamoto
Dept. of Computer Science
University of Tsukuba
yamamoto@mma.cs.tsukuba.ac.jp

Yasuyuki Maeda
Dept. of Computer Science
University of Tsukuba
maeda@mma.cs.tsukuba.ac.jp

Yasunori Futamura
Dept. of Computer Science
University of Tsukuba
futamura@mma.cs.tsukuba.ac.jp

Tetsuya Sakurai
Dept. of Computer Science
University of Tsukuba
sakurai@cs.tsukuba.ac.jp

Talk 3. **Application of the Sakurai-Sugiura method in the field of density functional theory on highly parallel systems**
Density Functional Theory (DFT) is one of the most important methods in computational material science. Despite the steadily increasing computational power, computation time is still the limiting factor for many systems of interest. In many cases the most time consuming part is solving a series of generalized eigenvalue problems that emerge inside an iterative loop. In the context of Siesta, a widely spread DFT software, the Sakurai-Sugiura method is a promising approach. This talk will show how, due to its three obvious levels of parallelization, this algorithm scales much better than other widely used libraries (e.g. ScaLAPACK), how it offers possibilities to use many GPUs in parallel, and how it also supports dealing with sparse matrices.

Georg Huhs
Barcelona Supercomputing Center,
Centro Nacional de Supercomputacion, Barcelona, Spain
georg.huhs@bsc.es

Talk 4. **MERAM for neutron physics applications using YML environment on post petascale heterogeneous architecture**
Eigenvalue problem is one of the key elements in neutron physics applications. Studying and designing efficient and sacalable eigenvalue solvers is thus necessary for post petascale neutrons physics applications. In this talk, after recalling the principle of multiple explicitly restarted Arnoldi method (MERAM), we will present the design model used for its implementation on distributed heterogeneous architectures. The performance results on CURIE and GRID5000 platforms making use of the software environments KASH (Krylov bAsed Solvers for Hybrid architectures) YML and PETSc/SLEPc for typical neutron physics problems will be presented.

Christophe Calvin
CEA DEN DANS DM2S SERMA CEA Saclay
christophe.calvin@cea.fr

Nahid Emad
University of Versailles
Nahid.Emad@prism.uvsq.fr

Serge G. Petiton
INIRIA University of Lille
serge.petiton@lifl.fr

Jérôme Dubois
CEA DEN DANS DM2S SERMA CEA Saclay
jerome.dubois@cea.fr

Makarem Dandouna
University of Versailles
makarem.dandouna@prism.uvsq.fr

MS 51. Accurate and verified numerical computations for numerical linear algebra

Talk 1. **Product decomposition and its applications**
A product decomposition algorithm of a real number on floating point system is proposed. The product decomposition of a real number x is a floating point decomposition defined by

$$x \simeq \tilde{x}_1 \left(1 + \tilde{x}_2\right) \left(1 + \tilde{x}_3\right) \cdots \left(1 + \tilde{x}_n\right),$$

where $\tilde{x}_i$ denote floating point numbers $(1 \leq i \leq n)$. $\tilde{x}_1$ implies an approximation of x and $\tilde{x}_i$ $(2 \leq i \leq n)$ involve approximations of relative errors of an approximate value by the decomposition using $\tilde{x}_1, \tilde{x}_2, \cdots, \tilde{x}_{i-1}$. This decomposition is used in numerical analysis to calculate the accurate logarithm value and so on. In this talk we present an efficient algorithm to construct the product decomposition and its applications.

Naoya Yamanaka
Research Institute for Science and Engineering, Waseda University
naoya_yamanaka@suou.waseda.jp

Shin'ichi Oishi

Faculty of Science and Engineering, Waseda University
oishi@waseda.jp

Talk 2. **The MPACK: multiple precision version of BLAS and LAPACK**

We have been developing a multiple precision version of linear algebra package based on BLAS and LAPACK. We translated and reimplimented FORTRAN by C++, and the MPACK supports GMP, MPFR, and QD (DD) multiple precision libraries; users can choose the library on their needs. Currently BLAS part is completed and 100 LAPACK routines are implemented and well tested. Moreover DD version of matrix-matrix multiplication routine has been accelerated using NVIDIA C2050 GPU. Development is ongoing at http://mplapack.sourceforge.net/, and available under open source (2-clause BSD) license.

Maho Nakata
Advanced Center for Computing and Communication, RIKEN
maho@riken.jp

Talk 3. **On eigenvalue computations of nonderogatory matrices**

In this talk I present some problems and results concerning the eigenvalue problem of nonderogatory matrices. The first group of problems is related to the detection of multiple eigenvalues of unreduced upper Hessenberg matrices and their refinements in multiple floating point arithmetic. The second group of problems is the perturbation of invariant subspaces and its characterizations in terms of the matrix perturbation.

Aurél Galántai
Institute of Intelligent Engineering Systems
Óbuda University, 1034 Budapest, Bécsi út 96/b, Hungary
galantai.aurel@nik.uni-obuda.hu

Talk 4. **Verified solutions of sparse linear systems**

Algorithms for calculating verified solutions of sparse linear systems are proposed. The proposed algorithms are based on standard numerical algorithms for a block $\mathrm{LDL}^{\mathrm{T}}$ factorization and error estimates for specified eigenvalues by Lehmann's theorem. Numerical results are presented for illustrating the performance of the proposed algorithms.

Takeshi Ogita
Division of Mathematical Sciences
Tokyo Woman's Christian University
ogita@lab.twcu.ac.jp

MS 52. Numerical linear algebra libraries for high end computing - Part I of II

Talk 1. **Large-scale eigenvalue computation with PETSc and YML**

In the context of parallel and distributed computation, the currently existing numerical libraries do not allow sequential and parallel code reuse. Besides, they are not able to exploit the multi-level parallelism offered by modern emerging numerical methods.

In this talk, we present a design model for numerical libraries based on a component approach allowing code reuse and problem solving scalability. We present then, an implementation of this design using YML scientific workflow environment jointly with the object oriented library PETSc. Some numerical experiments on GRID5000 platform and NERSC computers validate our approach and show its efficiency.

Makarem Dandouna
PRISM laboratory, University of Versailles, France
makarem.dandouna@prism.uvsq.fr

Nahid Emad
PRISM laboratory University of Versailles, France
nahid.emad@prism.uvsq.fr

L. A. (Tony) Drummond
Computational Research Division, Lawrence Berkeley National Laboratory, USA
ladrummond@lbl.gov

Talk 2. **Sparse matrix-matrix operations in PETSc**

Sparse matrix-matrix operations, $A * B$, $A^T * B$ (or $A * B^T$) and $P^T * A * P$ (or $R * A * R^T$), are computational kernels in the PETSc library. Recent addition of a geometric-algebraic multigrid preconditioner requires these matrix operations to be scalable to tens of thousands processors cores, which forces us to take an innovated approach in algorithm design and implementations for these operations, including some relevant data structures. In this talk, we will present our newly developed scalable sparse matrix-matrix algorithms, implementations and performance, along with lessons learned and experiences gained from this work.

Hong Zhang
Dept. of Computer Science Department, Illinois Institute of Technology, USA and Argonne National Laboratory, USA
hzhang@mcs.anl.gov

Barry Smith and PETSc Team
Mathematics and Computer Science Division, Argonne National Laboratory, USA
bsmith@mcs.anl.gov

Talk 3. **Hierarchical QR factorization algorithms for multi-core cluster systems**

This paper describes a new QR factorization algorithm which is especially designed for massively parallel platforms combining parallel distributed multi-core nodes. These platforms make the present and the foreseeable future of high-performance computing. Our new QR factorization algorithm falls in the category of the tile algorithms which naturally enables good data locality for the sequential kernels executed by the cores (high sequential performance), low number of messages in a parallel distributed setting (small latency term), and fine granularity (high parallelism).

Julien Langou
University of Colorado Denver, USA
supported by the National Science Foundation grant # NSF CCF 1054864
julien.langou@ucdenver.edu

Jack Dongarra
University of Tennessee Knoxville, USA
Oak Ridge National Laboratory, USA
Manchester University, UK
dongarra@eecs.utk.edu

Mathieu Faverge
University of Tennessee Knoxville, USA
mfaverge@eecs.utk.edu

Thomas Herault
University of Tennessee Knoxville, USA
therault@eecs.utk.edu

Yves Robert
University of Tennessee Knoxville, USA
Ecole Normale Supérieure de Lyon, France
yves.robert@ens-lyon.fr

Talk 4. **Towards robust numerical algorithms for exascale simulation**

The advent of exascale machines will require the use of parallel resources at an unprecendent scale, leading to a high rate of

hardware faults. High Performance Computing applications that aim at exploiting all these resources will thus need to be resilient, i.e., being able to compute a correct output in presence of faults. Contrary to checkpointing techniques or Algorithm Based Fault Tolerant (ABFT) mechanisms, strategies based on interpolation for recovering lost data do not require extra work or memory when no fault occurs. We apply this latter strategy to Krylov iterative solvers, which are often the most computational intensive kernels in HPC simulation codes. Our main contribution is the proposition and discussion of several variants compared to previous works. For that, we propose a new variant for recovering data, we study the occurrence of multiple faults, we consider the GMRES, CG and BICGSTAB solvers, and we inject faults according to an advanced model of fault distribution. We assess the impact of the recovery method, the fault rate and the number of processors on resilience. Rather than implementing a particular actual parallel code, we assess all our strategies based on sequential Matlab implementations that simulate parallel executions.

Emmanuel Agullo
INRIA Bordeaux - Sud-Ouest, 351, Cours de la Libération, Bâtiment A29 bis, 33405 Talence Cedex France
Emmanuel.Agullo@inria.fr

Luc Giraud
INRIA Bordeaux - Sud-Ouest, France
Luc.Giraud@inria.fr

Abdou Guermouche
INRIA Bordeaux - Sud-Ouest, France
abdou.guermouche@inria.fr

Jean Roman
INRIA, France
Jean.Roman@labri.fr

Mawussi Zounon
INRIA, France
mawussi.zounon@inria.fr

MS 53. Efficient preconditioners for real world applications - Part I of II

Talk 1. **A parallel factored preconditioner for non-symmetric linear systems**
The efficient solution to non-symmetric linear systems is still an open issue on parallel computers. In this communication we generalize to the non-symmetric case the Block FSAI (BFSAI) preconditioner which has already proved very effective on symmetric problems arising from different applications. BFSAI is a hybrid approach combining an "inner" preconditioner, with the aim of transforming the system in a block diagonal one, with an "outer" one, a block diagonal incomplete decomposition, intended to decrease the conditioning of each block. The proposed algorithm is experimented with in a number of large size problems showing both good robustness and scalability.

Carlo Janna
Dept. of Mathematical Methods and Models for Scientific Applications
University of Padova, Italy
carlo.janna@unipd.it

Massimiliano Ferronato
Dept. of Mathematical Methods and Models for Scientific Applications
University of Padova, Italy
massimiliano.ferronato@unipd.it

Giorgio Pini
Dept. of Mathematical Methods and Models for Scientific Applications
University of Padova, Italy
giorgio.pini@unipd.it

Talk 2. **Preconditioning for linear least-squares problems**
In this talk we deal with iterative methods for solving large and sparse linear least squares problems. In particular we describe two new preconditioning techniques for the CGLS method. First we consider the strategy which is based on the LU factorization. Our approach includes a new reordering based on a specific weighting transversal problem. Direct preconditioning of the normal equations by the balanced symmetric and positive definite factorization is our second approach. Numerical experiments demonstrate effectiveness of the algorithmic and implementational features of the new approaches.

Miroslav Tůma
Institute of Computer Science
Academy of Sciences of the Czech Republic
tuma@cs.cas.cz

Rafael Bru
Institut de Matemàtica Multidisciplinar
Universitat Politècnica de Valencia
rbru@imm.upv.es

José Mas
Institut de Matemàtica Multidisciplinar
Universitat Politècnica de Valencia
jmasm@imm.upv.es

José Marín
Institut de Matemàtica Multidisciplinar
Universitat Politècnica de Valencia
jmarinma@imm.upv.es

Talk 3. **Robust and parallel preconditioners for mechanical problems**
We consider the simulation of displacements under loading for mechanical problems. Large discontinuities in material properties, lead to ill-conditioned systems of linear equations, which leads to slow convergence of the Preconditioned Conjugate Gradient (PCG) method. This paper considers the Recursively Deflated Preconditioned Conjugate Gradient (RDPCG) method for solving such systems. Our deflation technique uses as deflation space the rigid body modes of sets of elements with homogeneous material properties. We show that in the deflated spectrum the small eigenvalues are mapped to zero and no longer negatively affect the convergence. We justify our approach through mathematical analysis and we show with numerical experiments on both academic and realistic test problems that the convergence of our RDPCG method is independent of discontinuities in the material properties.

