MATHEMATISCHES FORSCHUNGSINSTITUT OBERWOLFACH

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"Domain Decomposition and Multifield Theories"

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Domain decomposition methods including those based on macro-hybrid variational formulations of partial differential equations involving multiple fields have attracted considerable interest during the past two decades. Originating from early work done by H.A. Schwarz more than a century ago related to the study of harmonic functions in domains of complex geometric structure, these techniques have experienced an extensive growth since the late seventies of this century in the need for appropriate parallel computing platforms. Roughly speaking, domain decomposition techniques can be subdivided into two classes. The first one comprises methods that are closely related to the original Schwarz alternating scheme and therefore are referred to as Schwarz methods. On the other hand, the second class of methods is based on static condensation of the unknowns associated with the individual subdomains thus giving rise to a Schur complement system on the interfaces. For this reason, these techniques are called Schur complement methods. Both types of methods have been under intensive investigation over the last couple of years with emphasis on the development of fast iterative solvers and their appropriate implementation featuring scalability and optimal efficiency. Domain decomposition methods offer a great amount of flexibility in treating different kind of problems so that their range of applicability has been widened substantially. Nowadays, the scope of the methodology ranges from the theory of partial differential and integral equations, numerical mathematics and parallel computation to the mathematical modeling and numerical simulation of complex technological processes.

The conference on "Domain Decomposition and Multifield Theories" was aimed to bring together the leading experts in this field to present and dicuss the latest results and new developments. It has been organized jointly by Prof.Dr. Franco Brezzi (CNR, Pavia), Prof.Dr. Ronald H.W. Hoppe (University of Augsburg), and Prof.Dr. Yuri A. Kuznetsov (University of Houston). 47 scientists from 10 countries took part in the conference. 29 lectures have been given and there were two special after dinner sessions on "least squares problems" and "mortar elements".

The talks given during the conference and the lively discussions thereafter and in the evenings reflected to a great extent the progress that has been made over the past couple of years concerning theoretical investigations, algorithmic developments and applications oriented issues. They also contributed to find out what the most challenging still open problems are and what can be done with regard to achieve successful solutions.

In particular, both Schwarz methods and Schur complement techniques have been addressed with emphasis on extensions to three-dimensional and nonlinear problems as well as the construction and analysis of robust preconditioners that work well, e.g., for convection-diffusion problems and in case of discontinuous coefficients. Besides standard finite element approximations, several contributions highlighted other types of discretizations such as boundary element and spectral methods as well as wavelet elements.

As far as applications of domain decomposition methods are concerned, there were several contributions featuring problems in acoustics, biomedicine, electromagnetism, fluid flow in porous media, and in fluid and structural mechanics. Some of the contributions also reported on programme packages realizing efficient numerical solution