Kees Vuik
Delft Institute of Applied Mathematics
Technology University of Delft, The Netherlands
c.vuik@math.tudelft.nl

Tom Jönsthövel
Delft Institute of Applied Mathematics
Technology University of Delft, The Netherlands
t.b.jonsthovel@tudelft.nl

Martin van Gijzen
Delft Institute of Applied Mathematics
Technology University of Delft, The Netherlands
m.b.vangijzen@tudelft.nl

Talk 4. **Block factorized forms of SPAI**
In this talk we present new results on block versions of sparse approximate inverse preconditioners M for sparse matrix A. We consider the Frobenius norm minimization $\min_M \|AM - I\|_F$. Blocked versions are interesting because often the underlying problem introduces in a natural way a block structure. Furthermore, they allow a more efficient memory access, and

they reduce the number of least squares problems that have to be considered in the construction of the preconditioner M. We are interested in determining appropriate block patterns for a general sparse matrix. Therefore, we want to combine columns of M with similar least squares problems to blocks in order to reduce the number of least squares problems that have to be solved for constructing the preconditioner. Furthermore, given an arbitrary blocking we also have to find the nonzero blocks that we have to include to derive a good preconditioner.

Thomas Huckle
Institut für Informatik
Technische Universität München, Germany
huckle@in.tum.de

Matous Sedlacek
Institut für Informatik
Technische Universität München, Germany
sedlacek@in.tum.de

MS 54. Solving ill-posed systems via signal-processing techniques - Part I of II

Talk 1. **Sequential updates for L1 minimization: sparse Kalman filtering, reweighted L1, and more**
Sparse signal recovery often involves solving an L1-regularized optimization problem. Most of the existing algorithms focus on the static settings, where the goal is to recover a fixed signal from a fixed system of equations. In this talk, we present a collection of homotopy-based algorithms that dynamically update the solution of the underlying L1 problem as the system changes. The sparse Kalman filter solves an L1-regularized Kalman filter equation for a time-varying signal that follows a linear dynamical system. Our proposed algorithm sequentially updates the solution as the new measurements are added and the old measurements are removed from the system.

Justin Romberg
Electrical and Computer Engineering
Georgia Institute of Technology
jrom@gatech.edu

M. Salman Asif
Electrical and Computer Engineering
Georgia Institute of Technology
sasif@gatech.edu

Talk 2. **Solving basis pursuit: infeasible-point subgradient algorithm, computational comparison, and improvements**
We propose a subgradient algorithm called ISAL1 for the l1-minimization (Basis Pursuit) problem which applies approximate projections via a truncated CG scheme. We will also present results of an extensive computational comparison of our method and various state-of-the-art l1-solvers on a large testset. It turns out our algorithm compares favorably. Moreover, we show how integrating a new heuristic optimality check called HSE can improve the solution speed and accuracy of several of these solvers.

Andreas Tillmann
Institute for Mathematical Optimization
Technische Universität Braunschweig
a.tillmann@tu-bs.de

Dirk Lorenz
Institute for Analysis and Algebra
Technische Universität Braunschweig
d.lorenz@tu-bs.de

Marc Pfetsch
Institute for Mathematical Optimization
Technische Universität Braunschweig
m.pfetsch@tu-bs.de

Talk 3. **Semismooth Newton methods with multi-dimensional filter globalization for l_1 optimization**
We present a class of methods for l_1-regularized optimization problems. They are based on a flexible combination of semismooth Newton steps and globally convergent descent methods. A multidimensional filter framework is used to control the acceptance of semismooth Newton steps. We prove global convergence and transition to fast local convergence for both the convex and the nonconvex case. Numerical results show the efficiency of the method.

Andre Milzarek
Department of Mathematics, TopMath
Technische Universität Muenchen
milzarek@ma.tum.de

Michael Ulbrich
Chair of Mathematical Optimization
Technische Universität Muenchen
mulbrich@ma.tum.de

Talk 4. **Improved first-order methods: how to handle constraints, non-smoothness, and slow convergence**
There are many specialized solvers that solve specific convex programs efficiently, but few algorithms can deal with general complicated constraints and non-smooth functions. To address these difficult problems, we introduce a framework and software package called TFOCS (Becker/Candès/Grant). The method relies on two tricks: dualization and smoothing. This talk describes the framework and also discusses recent splitting methods such as the method by Chambolle and Pock and by Combettes et al. We also cover recent progress in improving the convergence of first-order algorithms by using non-diagonal preconditioners (with J. Fadili).

Stephen Becker
FSMP, laboratoire Jacques-Louis Lions
UPMC (Paris-6)–CNRS
stephen.becker@upmc.fr

Jalal Fadili
CNRS-ENSICAEN
Université de Caen
Jalal.Fadili@ensicaen.fr

Emmanuel Candès
Departments of Mathematics and Statistics
Stanford University
candes@stanford.edu

Michael Grant
CVX Research
mcg@cvxr.com

MS 55. Max-algebra - Part I of II

Talk 1. **Tropical bounds for the eigenvalues of structured matrices**
We establish several inequalities of log-majorization type, relating the moduli of the eigenvalues of a complex matrix or matrix polynomial with the tropical eigenvalues of auxiliary matrix polynomials. This provides bounds which can be computed by combinatorial means. We consider in particular structured matrices and obtain bounds depending on the norms of block submatrices and on the pattern (graph structure) of the matrix.

Marianne Akian
INRIA Saclay–Ile-de-France and CMAP

CMAP, Ecole Polytechnique, Route de Saclay, 91128 Palaiseau Cedex, France
marianne.akian@inria.fr

Stéphane Gaubert
INRIA Saclay–Ile-de-France and CMAP
CMAP, Ecole Polytechnique, Route de Saclay, 91128 Palaiseau Cedex, France
stephane.gaubert@inria.fr

Meisam Sharify
INRIA Saclay–Ile-de-France and LRI
LRI, Bât 650 Université Paris-Sud 11 91405 Orsay Cedex, France
Meisam.Sharify@inria.fr

Talk 2. **Sensitivity in extremal systems of linear equations and inequalities**
A survey of some recent results concerning the properties of finite systems of linear equations and inequalities in extremal algebra will be presented. Problems connected with sensitivity and parametric analysis of such systems will be discussed. Possible applications of the results for post-optimal analysis of optimization problems, the set of feasible solutions of which is described by the systems of (max, min) and (max, plus) linear systems, will be shown. The objective functions of the optimization problems are expressed as the maximum of finitely many continuous functions, each depending on one variable.

Karel Zimmermann
Faculty of Mathematics and Physics
Charles University in Prague, Czech Republic
Karel.Zimmermann@mff.cuni.cz

Martin Gavalec
Faculty of Informatics and Management
University of Hradec Králové, Czech Republic
Martin.Gavalec@uhk.cz

Talk 3. **Multiplicative structure of tropical matrices**
I shall report on a programme of research aiming to understand the structure of tropical (max-plus) matrix semigroups. This structure turns out to be intimately connected with the geometry of tropical convexity; indeed, it transpires that almost every algebraic property of the full $n \times n$ tropical matrix semigroup manifests itself in some beautiful geometric phenomenon involving polytopes. Various parts of the programme are joint work with people including Christopher Hollings, Zur Izhakian and Marianne Johnson.

Mark Kambites
School of Mathematics
University of Manchester
Mark.Kambites@manchester.ac.uk

Talk 4. **Transience bounds for matrix powers in max algebra**
In this talk we demonstrate how the concept of CSR expansions developed by Schneider and Sergeev helps to unify and compare the bounds on periodicity transient existing in the literature. Unlike in the theory of graph exponents, these bounds are not strongly polynomial. To this end, we also present some max-algebraic extensions of polynomial bounds on graph exponents, due to Wielandt and Schwartz.

Sergeĭ Sergeev
School of Mathematics
University of Birmingham, UK
sergiej@gmail.com

MS 56. Eigenvalue perturbations and pseudospectra - Part I of II

Talk 1. **Inclusion theorems for pseudospectra of block triangular matrices**
The ϵ-pseudospectrum of $A \in \mathbb{C}^{n\times n}$, denoted by $\sigma_\epsilon(A)$, is the union of the spectra of the matrices $A + E$, where $E \in \mathbb{C}^{n\times n}$ and $\|E\|_2 \leq \epsilon$. In this talk we consider inclusion relations of the form

$$\begin{aligned}\sigma_{f(\epsilon)}(A_{11}) \cup \sigma_{f(\epsilon)}(A_{22}) &\subseteq \sigma_\epsilon\left(\begin{bmatrix} A_{11} & A_{12} \\ 0 & A_{22}\end{bmatrix}\right) \\ &\subseteq \sigma_{g(\epsilon)}(A_{11}) \cup \sigma_{g(\epsilon)}(A_{22}).\end{aligned}$$

We derive formulae for $f(\epsilon)$ and $g(\epsilon)$ in terms of $\mathrm{sep}_\lambda(A_{11}, A_{22})$ and $\|R\|_2$, where R is the solution of the Sylvester equation $A_{11}R - RA_{22} = A_{12}$.

Michael Karow
Dept. of Mathematics
Technical University of Berlin
karow@math.tu-berlin.de

Talk 2. **Conjectures on pseudospectra of matrices**
We discuss some conjectures concerning coalescence points of connected components of pseudospectra of a square complex matrix A. We call pseudospectrum of A of order j and level ε, $\Lambda_{\varepsilon,j}(A)$, to the set of eigenvalues of multiplicity $\geq j$ of matrices whose distance to A is $\leq \varepsilon$.

- The coalescence points of the components of $\Lambda_{\varepsilon,j}(A)$ are points where the pseudospectra $\Lambda_{\varepsilon,j+1}(A)$ arise from.
- The coalescence points of the components of $\Lambda_{\varepsilon,1}(A)$ are in line segments connecting eigenvalues of A, and analogously for $\Lambda_{\varepsilon,j}(A)$.

Juan-Miguel Gracia
Dept. of Applied Mathematics and Statistics
University of the Basque Country UPV/EHU, Spain
juanmiguel.gracia@ehu.es

Talk 3. **Sensitivity of eigenvalues of an unsymmetric tridiagonal matrix**
The Wilkinson condition number ignores the tridiagonal form and so can be unduly pessimistic. We propose several *relative* condition numbers that exploit the tridiagonal form. Some of these numbers are derived from different factored forms (or representations) of the (possibly shifted) matrix and so they shed light on which factored forms are best for computation. We show some interesting examples.

Carla Ferreira
Mathematics and Applications Department
University of Minho, Portugal
caferrei@math.uminho.pt

Beresford Parlett
University of California, Berkeley

Froilán Dopico
Universidad Carlos III de Madrid, Spain

Talk 4. **First order structured perturbation theory for eigenvalues of skew-adjoint matrices**
The main goal of structured matrix perturbation theory is to identify situations where eigenvalues are much less sensitive to structured perturbations (i.e., those belonging to the same kind of matrices as the unperturbed one) than to unstructured ones. In this talk we analyze one such situation: the relevant structure is skew-adjointness with respect to an indefinite scalar product. Explicit formulas are obtained for both the leading exponent and the leading coefficient of asymptotic perturbation expansions when the perturbations are taken to be also skew-adjoint. Using

the Newton diagram as the main tool, it is shown that the leading coefficient depends on both first (i.e., eigenvectors) and second vectors in the longest Jordan chains associated with the eigenvalue under study.

Julio Moro
Departamento de Matemáticas
Universidad Carlos III de Madrid
Madrid (Spain)
jmoro@math.uc3m.es

María José Peláez
Departamento de Matemáticas
Universidad Católica del Norte
Antofagasta (Chile)
mpelaez@ucn.cl

MS 57. Numerical linear algebra and optimization in imaging applications - Part I of II

Talk 1. **Some numerical linear algebra and optimization problems in spectral imaging**
In this talk we overview some of our recent work on numerical algorithms for spectral image analysis. Spectral imaging collects and processes image information from across the electromagnetic spectrum (often represented visually as a cube), and has a wide array of modern applications, for example in remote sensing for ecology and surveillance. Here we describe some of our work on the design and analysis of mathematical techniques for compressive sensing, processing, and analysis of spectral data. Topics considered include: (1) random SVD methods for dimensionality reduction, (2) joint reconstruction and classification of spectral images, and (3) applications of unmixing, clustering and classification methods to target identification. Tests on real data are described.
This represents is joint work with several people, including team members on projects funded by the U.S. Air Force Office of Scientific Research and the National Geospatial-Intelligence Agency.

Bob Plemmons
Depts. of Computer Science and Mathematics
Wake Forest University
plemmons@wfu.edu

Jennifer Erway
Dept. of Mathematics
Wake Forest University
erwayjb@wfu.edu

Nicolas Gillis
Dept. of Combinatorics & Optimization
University of Waterloo
ngillis@uwaterloo.ca

Xiaofei Hu
Dept. of Mathematics
Wake Forest University
hux@wfu.edu

Michael Ng
Dept. of Mathematics
Hong Kong Baptist University
mng@math.hkbu.edu.hk

Paul Pauca
Dept. of Computer Science
Wake Forest University
paucavp@wfu.edu

Sudhakar Prasad
Dept. of Astronomy and Physics
University of New Mexico
sprasad@unm.edu

Jiani Zhang
Dept. of Mathematics
Wake Forest University
zhanj210@wfu.edu

Qiang Zhang
Dept. of Health Sciences
Wake Forest University
qizhang@wakehealth.edu

Talk 2. **Image restoration via constrained optimization: an approach using feasible direction methods**
Image restoration is an ill-posed inverse problem which requires regularization. Regularization leads to reformulate the original restoration problem as a constrained optimization problem where the objective function is a regularization term and the constraint imposes fidelity to the data.
In this talk, we present a feasible direction method for obtaining restored images as solutions of the optimization problem. The presented method computes feasible search directions by inexactly solving trust region subproblems whose radius is adjusted in order to maintain feasibility of the iterates. Numerical results are presented to illustrate the effectiveness and efficiency of the proposed method.

Germana Landi
Dept. of Mathematics
University of Bologna
germana.landi@unibo.it

Talk 3. **On the solution of linear systems in Newton-type methods for image reconstruction**
Some imaging applications are usually modeled as a minimization problem with nonnegative constraints on the solution. For large size problems, projected-Newton methods are very attractive because of their fast convergence. In order to make them computationally competitive, the inner linear system for the search direction computation should be solved efficiently. In this talk we focus on the solution of the linear system when different objective functions are considered. The objective function is related to the application, to the noise affecting the recorded image and to the kind of regularization chosen.

Elena Piccolomini
Dept. of Mathematics
University of Bologna
elena.loli@unibo.it

Talk 4. **Alternating direction optimization for convex inverse problems. Application to imaging and hyperspectral unmixing**
In this talk I will address a new class of fast of algorithms for solving convex inverse problems where the objective function is a sum of convex terms with possibly convex constraints. Usually, one of terms in the objective function measures the data fidelity, while the others, jointly with the constraints, enforce some type of regularization on the solution. Several particular features of these problems (huge dimensionality, nonsmoothness) preclude the use of off-the-shelf optimization tools and have stimulated a considerable amount of research. In this talk, I will present a new class of algorithms to handle convex inverse problems tailored to image recovery applications and to hyperspectral unmixing. The proposed class of algorithms is an instance of the so-called alternating direction method of multipliers (ADMM), for which convergence sufficient conditions are known. We show that these conditions are satisfied by the proposed algorithms. The effectiveness of the proposed approach is illustrated in a series of imaging inverse problems, including

deconvolution and reconstruction from compressive observations, and hyperspectral unmixing problems, including sparse unmixing and positive matrix factorization.

Jose Bioucas-Dias
Instituto de Telecomunicaes and Department of Electrical and Computer Engineering,
Instituto Superior Tcnico, Portugal
bioucas@lx.it.pt

Mario Figueiredo
Instituto de Telecomunicaes and Department of Electrical and Computer Engineering,
Instituto Superior Tcnico, Portugal
mtf@lx.it.pt

MS 58. Parametric eigenvalue problems - Part I of II

Talk 1. **Computing double eigenvalues via the two-parameter eigenvalue problem**
A task of computing all values of the parameter λ, such that the matrix $A + \lambda B$ has a double eigenvalue, can be interpreted as a singular (quadratic) two-parameter eigenvalue problem. Using a numerical method for the singular two-parameter eigenvalue problem it is possible to obtain all solutions as eigenvalues of a certain generalized eigenvalue problem.

Bor Plestenjak
IMFM & Department of Mathematics
University of Ljubljana
bor.plestenjak@fmf.uni-lj.si

Andrej Muhič
IMFM & Department of Mathematics
University of Ljubljana
andrej.muhic@fmf.uni-lj.si

Talk 2. **Lyapunov inverse iteration for identifying Hopf bifurcations in models of incompressible flow**
The identification of instability in large-scale dynamical systems caused by Hopf bifurcation is difficult because of the problem of computing the rightmost pair of complex eigenvalues of large sparse generalised eigenvalue problems. A method developed in [Meerbergen & Spence, SIMAX (2010), pp.1982-1999] avoids this computation, instead performing an inverse iteration for a certain set of real eigenvalues that requires the solution of a large-scale Lyapunov equation at each iteration. This talk discusses a refinement of the method of Meerbergen & Spence and tests it on challenging problems arising from fluid dynamics.

Alastair Spence
Dept. of Mathematical Sciences
University of Bath, UK
a.spence@bath.ac.uk

Howard Elman
Dept. of Computer Science
University of Maryland, USA
elman@cs.umd.edu

Karl Meerbergen
Dept. of Computer Science
Katholieke Universiteit Leuven, Belgium
Karl.Meerbergen@cs.kuleuven.be

Minghao Wu
Dept. of Applied Mathematics & Statistics
University of Maryland, USA
mwu@math.umd.edu

Talk 3. **A quadratically convergent algorithm for matrix distance problems**
We discuss a method for the computation of the distance of a stable matrix to the unstable matrices with respect to the open left-half plane. First, we provide a fast algorithm to compute the *complex unstructured stability radius*. Second, based on a formula by Qiu et al. (Automatica, 31 (1995), pp. 879–890) we give a new fast method to compute the *real structured stability radius*. Both algorithms are based on finding Jordan blocks corresponding to a pure imaginary eigenvalue in a parameter-dependent Hamiltonian eigenvalue problem. Numerical results show the performance of both algorithms for several examples.

Melina A. Freitag
Dept. of Mathematical Sciences
University of Bath
M.A.Freitag@bath.ac.uk

Alastair Spence
Dept. of Mathematical Sciences
University of Bath
A.Spence@bath.ac.uk

Talk 4. **A real Jacobi-Davidson algorithm for the 2-real-parameter eigenvalue problem**
We consider the nonlinear eigenvalue problem

$$(i\omega M + A + e^{-i\omega\tau}B)u = 0$$

for real matrices $M, A, B \in \mathbb{R}^{n\times n}$ with invertible M. Sought are triples (ω, τ, u) consisting of a complex eigenvector $u \in \mathbb{C}^n$ and two *real* eigenvalues ω and τ.
Problems of this type appear e.g. in the search for critical delays of linear time invariant delay differential equations (LTI-DDEs)

$$M\dot{x}(t) = -Ax(t) - Bx(t-\tau).$$

In [Meerbergen, Schröder, Voss, 2010, submitted] this problem is discussed for complex M, A, B. Like there we are considering a Jacobi-Davidson-like projection method. The main differences in the real case are that a) the search space is kept real and b) a specialized method for the small projected problem is used. Numerical experiments show the effectiveness of the method.

Christian Schröder
Dept. of Mathematics
TU Berlin
schroed@math.tu-berlin.de

MS 59. Structured matrix computations - Part I of II

Talk 1. **Factorization of $\mathcal{H}^2$-matrices**
Hierarchical matrices ($\mathcal{H}$-matrices) have been shown to be very useful tools for a variety of applications, e.g., the construction of efficient and robust preconditioners for the solution of elliptic partial differential equations and integral equations. Most $\mathcal{H}$-matrix algorithms are based on a recursive algorithm that approximates the product of two $\mathcal{H}$-matrices by a new $\mathcal{H}$-matrix, since this fundamental algorithm can be combined with simple recursive techniques to approximate the inverse or the LR factorization.
Combining $\mathcal{H}$-matrices with multilevel techniques leads to $\mathcal{H}^2$-matrices that can reach significantly higher compression rates, particularly for very large matrices. Although most algorithms can take advantage of the rich multilevel structure to significantly improve efficiency, the construction of $\mathcal{H}^2$-matrices poses a challenge since the connections between a large number of blocks have to be taken into account at each step.
The talk presents a new approach to the latter task: by adding a small amount of book-keeping information to the usual

$\mathcal{H}^2$-matrix structure, it is possible to develop an algorithm that computes a low-rank update of a submatrix $G|_{t\times s}$ in an $\mathcal{H}^2$-matrix in $\mathcal{O}(k^2(\#t+\#s))$ operations, where k is the local rank.
With this new algorithm at our disposal, several important higher-level operations become very simple: Low-rank approximations of submatrices, e.g., computed by popular cross approximation schemes, can easily be merged into an $\mathcal{H}^2$-matrix, leading to an algorithm of complexity $\mathcal{O}(nk^2\log n)$. The multiplication of two $\mathcal{H}^2$-matrices can be implemented as a sequence of low-rank updates, the resulting algorithm also has a complexity of $\mathcal{O}(nk^2\log n)$. Using the matrix multiplication, we can also construct the inverse and the LR factorization in $\mathcal{O}(nk^2\log n)$ operations.
Similar to $\mathcal{H}$-matrix techniques, the new algorithm is fully adaptive, e.g., it can reach any given accuracy, and it is able to easily handle matrices resulting from the discretization of two- or three-dimensional geometries. Its main advantages over $\mathcal{H}$-matrix algorithms are the significantly reduced storage requirements and the higher efficiency for large matrices.

Steffen Börm
Institut für Informatik
Christian-Albrechts-Universität zu Kiel
24118 Kiel, Germany
steffen@boerm.net

Talk 2. **The polynomial root finding problems and quasiseparable representations of unitary matrices**
The effective tool to compute all the roots of a polynomial is to determine the eigenvalues of the corresponding companion matrix using the QR iteration method. The companion matrix belongs to the class of upper Hessenberg matrices which are rank one perturbations of unitary matrices. This class is invariant under QR iterations. Moreover it turns out that for every matrix in this class the corresponding unitary matrix has quasiseparable structure. This structure may be used to develop fast algorithms to compute eigenvalues of companion matrices. We discuss implicit fast QR eigenvalue algorithms solving this problem. The obtained algorithm is of complexity $O(N)$ in contrast to $O(N^2)$ for non-structured methods.

Yuli Eidelman
School of Mathematical Sciences
Tel-Aviv University
Ramat-Aviv 69978, Israel
eideyu@post.tau.ac.il

Talk 3. **A fast direct solver for structured matrices arising from non-oscillatory integral equations**
We present a fast direct solver for structured dense matrices arising from non-oscillatory integral equations. The solver is based on (1) multilevel matrix compression techniques that exploit a complex hierarchical low-rank block structure, and (2) a sparse matrix embedding that allows fast and robust matrix factorization and inverse application. For boundary integral equations in 2D, the solver has optimal $\mathcal{O}(N)$ complexity, where N is the system size; in 3D, it incurs an $\mathcal{O}(N^{3/2})$ precomputation cost, followed by $\mathcal{O}(N\log N)$ solves. Numerical experiments suggest the utility of our method as both a direct solver and a preconditioner for complex problems.

Kenneth L. Ho
Courant Institute of Mathematical Sciences
New York University
ho@courant.nyu.edu

Leslie Greengard
Courant Institute of Mathematical Sciences
New York University
greengard@courant.nyu.edu

Talk 4. **Multivariate orthogonal polynomials and inverse eigenvalue problems**
It is well known that the computation of the recurrence coefficients of orthogonal polynomials with respect to a discrete inner product is related to an inverse eigenvalue problem. In this talk we present an algorithm to compute these recurrence coefficients for multivariate orthogonal polynomials. This algorithm generalizes previous results for the bivariate case and uses Givens transformations to solve the related inverse eigenvalue problem. We give a number of numerical examples using different configurations of points that define the discrete inner product.

Matthias Humet
Dept. of Computer Science
University of Leuven
matthias.humet@cs.kuleuven.be

Marc Van Barel
Dept. of Computer Science
University of Leuven
marc.vanbarel@cs.kuleuven.be

MS 60. Numerical linear algebra libraries for high end computing - Part II of II

Talk 1. **Thick-restart Lanczos methods for symmetric-indefinite generalized eigenproblems in SLEPc**
In this talk we present results on a Lanczos method for generalized eigenvalue problems $Ax=\lambda Bx$ where both A and B are symmetric matrices but the pair (A,B) is not definite. In this case, eigenvalues are not guaranteed to be real and also an eigenvalue can be defective. The standard B-Lanczos cannot be used, but still the symmetry of the matrices can be exploited to some extent by means of the pseudo-Lanczos process. We show results of a thick-restart variant implemented in the SLEPc library, and compare it with other solvers that totally ignore symmetry.

Jose E. Roman
Dept. de Sistemes Informàtics i Computació
Universitat Politècnica de València, Spain
jroman@dsic.upv.es

Carmen Campos
Dept. de Sistemes Informàtics i Computació
Universitat Politècnica de València, Spain
carcamgo@upvnet.upv.es

Talk 2. **Parametric approach to smart-tuning and auto-tuning of the DOE ACTS collection**
The Advanced CompuTational Software (ACTS) Collection is a set of computational tools and libraries developed primarily at DOE laboratories. Here we look at deriving parameters to automatically identify, at run-time, the most suitable auto-tuned kernels to load with a given application. Additionally, these parameters can be used in the context of "Smart-Tuning" to select the best algorithmic functionality and arguments to a library's API.

L. A. (Tony) Drummond
Computational Research Division, Lawrence Berkeley National Laboratory, USA
LADrummond@lbl.gov

Osni Marques

Computational Research Division, Lawrence Berkeley National Laboratory, USA
OAMarques@lbl.gov

Talk 3. **Trilinos: foundational libraries that enable next-generation computing**
With the availability and diversity of powerful computational resources, including multi-core CPU and GPU technology, there is significant interest in numerical software libraries that allow a developer to optimize the trade-off between effort and impact. In this talk we will discuss the current and ongoing efforts by which Trilinos is providing enabling technologies for the development of academic and industrial software targeted at next-generation architectures. We will cover a wide variety of Trilinos packages, from the foundational libraries for numerical linear algebra to the solver libraries that can leverage these fundamental capabilities to develop next-generation algorithms.

Heidi Thornquist
Electrical Systems Modeling Department
Sandia National Laboratories
hkthorn@sandia.gov

Talk 4. **Rethinking distributed dense linear algebra**
It is a commonly held misconception that matrices must be distributed by blocks in order to translate the local computation of classical dense matrix operations into level 3 BLAS operations. In this talk, the performance and programmability implications of element-wise matrix distributions are discussed in the context of a recently introduced implementation, Elemental. In order to be able to effectively convey code samples, both the FLAME methodology and its extension to distributed-memory computation will be briefly introduced.

Jack Poulson
Institute for Computational Engineering and Sciences
The University of Texas at Austin
poulson@ices.utexas.edu

MS 61. Efficient preconditioners for real world applications - Part II of II

Talk 1. **Relaxed mixed constraint preconditioners for ill-conditioned symmetric saddle point linear systems**
We develop efficient preconditioners for generalized saddle point linear system $\mathcal{A}\boldsymbol{x} = \boldsymbol{b}$, where $\mathcal{A} = \begin{bmatrix} A & B^\top \\ B & -C \end{bmatrix}$ and $A > 0, C \geq 0$ and B a full-rank rectangular matrix. Given two preconditioners for A (P_A and $\widetilde{P_A}$) and a preconditioner (P_S) for $S = B\widetilde{P_A}^{-1}B^\top + C$, the Relaxed Mixed Constraint Preconditioners (RMCP) is denoted by $\mathcal{M}^{-1}(\omega)$ where

$$\mathcal{M}(\omega) = \begin{bmatrix} I & 0 \\ BP_A^{-1} & I \end{bmatrix} \begin{bmatrix} P_A & 0 \\ 0 & -\omega P_S \end{bmatrix} \begin{bmatrix} I & P_A^{-1}B^\top \\ 0 & I \end{bmatrix}.$$

Eigenanalysis of $\mathcal{M}^{-1}(\omega)\mathcal{A}$ shows that the optimal ω is related to the (cheaply estimated) spectral radius of $P_A^{-1}A$ and $P_S^{-1}S$. Results regarding large linear systems arising from discretizations of geomechanical problems as well as fluid flow in porous media, show that proper choice of ω improves considerably the MCP performance.

Luca Bergamaschi
Dipartimento di Ingegneria Civile Edile Ambientale
University of Padova, Italy
luca.bergamaschi@unipd.it
Ángeles Martínez
Dipartimento di Matematica
University of Padova, Italy
angeles.martinez@unipd.it

Talk 2. **Chebychev acceleration of iterative refinement**
Gaussian elimination with partial pivoting followed by iterative refinement can compute approximate solutions of linear systems of equations that are backward stable. In some situations, the number of refinement steps can be large and their cost prohibitive. Limiting the number of steps is particularly important on multicore architectures where the solve phase of a sparse direct solver can represent a bottleneck.
We propose variants of the Chebyshev algorithm that can be used to accelerate the refinement procedure without loss of numerical stability. Numerical experiments on sparse problems from practical applications corroborate the theory and illustrate the potential savings offered by Chebyshev acceleration.

Jennifer Scott
Computational Science & Engineering Department
Science and Technology Faculties Council, UK
jennifer.scott@stfc.ac.uk
Mario Arioli
Computational Science & Engineering Department
Science and Technology Faculties Council, UK
mario.arioli@stfc.ac.uk

Talk 3. **Parallel deflated GMRES with the Newton basis**
The GMRES iterative method is widely used as a Krylov subspace accelerator for solving sparse linear systems when the coefficient matrix is nonsymmetric. The Newton basis implementation has been proposed for distributed memory computers as an alternative of the Arnoldi-based approach to avoid low-grained commmunications. The aim of our work here is to introduce a modification based on deflation techniques. This approach builds an augmented subspace in an adaptive way to accelerate the convergence of the restarted formulation. In our numerical experiments, we show the benefits of using this implementation in the PETSc package with Schwarz preconditioners for solving large CFD linear systems.

Désiré Nuentsa Wakam
INRIA, Bordeaux, France
desire.nuentsa_wakam@inria.fr
Jocelyne Erhel
INRIA, Rennes, France
jocelyne.erhel@inria.fr

Talk 4. **Rank-k updates of incomplete Sherman-Morrison preconditioners**
Let $B = A + PQ^T$ be a large and sparse matrix where A is a nonsingular matrix and PQ^T is a rank$-k$ matrix. In this work we are interested in solving the updated linear system $Bx = b$ by preconditioned iterations. We study the problem of updating an already existing preconditioner M for the matrix A. In particular we consider how to update the incomplete LU factorization computed by the BIF algorithm (SIAM J. Sci. Comput. Vol. 30(5), pp. 2302-2318, (2008)). The results of the numerical experiments with different types of problems will be presented.

José Marín
Instituto de Matemática Multidisciplinar
Universidad Politécnica de Valencia
Camino de Vera s/n, 46022 Valencia, España.
jmarinma@mat.upv.es
Juana Cerdán
Instituto de Matemática Multidisciplinar
Universidad Politécnica de Valencia

Camino de Vera s/n, 46022 Valencia, España.
jcerdan@mat.upv.es
José Mas
Instituto de Matemática Multidisciplinar
Universidad Politécnica de Valencia
Camino de Vera s/n, 46022 Valencia, España.
jmasm@mat.upv.es

MS 62. Solving ill-posed systems via signal-processing techniques - Part II of II

Talk 1. **Effects of prox parameter selection strategies in exact and inexact first-order methods for compressed sensing and other composite optimization problems**

We will discuss theoretical and practical implications of various strategies for choosing the prox parameter in prox gradient methods and related alternating direction methods. We will show extension of existing convergence rates for both accelerated and classical first-order methods. Practical comparison based on a testing environment for L1 optimization will be presented.

Katya Scheinberg
Department of Industrial and Systems Engineering
Lehigh University
katyas@lehigh.edu
Donald Goldfarb
IEOR Department
Columbia University
goldfarb@columbia.edu
Shiqian Ma
Institute for Mathematics and its Applications
University of Minnesota
sm2756@gmail.com

Talk 2. **An adaptive inverse scale space method for compressed sensing**

In this talk a novel adaptive approach for solving ℓ^1-minimization problems as frequently arising in compressed sensing is introduced, which is based on the recently introduced inverse scale space method. The scheme allows to efficiently compute minimizers by solving a sequence of low-dimensional nonnegative least-squares problems. Moreover, extensive comparisons between the proposed method and the related orthogonal matching pursuit algorithm are presented.

Martin Benning
Institute for Computational and Applied Mathematics
University of Münster
martin.benning@wwu.de
Michael Möller
Institute for Computational and Applied Mathematics
University of Münster
m.moeller@wwu.de
Pia Heins
Institute for Computational and Applied Mathematics
University of Münster
pia.heins@uni-muenster.de

Talk 3. **CGSO for convex problems with polyhedral constraints**

Conjugate Gradient with Subspace Optimization (CGSO) is a variant of conjugate gradient algorithm that achieves the optimal complexity bound of Nemirovski-Yudin's algorithm for the class of strongly convex functions. In this talk we are extending CGSO to constrained problems in which we are minimizing a strictly convex function over a convex polyhedron. We discuss the theoretical properties of CGSO for this class of problems as well as its practical performance.

Sahar Karimi
Department of Combinatorics and Optimization
University of Waterloo
s2karimi@uwaterloo.ca
Stephen Vavasis
Department of Combinatorics and Optimization
University of Waterloo
vavasis@uwaterloo.ca

Talk 4. **Phase-retrieval using explicit low-rank matrix factorization**

Recently, Candes et al. proposed a novel methodology for phase retrieval from magnitude information by formulating it as a matrix-completion problem. In this work we develop an algorithm aimed at solving large-scale instances of this problem. We take advantage of the fact that the desired solution is of rank one and use low-rank matrix factorization techniques to attain considerable speed-up over existing approaches. We consider phase recovery in both the noisy and noiseless setting and study how various design choices affect the performance and reliability of the algorithm.

Ewout van den Berg
Department of Mathematics
Stanford University
ewout@stanford.edu
Emmanuel Candès
Departments of Mathematics and Statistics
Stanford University
candes@stanford.edu

MS 63. Max-algebra - Part II of II

Talk 1. **Three-dimensional convex polyhedra tropically spanned by four points**

In this talk we show how a 3–dimensional convex polyhedron T_A is obtained from a 4×4 normal tropically idempotent integer matrix A (i.e., $A = (a_{ij})$, $a_{ij} \in \mathbb{Z}_{\leq 0}$, $a_{ii} = 0$, $A \odot A = A$, with $\oplus = \max$, $\odot = +$).
Which polyhedra arise this way? T_A has 20 vertices and 12 facets, at most. By Euler's formula, the f–vector is $(20, 30, 12)$, at most. Facets have 6 vertices, at most.
We show that a polyhedron T_A combinatorially equivalent to the regular dodecahedron does not occur, for any A, i.e., the polygon–vector of T_A cannot be $(0, 0, 12, 0)$. The polygon–vector of T_A cannot be $(0, 1, 10, 1)$, either, but we have examples where the polygon–vector of T_A is $(0, 2, 8, 2)$. We provide families of matrices with T_A having polygon–vector $(0, 3, 6, 3)$. Finally, certain families of circulant matrices yield T_A with polygon–vector $(0, 4, 4, 4)$ i.e., the facets of T_A are 4 quadrilaterals, 4 pentagons and 4 hexagons. Previous work has been done by Joswig and Kulas, Develin and Sturmfels.

María Jesús de la Puente
Facultad de Matemáticas
Universidad Complutense (UCM)
mpuente@mat.ucm.es
Adrián Jiménez
Facultad de Matemáticas
Universidad Complutense (UCM)
mpuente@mat.ucm.es

Talk 2. **Algorithmic problems in tropical convexity**

We present recent advances in tropical computational geometry, including the fundamental problem of computing the vertices of a tropical polyhedron described as intersection of half-spaces, or inversely. We also discuss the connection of these problems with

hypergraph transversals, directed hypergraphs, and mean payoff games. We finally point out applications of tropical convexity to other fields in computer science, such as formal verification.

Xavier Allamigeon
INRIA Saclay – Ile-de-France and CMAP
Ecole Polytechnique, France
xavier.allamigeon@inria.fr
Stéphane Gaubert
INRIA Saclay – Ile-de-France and CMAP
Ecole Polytechnique, France
stephane.gaubert@inria.fr
Eric Goubault
CEA Saclay Nano-INNOV
Institut Carnot CEA LIST, DILS/MeASI, France
eric.goubault@cea.fr
Ricardo D. Katz
CONICET. Instituto de Matemática "Beppo Levi"
Universidad Nacional de Rosario, Argentina
rkatz@fceia.unr.edu.ar

Talk 3. **On the weak robustness of interval fuzzy matrices**
A fuzzy matrix A (i.e. matrix in a (max, min)-algebra) is called weakly robust if every orbit sequence of A with starting vector x contains no eigenvectors, unless x itself is an eigenvector of A. Weak robustness is extended to interval fuzzy matrices and their properties are studied. A characterization of weakly robust interval fuzzy matrices is described and a quadratic algorithm for checking the weak robustness of a given interval fuzzy matrix is presented.

Ján Plávka
Department of Mathematics and Theoretical Informatics
Technical University in Košice
Jan.Plavka@tuke.sk
Martin Gavalec
Department of Information Technologies
University of Hradec Králové
Martin.Gavalec@uhk.cz

Talk 4. **Weakly stable matrices**
Given a square matrix A and a vector x the sequence $\left\{A^k \otimes x\right\}_{k=0}^{\infty}$ in the max-plus algebra is called the orbit of A with starting vector x. For some matrices the orbit never reaches an eigenspace unless it starts in one; such matrices are called weakly stable. We will characterise weakly stable matrices both in the reducible and irreducible case. It turns out that irreducible weakly stable matrices are exactly matrices whose critical graph is a Hamiltonian cycle in the associated graph. This talk is based on joint work with S. Sergeev and H. Schneider.

Peter Butkovič
School of Mathematics
University of Birmingham
p.butkovic@bham.ac.uk

MS 64. Eigenvalue perturbations and pseudospectra - Part II of II

Talk 1. **Ritz value localization for non-Hermitian matrices**
The Ritz values of Hermitian matrices have long been well understood, thanks to the Cauchy Interlacing Theorem. Recent progress has begun to uncover similar properties for Ritz values of non-Hermitian matrices. For example, the "inverse field of values problem" asks whether a set of k points in the field of values can be Ritz values from a k dimensional subspace. We survey results on this problem, describe how majorization can lead to Ritz value containment regions, and provide a detailed analysis for a Jordan block.

Mark Embree
Department of Computational and Applied Mathematics
Rice University
embree@rice.edu
Russell Carden
Department of Computational and Applied Mathematics
Rice University
Russell.L.Carden@rice.edu

Talk 2. **Optimization of eigenvalues of Hermitian matrix functions**
This work concerns a Hermitian matrix function depending on its parameters analytically. We introduce a numerical algorithm for the global optimization of a specified eigenvalue of such a Hermitian matrix function. The algorithm is based on constructing piece-wise quadratic under-estimators for the eigenvalue function, and finding global minimizers of these quadratic models. In the multi-dimensional case finding the global minimizers of the quadratic models is equivalent to solving quadratic programs. The algorithm generates sequences converging to global optimizers (linearly in practice). The applications include the H-infinity norm of a linear system, and the distance from a matrix to defectiveness.

Emre Mengi
Dept. of Mathematics
Koç University
emengi@ku.edu.tr
Mustafa Kılıç
Dept. of Mathematics
Koç University
mukilic@ku.edu.tr
E. Alper Yıldırım
Department of Industrial Engineering
Koç University
alperyildirim@ku.edu.tr

Talk 3. **Algorithms for approximating the H_∞ norm**
H_∞ norm methods are used in control theory to design optimal controllers. The controllers are designed so as to minimize the H_∞ norm of the $n \times n$ closed-loop transfer matrix where n is the system order. This optimization procedure necessitates efficient methods for the computation of the H_∞ norm itself. Existing methods compute the H_∞ norm accurately but the cost is multiple singular value decompositions and eigenvalue decompositions of size n, making them impractical when n is large. We present a novel method which provides a fast computation of the H_∞ norm for large and sparse matrices, such as the ones arising in the control of PDE's. The method is a nested fixed point iteration, where the outer iteration is a Newton step and the inner iteration is associated with the problem of the computation of the ε-pseudospectral abscissa, i.e. the real part of a righmost point of the ε-pseudospectrum of a certain linear operator. The fixed points of the iteration are characterized, local linear convergence of the algorithm for small enough ε is given and some applications to the control of PDE's are discussed.

Michael L. Overton
Courant Institute, New York University
overton@cs.nyu.edu
Mert Gürbüzbalaban
Courant Institute, New York University
mert@cims.nyu.edu
Nicola Guglielmi
University of L'Aquila
guglielm@units.it

Talk 4. **Reduced basis methods for computing pseudospectral**

quantities
Reduced basis methods have been developed to efficiently solve parameter-dependent partial differential equations and, after a spatial discretization, the resulting linear systems. They typically consist of two phases. In an offline phase, the linear system is solved for several parameter samples and a low-dimensional subspace containing these solutions (approximately) is constructed. In an online phase, only the compression of the linear system with respect to this subspace needs to be solved, leading to greatly reduced execution times. The effectivity of reduced basis methods crucially depends on the regularity of the parameter dependence and the chosen sampling strategy.
In this talk, we show how an approach inspired by reduced basis methods can be used to compute pseudospectra and associated quantities of a matrix A. Instead of solving a parameter-dependent linear system, one needs to consider the computation of the singular vector(s) belong to the smallest singular value(s) of $A - zI$ for all values of the complex parameter z of interest. While the computation of pseudospectra itself is still under development, we show how these technique can already be used to speed up a recently proposed algorithm by Gulgielmi and Overton for computing the pseudospectral abscissa.

Daniel Kressner
MATHICSE-ANCHP
EPF Lausanne
daniel.kressner@epfl.ch

MS 65. Numerical linear algebra and optimization in imaging applications - Part II of II

Talk 1. **A recursion relation for solving L-BFGS systems with diagonal updates**
We investigate a formula to solve limited-memory BFGS quasi-Newton Hessian systems with full-rank diagonal updates. Under some mild conditions, the system can be solved via a recursion that uses only vector inner products. This approach has broad applications in trust region and barrier methods in large-scale optimization.

Jennifer B. Erway
Dept. of Mathematics
Wake Forest University
erwayjb@wfu.edu
Roummel F. Marcia
School of Natural Sciences
University of California, Merced
rmarcia@ucmerced.edu

Talk 2. **Wavefront gradients reconstruction using $l^1 - l^p$ models**
Images of objects in outer space acquired by ground-based telescopes are usually blurred by atmospheric turbulence. To improve the quality of these images, the wavefront of the light is utilized to derive the point spread function (PSF). We proposed the $l^1 - l^p$ $(p = 1, 2)$ model for reconstructing the wavefront gradients and hence the wavefront itself. The model can give a more accurate PSF and therefore better restored images. Numerical results are given to illustrate the performance of the proposed models.

Raymond H. Chan
Dept. of Mathematics
The Chinese University of Hong Kong
rchan@math.cuhk.edu.hk
Xiaoming Yuan
Dept. of Mathematics
Hong Kong Baptist University
xmyuan@hkbu.edu.hk
Wenxing Zhang
Dept. of Mathematics
Nanjing University
wenxing84@gmail.com

Talk 3. **Edge-preserving image enhancement via blind deconvolution and upsampling operators**
We consider the super-resolution model introduced by S.J. Osher and A. Marquina in J. Sci. Comput., 2008 volume 37, 367382, consisting of the solution of a total-variation based variational problem that solves a linear degradation model involving a convolution operator and a down- sampling operator. In this research work we explore different edge preserving up/down-sampling operators with different orders of spatial accuracy and estimated convolution operators to remove unknown blur from degraded low resolved images to solve this genuine inverse problem. Some numerical examples are provided to show the features of the proposed algorithm.

Antonio Marquina
Department of Applied Mathematics,
University of Valencia, Spain
antonio.marquina@uv.es
Stanley J. Osher
Department. of Mathematics,
UCLA, USA
sjo@math.ucla.edu
Shantanu H. Joshi
LONI,
UCLA, USA
sjoshi@loni.ucla.edu

Talk 4. **A new hybrid-optimization method for large-scale, non-negative, full regularization**
We present a new method for solving the *full* regularization problem of computing both the regularization parameter and the corresponding solution of a linear or nonlinear ill-posed problem. The method is based on stochastic and fast, gradient-based optimization techniques, and computes non-negative solutions to ℓ_1 or ℓ_2 regularization problems. We describe the method and present numerical results for large-scale image restoration problems.

Marielba Rojas
Delft Institute of Applied Mathematics
Delft University of Technology, The Netherlands
marielba.rojas@tudelft.nl
Johana Guerrero
Department of Computer Science
University of Carabobo, Venezuela
jguerrer@uc.edu.ve
Marcos Raydan
Department of Scientific Computing and Statistics
Simón Bolívar University, Venezuela
mraydan@usb.ve

MS 66. Parametric eigenvalue problems - Part II of II

Talk 1. **A subspace optimization technique for the generalized minimal maximal eigenvalue problem.**
Consider the Generalized Minimal Maximal Eigenvalue

Problem:

$$\lambda^*_{\max} := \min_x \max_{\lambda,\vec{v}} \lambda$$
$$\text{st} : \begin{cases} \mathbf{K}(x)\vec{v} = \lambda \mathbf{M}(x)\vec{v}, \\ x \in \mathcal{H} \subset \mathbb{R}^p, \\ \vec{v} \in \mathbb{R}^n \end{cases}$$

where the matrices $\mathbf{K}(x)$ and $\mathbf{M}(x)$ are affine matrix functions, creating a symmetric positive definite pencil $(\mathbf{M}(x), \mathbf{M}(x))$ on the hypercube $\mathcal{H}$. It is a quasi-convex, non-smooth optimization problem.

We present a subspace iteration method for computing the minimal maximal eigenvalue of a large scale eigenvalue problem. The idea is based on Kelley's Classical cutting plane method for convex problems. In each iteration λ_1 and a corresponding eigenvector $\vec{v}$ are computed for a specific x. The eigenvector $\vec{v}$ is then used to expand the subspace and the next iterate x is determined from the minimal maximum eigenvalue of the small scale projected problem. Convergence theory of the method relies on the fact that the maximal Ritz value is a support to the maximal eigenvalue.

Jeroen De Vlieger
Dept. of Computer Science
KULeuven
Jeroen.DeVlieger@cs.kuleuven.be
Karl Meerbergen (promotor)
Dept. of Computer Science
KULeuven
Karl.Meerbergen@cs.kuleuven.be

Talk 2. **An iterative method for computing pseudospectral abscissa and stability radii for nonlinear eigenvalue problems**

We consider the following class of nonlinear eigenvalue problems,

$$\left(\sum_{i=1}^{m} A_i p_i(\lambda) \right) v = 0,$$

where $A_1, \ldots, A_m$ are given $n \times n$ matrices and the functions $p_1, \ldots, p_m$ are assumed to be entire. This does not only include polynomial eigenvalue problems but also eigenvalue problems arising from systems of delay differential equations. Our aim is to compute the ϵ-pseudospectral abscissa, i.e. the real part of the rightmost point in the ϵ-pseudospectrum, which is the complex set obtained by joining all solutions of the eigenvalue problem under perturbations $\{\delta A_i\}_{i=1}^m$, of norm at most ϵ, of the matrices $\{A_i\}_{i=1}^m$.

In analogy to the linear eigenvalue problem we prove that it is sufficient to restrict the analysis to rank-1 perturbations of the form $\delta A_i = \beta_i u v^*$ where $u \in \mathbb{C}^n$ and $v \in \mathbb{C}^n$ with $\beta_i \in \mathbb{C}$ for all i. Using this main - and unexpected - result we present new iterative algorithms which only require the computation of the spectral abscissa of a sequence of problems obtained by adding rank one updates to the matrices A_i. These provide lower bounds to the pseudspectral abscissa and in most cases converge to it. A detailed analysis of the convergence of the algorithms is made.

The methods available for the standard eigenvalue problem in the literature provide a robust and reliable computation but at the cost of full eigenvalue decompositions of order $2n$ and singular value decompositions, making them unfeasible for large systems. Moreover, these methods cannot be generalized to nonlinear eigenvalue problems, as we shall explain. Therefore, the presented method is the first generally applicable method for nonlinear problems. In order to be applied it simply requires a procedure to compute the rightmost eigenvalue and the corresponding left and right eigenvectors. In addition, if the matrices A_i are large and sparse then the computation of the rightmost eigenvalue can for many classes of nonlinear eigenvalue problems be performed in an efficient way by iterative algorithms which only rely on matrix vector multiplication and on solving systems of linear equations, where the structure of the matrices (original sparse matrices plus rank one updates) can be exploited. This feature, as well other properties of the presented numerical methods, are illustrated by means of the delay and polynomial eigenvalue problem.

Wim Michiels
Department of Computer Science
KU Leuven
Wim.Michiels@cs.kuleuven.be
Nicola Guglielmi
Dipartimento di Matematica Pura e Applicata
Università dell'Aquila
guglielm@univaq.it

Talk 3. **Statistical pseudospectrum and eigenvalue robustness to rank-one disturbance**

In this talk, we present a new statistical measure of the robustness (or sensitivity) of linear dynamic systems to rank-one random disturbances. The sensitivity assessment is a statistical pseudospectrum: given the probability distribution of the random disturbance magnitude, it measures the expected frequency region where the system eigenvalues are located . We discuss the properties of the robustness and sensitivity measure. We notably stress the existence of an invariant of the measure that consequently shows that under certain conditions, the rate of increase of a rank-one pseudospectrum area is constant as a function of the disturbance magnitude.

Christophe Lecomte
Institute of Sound and Vibration Research (ISVR) and
Southampton Statistical Sciences Research Institute (S3RI)
University of Southampton
C.Lecomte@soton.ac.uk
Maryam Ghandchi Tehrani
Institute of Sound and Vibration Research (ISVR) and
University of Southampton
University Road, Highfield
M.Ghandchi-Tehrani@soton.ac.uk

MS 67. Structured matrix computations - Part II of II

Talk 1. **Randomized numerical matrix computations with applications**

It is long and well known that random matrices tend to be well conditioned, but exploitation of this phenomenon in numerical matrix computations is more recent and there are still various new directions to investigate. Some of them will be covered in this talk. This includes pivoting-free but safe Gaussian elimination, randomized preconditioning of linear systems of equations, computation of a basis for the null space of a singular matrix, approximation by low-rank matrices, and applications to polynomial root-finding.

Victor Pan
Department of Mathematics and Computer Science
Lehman College - City University of New York
Bronx, New York 10468

victor.pan@lehman.cuny.edu

Talk 2. **Massively parallel structured direct solver for the equations describing time-harmonic seismic waves**
We consider the discretization and approximate solutions of equations describing time-harmonic seismic waves in 3D. We discuss scalar qP polarized waves, and multi-component elastic waves in inhomogeneous anisotropic media. The anisotropy comprises general (tilted) TI and orthorhombic symmetries. We are concerned with solving these equations for a large number of different sources on a large domain. We consider variable order finite difference schemes, to accommodate anisotropy on the one hand and allow higher order accuracy – to control sampling rates for relatively high frequencies – on the other hand.
We make use of a nested dissection based domain decomposition, with separators of variable thickness, and introduce an approximate direct (multifrontal) solver by developing a parallel Hierarchically SemiSeparable (HSS) matrix compression, factorization, and solution approach. In particular, we present elements of the following new parallel algorithms and their scalability: The parallel construction of an HSS representation or approximation for a general dense matrix, the parallel ULV factorization of such a matrix, and the parallel solution with multiple right-hand sides. The parallel HSS construction consists of three phases: Parallel rank revealing QR (RRQR) factorization based on a Modified Gram-Schmidt (MGS) method with column pivoting, parallel row compression, and parallel column compression. The parallel HSS factorization involves the use of two children's contexts for a given parent context. The communication patterns are composed of intra-context and inter-context ones. Similar strategies are applied to the HSS solution.
We present various examples illustrating the performance of our algorithm as well as applications in so-called full waveform inversion.

Maarten V. de Hoop
Department of Mathematics and Department of Earth and Atmospheric Sciences
Purdue University
West Lafayette, Indiana 47907, USA
mdehoop@math.purdue.edu
Shen Wang
Department of Mathematics and Department of Earth and Atmospheric Sciences
Purdue University
West Lafayette, Indiana 47907, USA
wang273@purdue.edu
Jianlin Xia
Department of Mathematics
Purdue University
West Lafayette, Indiana 47907, USA
xiaj@math.purdue.edu
Xiaoye S. Li
Computational Research Division
Lawrence Berkeley National Laboratory
Berkeley, CA 94720
xsli@lbl.gov

Talk 3. **On the conditioning of incomplete Cholesky factorizations with orthogonal dropping**
We consider incomplete Cholesky factorizations based on orthogonal dropping for the iterative solution of symmetric positive definite linear systems. These methods become increasingly popular tools for computing an approximate factorization of large dense matrices, including update matrices and Schur complements that arise in spares solvers. For the system preconditioned with these incomplete factorizations we present an upper bound on the condition number which only depends on the accuracy of the individual approximation (dropping) steps. The analysis is illustrated with some existing factorization algorithms in the context of discretized elliptic partial differential equations.

Artem Napov
Computational Research Division
Lawrence Berkeley National Laboratory
Berkeley, CA 94720, USA
anapov@lbl.gov

Talk 4. **Randomized direct solvers**
We propose some new structured direct solvers for large linear systems, using randomization and other techniques. Our work involves new flexible methods to exploit structures in large matrix computations. Our randomized structured techniques provide both higher efficiency and better applicability than some existing structured methods. New efficient ways are proposed to conveniently perform various complex operations which are difficult in standard rank-structured solvers. Extension of the techniques to least squares problems and eigenvalue problems will also be shown.
We also study the following issues:

1. Develop matrix-free structured solvers.
2. Update a structured factorization when few matrix entries change.
3. Relaxed rank requirements in structured solvers. We show the feasibility of our methods for solving various difficult problems, especially high dimensional ones.
4. Develop effective preconditioners for problems without significant rank structures. We analyze the criterion for compressing off-diagonal blocks so as to achieve nearly optimal effectiveness and efficiency in our preconditioner.

Jianlin Xia
Department of Mathematics
Purdue University
West Lafayette, Indiana 47907, USA
xiaj@math.purdue.edu
Maarten V. de Hoop
Department of Mathematics and Department of Earth and Atmospheric Sciences
Purdue University
West Lafayette, Indiana 47907, USA
mdehoop@math.purdue.edu
Xiaoye S. Li
Computational Research Division
Lawrence Berkeley National Laboratory
Berkeley, CA 94720
xsli@lbl.gov
Shen Wang
Department of Mathematics and Department of Earth and Atmospheric Sciences
Purdue University
West Lafayette, Indiana 47907, USA
wang273@purdue.edu

MS 68. Linear algebra for structured eigenvalue computations arising from (matrix) polynomials

Talk 1. **A QR algorithm with generator compression for structured eigenvalue computation**

In this talk we present a new structured implicit QR algorithm for fast computation of matrix eigenvalues. The algorithm, which relies on the properties of quasiseparable structure, applies to unitary-plus-rank-one Hessenberg matrices and, in particular, to Frobenius companion matrices. It computes the eigenvalues of an $n \times n$ matrix in $\mathcal{O}(n^2)$ operations with $\mathcal{O}(n)$ memory. The introduction of a generator compression step allows to reduce complexity – without spoiling accuracy – with respect to a previous fast eigensolver for companion matrices ([Bini, Boito, Eidelman, Gemignani, Gohberg, LAA 2010]). Numerical results will be presented for the single- and double shift strategies.

Paola Boito
XLIM-DMI
University of Limoges
paola.boito@unilim.fr
Yuli Eidelman
School of Mathematical Sciences
Raymond and Beverly Sackler Faculty of Exact Sciences
Tel-Aviv University
eideyu@post.tau.ac.il
Luca Gemignani
Dept. of Mathematics
University of Pisa
gemignan@dm.unipi.it
Israel Gohberg
School of Mathematical Sciences
Raymond and Beverly Sackler Faculty of Exact Sciences
Tel-Aviv University

Talk 2. **Quadratic realizability for structured matrix polynomials**
Which lists of elementary divisors $\mathcal{L}$ can be realized by some quadratic matrix polynomial $Q(\lambda)$? For regular $Q(\lambda)$ over the field $\mathbb{C}$, this problem has recently been solved by several researchers. Indeed, if $\mathcal{L}$ can be realized at all by some regular Q over $\mathbb{C}$, then it can always be realized by some upper triangular Q; several independent proofs are now known. This talk focuses on the analogous question for structured matrix polynomials. If $\mathcal{S}$ is a class of structured polynomials, which elementary divisor lists $\mathcal{L}$ can be realized by some quadratic $Q(\lambda)$ in $\mathcal{S}$? We survey current progress on this problem for various structure classes $\mathcal{S}$, including palindromic, alternating, and Hermitian matrix polynomials. As time permits we will also consider the quadratic realizability of additional features, such as sign characteristics and minimal indices, for these same structure classes.

D. Steven Mackey
Dept. of Mathematics
Western Michigan University
steve.mackey@wmich.edu
Fernando De Terán
Depto. de Matemáticas
Universidad Carlos III de Madrid
fteran@math.uc3m.es
Froilán M. Dopico
ICMAT/Depto. de Matemáticas
Universidad Carlos III de Madrid
dopico@math.uc3m.es
Françoise Tisseur
School of Mathematics
The University of Manchester
ftisseur@maths.manchester.ac.uk

Talk 3. **Fast computation of zeros of a polynomial**
The usual method for computing the zeros of a polynomial is to form the companion matrix and compute its eigenvalues. In recent years several methods that do this computation in $O(n^2)$ time with $O(n)$ memory by exploiting the structure of the companion matrix have been proposed. We propose a new method of this type that makes use of Fiedler's factorization of a companion matrix into a product of $n-1$ essentially 2×2 matrices. Our method is a non-unitary variant of Francis's implicitly-shifted QR algorithm that preserves this structure. As a consequence the memory requirement is a very modest $4n$, and the flop count is $O(n)$ per iteration (and $O(n^2)$ overall). We will present numerical results and compare our method with other methods.

David S. Watkins
Department of Mathematics
Washington State University
watkins@wsu.edu
Jared L. Aurentz
Department of Mathematics
Washington State University
lee.aurentz@gmail.com
Raf Vandebril
Department of Computer Science
K. U. Leuven
raf.vandebril@cs.kuleuven.be

Talk 4. **Eigenvector recovery of linearizations and the condition number of eigenvalues of matrix polynomials**
The standard formula for the condition number of a simple eigenvalue of a matrix polynomial involves the left and right eigenvectors associated with the eigenvalue [F. TISSEUR, *Backward error and condition of polynomial eigenvalue problems*, Linear Algebra Appl., 309 (2000) 339–361]. The usual way to solve polynomial eigenvalue problems is by using linearizations. In the past few years, different families of linearizations have been introduced. In order to compare the condition number for the eigenvalues of these linearizations, we need formulas for the associated eigenvectors. We present in this talk formulas for the eigenvectors of several families of Fiedler-lyke linearizations. These formulas are introduced using the notion of *eigencolumn*, which allows us to relate the eigenvectors of the linearizations with the eigenvectors of the polynomial. This fact may allow also to compare the condition number of the eigenvalue in the polynomial with the condition number of the eigenvalue in the linearizations. Moreover, the use of eigencolumns allows us to express similar formulas for minimal bases of singular polynomials.

Fernando De Terán
Depto. de Matemáticas
Universidad Carlos III de Madrid
fteran@math.uc3m.es
Maria I. Bueno
Dept. of Mathematics
University of California at Santa Barbara
mbueno@math.ucsb.edu
Froilán M. Dopico
ICMAT/Depto. de Matemáticas
Universidad Carlos III de Madrid
dopico@math.uc3m.es
D. Steven Mackey
Dept. of Mathematics
Western Michigan University
steve.mackey@wmich.edu

MS 69. Advances in sparse matrix factorization

Talk 1. **A sparse inertia-revealing factorization**
We show how to apply Wilkinson's inertia-revealing factorization to sparse matrices in a way that preserves sparsity. No other inertia-revealing factorization is guaranteed to preserve sparsity. The input matrix A is factored row by row, thereby producing the triangular factors of all its leading blocks. the inertia is derived from the number of sign changes in the sequence of determinants (revealed by the factors) of these blocks. We show that the fill in the triangular factors is bounded by the fill in the QR factorization of A. Therefore, symmetrically pre-permuting A to a doubly-bordered form guarantees sparsity in our algorithm.

Alex Druinsky
School of Computer Science
Tel-Aviv University
alexdrui@post.tau.ac.il
Sivan Toledo
School of Computer Science
Tel-Aviv University
stoledo@tau.ac.il

Talk 2. **Multifrontal factorization on heterogeneous multicore systems**
When solving the sparse linear systems that arise in MCAE applications, the multifrontal method is particularly attractive as it transforms the sparse matrix factorization into an elimination tree of dense matrix factorizations. The vast majority of the floating point operations can be performed with calls to highly tuned BLAS3 routines, and near peak throughput is expected. Such computations are performed today on clusters of multicore microprocessors, often accelerated by by graphics processing units (GPUs). This talk discusses how concurrency in the multifrontal computation is processed with message passing (MPI), shared memory (OpenMP), and GPU accelerators (CUDA), exploiting the unique strengths of each.

Bob Lucas
Information Sciences Institute
University of Southern California
rflucas@isi.edu
Roger Grimes
Livermore Software Technology Corporation
grimes@lstc.com
John Tran
Information Sciences Institute
University of Southern California
jtran@isi.edu
Gene Wagenbreth
Information Sciences Institute
University of Southern California
genew@isi.edu

Talk 3. **Towards an optimal parallel approximate sparse factorization algorithm using hierarchically semi-separable structures**
Hierarchically semiseparable (HSS) matrix algorithms are emerging techniques in constructing the superfast direct solvers for both dense and sparse linear systems. We present a set of novel parallel algorithms for the key HSS operations that are needed for solving large linear systems, including the parallel rank-revealing QR factorization, the HSS constructions with hierarchical compression, the ULV HSS factorization, and the HSS solutions. We have appplied our new parallel HSS-embedded multifrontal solver to the anisotropic Helmholtz equations for seismic imaging, and were able to solve a linear system with 6.4 billion unknowns using 4096 processors, in about 20 minutes.

Xiaoye S. Li
Lawrence Berkeley National Laboratory
xsli@lbl.gov
Shen Wang
Purdue University
wang273@math.purdue.edu
Jianlin Xia
Purdue University
xiaj@math.purdue.edu
Maarten V. de Hoop
Purdue University
mdehoop@math.purdue.edu

Talk 4. **Improving multifrontal methods by means of low-rank approximation techniques**
By a careful exploitation of the low-rank property of discretized elliptic PDEs, a substantial reduction of the flops and memory consumption can be achieved for many linear algebra operations. In this talk, we present how low-rank approximations can be used to significantly improve a sparse multifrontal solver. We introduce a blocked, low-rank storage format for compressing frontal matrices and compare it to the HSS storage format. Finally, we present experimental results showing the reduction of flops and memory footprint achieved on the solution of large scale matrices from applications such as the acoustic wave equation and thermo-mechanics.

Clement Weisbecker
INPT(ENSEEIHT)-IRIT
University of Toulouse
clement.weisbecker@enseeiht.fr
Patrick Amestoy
INPT(ENSEEIHT)-IRIT
University of Toulouse
patrick.amestoy@enseeiht.fr
Cleve Ashcraft
LSTC, Livermore
cleve@lstc.com
Olivier Boiteau
EDF R&D, Clamart
olivier.boiteau@edf.fr
Alfredo Buttari
CNRS-IRIT
alfredo.buttari@enseeiht.fr
Jean-Yves L'Excellent
INRIA-LIP(ENS Lyon)
Jean-Yves.L.Excellent@ens-lyon.fr

MS 70. Accurate algorithms and applications

Talk 1. **High-precision and accurate algorithms in Physics and Mathematics**
In this talk we present a survey of recent applications in Physics and Mathematics where high level of numeric precision is required. Such calculations are facilitated, on one hand, by high-precision software packages that include high-level language translation modules to minimize the conversion effort, and on the other hand, by the use of theoretical error bounds and accurate algorithms when available. These applications include supernova simulations, planetary orbit calculations, Coulomb n-body atomic systems, scattering amplitudes of quarks, gluons and bosons, nonlinear oscillator theory, experimental mathematics, evaluation of recurrence relations, numerical integration of ODEs, computation of periodic orbits, studies of the splitting of separatrices, detection of strange non-chaotic

attractors, Ising theory, quantum field theory, and discrete dynamical systems. We conclude that high-precision arithmetic facilities are now an indispensable component of a modern large-scale scientific computing environment.

Roberto Barrio
Dept. Matemática Aplicada and IUMA,
Universidad de Zaragoza, Spain
rbarrio@unizar.es

David H. Bailey
Lawrence Berkeley National Laboratory,
Berkeley, USA
dhbailey@lbl.gov

Jonathan M. Borwein
CARMA, University of Newcastle,
Callaghan, Australia
jonathan.borwein@newcastle.edu.au

Sergio Serrano
Dept. Matemática Aplicada and IUMA,
Universidad de Zaragoza, Spain
sserrano@unizar.es

Talk 2. **Accurate evaluation of 1D and 2D polynomials in Bernstein form**
In this talk we present some fast and accurate algorithms to evaluate the 1D and 2D polynomials expressed in the Bernstein form in CAGD. As a well-known and stable algorithm, De Casteljau algorithm may be still less accurate than expected owing to cancelation in some circumstances. Our compensated algorithms, applying error-free transformation, can yield a result as accurate as if computed by the De Casteljau algorithm in twice working precision. Numerical tests illustrate that our algorithms can run significantly faster than the De Casteljau algorithm using double-double library.

Hao Jiang
PEQUAN team, LIP6,
Université of Pierre et Marie Curie
Hao.Jiang@lip6.fr

Roberto Barrio
Dept. Matemática Aplicada and IUMA,
Universidad de Zaragoza, Spain
rbarrio@unizar.es

Talk 3. **Some issues related to double roundings**
Double rounding is a phenomenon that may occur when different floating-point precisions are available on a same system, or when performing scaled operations whose final result is subnormal. Although double rounding is, in general, innocuous, it may change the behavior of some useful small floating-point algorithms. We analyze the potential influence of double roundings on the Fast2Sum and 2Sum algorithms, on some summation algorithms, and Veltkamp's splitting. We also show how to handle possible double roundings when performing scaled Newton-Raphson division iterations (to avoid possible underflow problems).

Jean-Michel Muller
CNRS, Laboratoire LIP
Université de Lyon, France
jean-michel.muller@ens-lyon.fr

Érik Martin-Dorel
École Normale Supérieure de Lyon, Laboratoire LIP
Université de Lyon, France
erik.martin-dorel@ens-lyon.fr

Guillaume Melquiond
INRIA, Proval team, LRI
Université Paris Sud, France
guillaume.melquiond@inria.fr

Talk 4. **Error bounds for floating-point summation and dot product**
The sum and dot product of vectors of floating-point numbers are ubiquitous in numerical calculations. Since four decades the error is bounded by the classical Wilkinson estimates. However, those contain some nasty denominator covering higher order terms. In this talk we show that the latter can be omitted. A key to the (mostly) simple proofs is our ufp-concept denoting the "unit in the first place". In contrast to the well-known ulp (unit in the last place) it is defined for real numbers and allows sharp, simple and nice error estimates for floating-point operations. The practical relevance of the new estimates is limited; however, they are aesthetically pleasing and confirm that it is true what one may (hope or) expect.

Siegfried M. Rump
Institute for Reliable Computing
Hamburg University of Technology
Hamburg, Germany, and
Faculty of Science and Engineering
Waseda University, Tokyo, Japan
rump@tu-harburg.de

MS 71. Theoretical and applied aspects of graph Laplacians

Talk 1. **Potential theory for perturbed Laplacian of finite networks**
Given a symmetric and irreducible M–matrix M, the off-diagonal entries of M can be identified with the conductance function of a connected network Γ. In particular the matrix obtained by choosing $d_i = \sum_{j=1, j\neq i}^{n} c_{ij}$, where n is the order of the network, is nothing but the combinatorial Laplacian of the network. Therefore, any matrix with off-diagonal values given by $-c_{ij}$ can be considered as a perturbed Laplacian of Γ
From the operator theory point of view, the perturbed Laplacians are identified with the so-called discrete Schrodinger operators of the network Γ. Our main objective is the study of positive semi–definite Schrodinger operators. In fact, many of our techniques and results appear as the discrete counterpart of the standard treatment of the resolvent of elliptic operators on Riemannian manifolds. Joint work with E. Bendito, A. Carmona and A.M. Encinas

Margarida Mitjana
Dep. Matemtica Aplicada I
Universitat Politécnica de Catalunya
margarida.mitjana@upc.edu

Enrique Bendito
Dep. Matemàtica Aplicada III
Universitat Politècnica de Catalunya
enrique.bendito@upc.edu

Ángeles Carmona
Dep. Matemàtica Aplicada III
Universitat Politècnica de Catalunya
angeles.carmona@upc.edu

Andrés M. Encinas
Dep. Matemàtica Aplicada III
Universitat Politècnica de Catalunya
andres.marcos.encinas@upc.edu

Talk 2. **Subclasses of graphs with partial ordering with respect to the spectral radius of generalized graph Laplacians.**
Brualdi and Solheid (1986) proposed the following general problem, which became a classical problem in spectral graph

theory: "Given a set G of graphs, find an upper bound for the spectral radius in this set and characterize the graphs in which the maximal spectral radius is attained." Now there exists extensive literature that characterizes such extremal graphs for quite a couple of such sets. Moreover, the problem has been generalized to the (signless) Laplacian matrix of graphs and there even exist a few contributions that provide results for non-linear generalizations of these matrices, such as the p-Laplacian.
Many of the proofs for these results apply graph perturbations that increase or decrease the spectral radius. In graph classes, like trees, one may eventually arrive at a graph with maximum or minimum spectral radius. As a by-product we get a partial ordering of graphs in such classes. This procedure may also work for generalized graph Laplacians (symmetric matrices with non-positive off-diagonal entries) like Dirichlet matrices.
In this talk we want to find a general framework for deriving such results. We present sets of graphs and generalized Laplacians where this procedure can be applied.
This is a joint work with Türker Bıyıkoğlu.

Josef Leydold
Institute for Statistics and Mathematics
WU Vienna University of Economics and Business
josef.leydold@wu.ac.at
Türker Bıyıkoğlu
Department of Mathematics
Işık University,
turker.biyikoglu@isikun.edu.tr

Talk 3. **Some new results on the signless Laplacian of graphs**
Since recently the signless Laplacian spectrum has attracted much attention in the literature. In this talk we will put focus on some new results about the signless Laplacian spectrum which are inspired by the results so far established for the adjacency or the Laplacian spectrum.

Slobodan K. Simić
Mathematical Institute of Serbian Academy of Science and Arts
sksimic@mi.sanu.ac.rs

Talk 4. **Graph bisection from the principal normalized Laplacian eigenvector**
Graph bisection is the most often encountered form of graph partitioning, which asks to divide the nodes of a network into two non-overlapping groups such that the number of links between nodes in different groups is minimized. However, graph bisection may also be understood as the search for the largest bipartite subgraph in the complement: if two groups of G should have sizes roughly equal to $n/2$, and if m_1 and m_2 are the numbers of intra-group links and inter-group links, respectively, then the numbers of intra-group and inter-group links in the complement G^C will be roughly equal to $n^2/4m_1$ and $n^2/4m_2$. Hence, the request to minimize m_2 translates into the request of maximizing $n^2/4m_2$.
Here we may relate to a well-known property of the spectrum of the normalized Laplacian matrix L^* of G, saying that G is bipartite if and only if 2 is the largest eigenvalue of L^*. If G is bipartite, then the signs of the components of the eigenvector corresponding to eigenvalue 2 of $L*$, yield the bipartition of G. In the more interesting case when G is not bipartite, one may still expect that the signs of the components of the eigenvector corresponding to the largest eigenvalue of L^* will yield a large bipartite subgraph of G. For example, it yields a perfect classification of club members in the Zacharys karate club network. More interestingly, the sizes of the bipartite subgraphs obtained in this way in instances of random networks show high similarity to those obtained by applying the old Erdös method, an iterative process which starts with a random partition in two groups and, as long as there exists a node having more than half of its neighbors in its own group, it moves such node to the other group. This similarity is explored in more detail in this talk.

Dragan Stevanović
University of Primorska, UP IAM, Koper Solvenia and
University of Niš, PMF
dragance106@yahoo.com

MS 72. Linear techniques for solving nonlinear equations

Talk 1. **A Gauss-Seidel process in iterative methods for solving nonlinear equations**
In this talk, we present a process named "Gauss-Seidelization" for solving nonlinear equations . It is an iterative process based on the well-known Gauss-Seidel method to numerically solve a system of linear equations. Together with some convergence results, we show several numerical experiments in order to emphasize how the Gauss-Seidelization process influences on the dynamical behaviour of an iterative method for solving nonlinear equations.

José M. Gutiérrez
Dept. Mathematics and Computer Sciences
University of La Rioja
Logroño, Spain
jmguti@unirioja.es
A. Magreñán
Dept. Mathematics and Computer Sciences
University of La Rioja
Logroño, Spain
magrenan@unirioja.es
J. L. Varona
Dept. Mathematics and Computer Sciences
University of La Rioja
Logroño, Spain
jvarona@unirioja.es

Talk 2. **A greedy algorithm for the convergence of a fractional blind deconvolution**
In this talk we present new results on a greedy algorithm to study the convergence of the Fractional Blind Deconvolution based on fractional powers of the laplacian. Greedy algorithms perform a theoretical background to prove the convergence in a Hilbert Space. We will show the theoretical results and an application to baroque paintings.

Vicente F. Candela
Departamento de Matemática Aplicada
Universidad de Valencia
candela@uv.es
Pantaleón David Romero Sánchez
Departamento de Ciencias Físicas, Matemáticas y de la Computación
Universidad CEU-Cardenal Herrera
pantaleon.romero@uch.ceu.es

Talk 3. **Overview of iterative methods using a variational approach**
In this talk, we introduce a general framework for the approximation of nonlinear equations in Banach spaces. We adapt a variational perspective recently introduced for the analysis of differential equations. In this new approach, some classical iterative methods, including their convergence analysis, can be obtained. The method can be considered as a

generalization of the discrete least squares method, which is a standard approach to the approximate solution of many types of problems including overdetermined systems of nonlinear equations.

S. Busquier
Dept. of Applied Mathematics and Statistics
U.P. Cartagena
sonia.busquier@upct.es

S. Amat
Dept. of Applied Mathematics and Statistics
U. P. Cartagena
sergio.amat@upct.es

P. Pedregal
E.T.S. Ingenieros Industriales.
Universidad de Castilla La Mancha
pablo.pedregal@uclm.es

Talk 4. **Iterative methods for ill-conditioned problems**
In this talk we study some features related to ill-conditioned nonlinear equations. A strategy to choose iterative methods for solving these equations is developed. In particular, we analyze a variation of Newton method, the so called perturbed Newton method. Important features to achieve good performance, such as choice of pivots and parameters provide degrees of freedom that can be suited for improvement of the method. We illustrate this analysis through examples.

Rosa M. Peris
Dept. of Applied Mathematics
University of Valencia
peris@uv.es

Vicente F. Candela
Dept. of Applied Mathematics
University of Valencia
candela@uv.es

MS 73. Algebraic Riccati equations associated with M-matrices: numerical solution and applications

Talk 1. **Monotone convergence of Newton-like methods for M-matrix algebraic Riccati equations**
The minimal nonnegative solution of an M-matrix algebraic Riccati equation can be obtained by Newton's method. Here we study Newton-like methods that have higher-order convergence and are not much more expensive each iteration, and are thus more efficient than Newton's method. For the Riccati equation, these Newton-like methods are actually special cases of the Newton–Shamanskii method. We show that, starting with zero initial guess or some other suitable initial guess, the sequence generated by the Newton–Shamanskii method converges monotonically to the minimal nonnegative solution.

Chun-Hua Guo
Dept. of Mathematics and Statistics
University of Regina
chguo@math.uregina.ca

Talk 2. **Accurate solution of M-matrix algebraic Riccati equation by ADDA: alternating-directional doubling algorithm**
It is known that that an M-matrix Algebraic Riccati Equation (MARE) $XDX - AX - XB + C = 0$ has a unique minimal nonnegative solution Φ. In this talk, we will discuss two recent developments:

- a relative perturbation theory that will show that small relative perturbations to the entries of A, B, C, and D introduce small relative changes to the entries of the nonnegative solution Φ, unlike the existing perturbation theory for (general) Algebraic Riccati Equations.
- an efficient Alternating-Directional Doubling Algorithm (ADDA) that can compute such a solution Φ as accurately as predicted by the relative perturbation theory.

Ren-Cang Li
Dept. of Mathematics
University of Texas at Arlington
rcli@uta.edu

Wei-guo Wang
School of Mathematical Sciences
Ocean University of China
wgwang@ouc.edu.cn

Wei-chao Wang
Dept. of Mathematics
University of Texas at Arlington
weichao.wang@mavs.uta.edu

Shufang Xu
School of Mathematical Sciences
Peking University
xsf@math.pku.edu.cn

Jungong Xue
School of Mathematical Science
Fudan University
xuej@fudan.edu.cn

Talk 3. **When fluid becomes Brownian: the morphing of Riccati into quadratic equations**
Ramaswami (2011) approximates Brownian motion using a Markov-modulated linear fluid model. This is extended to approximate Markov-modulated Brownian motion (MMBM); in particular, the Laplace matrix exponent of a Markov-modulated linear fluid model converges to that of an MMBM. When the MMBM is reflected at zero, its stationary distribution is the limit of that of the fluid model also reflected at zero. Proof of convergence combines probabilistic arguments and linear algebra. Starting from the Wiener-Hopf factorization of the modulating Markov chain, expressed as an algebraic Riccati equation, key matrices in the limiting stationary distribution are shown to be solutions of a new quadratic equation.

Giang T. Nguyen
Departément d'Informatique
Université Libre de Bruxelles
giang.nguyen@ulb.ac.be

Guy Latouche
Departément d'Informatique
Université Libre de Bruxelles
latouche@ulb.ac.be

V. Ramaswami
AT&T Labs, Research
vram@research.att.com

Talk 4. **Analyzing multi-type queues with general customer impatience using Riccati equations**
We consider a class of multi-type queueing systems with customer impatience, where the (phase-type) service time and (general) patience distribution is type dependent and the types of consecutive customers may be correlated.
To obtain the per-type waiting time distribution and probability of abandonment, we construct a fluid queue with r thresholds, the steady state of which can be expressed via the solution of $2r$ algebraic Riccati equations using matrix-analytic methods. Numerical examples indicate that thousands thresholds may be required to obtain accurate results, indicating the need for fast

and numerically stable algorithms to solve large sets of Riccati equations.

Benny Van Houdt
Dept. of Mathematics and Computer Science
University of Antwerp
benny.vanhoudt@ua.ac.be

MS 74. Recent advances in the numerical solution of large scale matrix equations

Talk 1. **Hierarchical and multigrid methods for matrix and tensor equations**

Hierarchical and Multigrid methods are among the most efficient methods for the solution of large-scale systems that stem, e.g. from the discretization of partial differential equations (PDE). In this talk we will review the generalization of these methods to the solution of matrix equations (*L. Grasedyck, W. Hackbusch, A Multigrid Method to Solve Large Scale Sylvester Equations, SIAM J. Matrix Anal. Appl. 29, pp. 870–894, 2007; L. Grasedyck, Nonlinear multigrid for the solution of large scale Riccati equations in low-rank and H-matrix format, Num.Lin.Alg.Appl. 15, pp. 779–807, 2008*), and equations that possess a tensor structure (*L. Grasedyck, Hierarchical Singular Value Decomposition of Tensors, SIAM J. Matrix Anal. Appl. 31, pp. 2029–2054, 2010.*). The standard hierarchical and multigrid methods can perfectly be combined with low rank (matrix) and low tensor rank representations. The benefit is that the solution is computable in almost optimal complexity with respect to the amount of data needed for the representation of the solution. As an example we consider a PDE posed in a product domain $\Omega \times \Omega$, $\Omega \subset \mathbb{R}^d$ and discretized with N^d basis functions for the domain Ω. Under separability assumptions on the right-hand side the system is solved in low rank form in $\mathcal{O}(N^d)$ complexity (instead of $\mathcal{O}(N^{2d})$ required for the full solution). For a PDE on the product domain $\Omega \times \cdots \times \Omega$ one can even solve the system in low tensor rank form in $\mathcal{O}(N \cdot d)$ complexity (instead of $\mathcal{O}(N^{2d})$ required for the full solution). The state of the art will be shortly summarized.

Lars Grasedyck
Inst. for Geometry and Practical Mathematics
RWTH Aachen
lgr@igpm.rwth-aachen.de

Talk 2. **A survey on Newton-ADI based solvers for large scale AREs**

Newton based solvers for the algebraic Riccati equation (ARE) have been arround for several decades. Only roughly one decade ago these have become applicable to large and sparse AREs when combined with the low rank Cholesky factor alternating directions implicit (LRCF-ADI) iteration for solving the Lyapunov equations arising in every Newton step. In this contribution we give a survey on accelerated variants of the low rank Cholesky factor Newton method (LRCF-NM) developed over the recent years. These include projection based methods and inexact Newton-like approaches.

Jens Saak
Computational Methods in Systems and Control Theory
Max Planck Institute for Dynamics of Complex Technical Systems
and Department of Mathematics
Chemnitz University Technology
saak@mpi-magdeburg.mpg.de

Talk 3. **An invariant subspace method for large-scale algebraic Riccati and Bernoulli equations**

We present a new family of low-rank approximations of the solution of the algebraic Riccati equation based on stable invariant subspaces of the Hamiltonian matrix (*L. Amodei and J.-M. Buchot, An invariant subspace method for large-scale algebraic Riccati equations, Appl. Numer. Math., 60 (11), 1067-1082, 2010.*). The approximations are given by a factorized form which preserves the positive semi-definiteness of the exact solution. By using the same general factorization, we deduce a reduced rank expression of the exact solution of the Bernoulli equation. We illustrate the effectiveness of this formulation by considering the stabilization of the nonstationary incompressible Navier-Stokes equations by a boundary feedback control obtained from the solution of the Bernoulli equation (*L. Amodei and J.-M. Buchot, A stabilization algorithm of the Navier-Stokes equations based on algebraic Bernoulli equation, Numer. Linear Algebra Appl., DOI: 10.1002/nla.799, 2011.*).

Luca Amodei
Institut de Mathématiques de Toulouse
Université Paul Sabatier
118 route de Narbonne
31062 Toulouse Cedex 9, France
luca.amodei@math.univ-toulouse.fr

Jean-Marie Buchot
Institut de Mathématiques de Toulouse
Université Paul Sabatier
Jean-Marie.Buchot@math.univ-toulouse.fr

Talk 4. **Delay Lyapunov equations and model order reduction of time delay systems**

We present a version of balanced truncation for model order reduction of linear time-delay systems. The procedure is based on a coordinate transformation of the position and preserves the delay structure of the system. To every position we associate quantities representing energies for the *controllability* and *observability* of the position. We show that these energies can be expressed explicitly in terms of Gramians which are given as solutions to corresponding *delay Lyapunov equations*. Balanced truncation can be based on these Gramians in the usual way.

Tobias Damm
Dept. of Mathematics
University of Bayreuth
tobias.damm@uni-bayreuth.de

Elias Jarlebring
Dept. Num. Analysis,
KTH, Stockholm
eliasj@kth.se

Wim Michiels
Department of Computer Science
K.U. Leuven
wim.michiels@cs.kuleuven.be

MS 75. Points that minimize potential functions

Talk 1. **Discretizing compact manifolds with minimal energy**

One approach to generate "good" point configurations is inspired by physics: points emulate repelling unit point charges interacting through a Coulomb potential $1/r$, where r measures the Euclidean distance between points in the ambient space. Points on the sphere that minimize the corresponding energy (potential energy) are uniformly distributed even if a Riesz s-potential $1/r^s$ governs the point interaction.
On other compact manifolds minimal energy systems are uniformly distributed if s is greater than the dimension d of the manifold ("Poppy Seed Bagle" theorem).

This talk gives an introduction into the discrete minimal Riesz s-energy problem on compact manifolds.

Johann S. Brauchart
School of Mathematics and Statistics
University of New South Wales
j.brauchart@unsw.edu.au

Talk 2. **Well conditioned spherical designs and potential functions**
A spherical t-design is a set of N points on the unit sphere such that equal weighted numerical integration at these points is exact for all spherical polynomials of degree at most t. This talk will look at the calculation and properties of spherical designs with N between $t^2/2$ and $(t+1)^2$, their characterization by different potential functions, and using any degrees of freedom to also minimize the condition number of the basis matrix or maximize the determinant of the associated Gram matrix.

Robert S. Womersley
School of Mathematics and Statistics
University of New South Wales
R.Womersley@unsw.edu.au

Talk 3. **Probabilistic frames in the 2-Wasserstein metric**
In this talk I will review the notion of probabilistic frames and indicate how it is a natural generalization of frames. In addition, I will show how within the framework of the 2-Wasserstein metric, probabilistic frames can be constructed and analyzed. This is based on joint work with M. Ehler.

Kasso Okoudjou
Dept. of Mathematics
University of Maryland
kasso@math.umd.edu

Talk 4. **Numerical minimization of potential energies on specific manifolds**
In this talk we consider the problem of computing local minimizers of potential energies of the form

$$E(\boldsymbol{x}_1, \ldots, \boldsymbol{x}_M) := \sum_{i,j=1; i \neq j}^{M} K(\boldsymbol{x}_i, \boldsymbol{x}_j),$$

with $\boldsymbol{x}_i \in \mathcal{M},\ i = 1, \ldots, M$, where $\mathcal{M} \subset \mathbb{R}^n$ is a d-dimensional compact manifold and $K : \mathcal{M} \times \mathcal{M} \to \mathbb{R}$ is a given function. The optimization approach is based on a nonlinear conjugate gradient method on Riemannian manifolds, which is a generalization of the CG-method in Euclidean space. This method was already successfully applied to the computation of spherical t-designs in [Numer. Math., 119:699 – 724, 2011] and low discrepancy points for polynomial kernels K, cf. [TU Chemnitz, Preprint 5, 2011]. Now, we present interesting numerical results for localized non-polynomial discrepancy kernels K.

Manuel Gräf
Dept. of Mathematics
Chemnitz University of Technology
m.graef@mathematik.tu-chemnitz.de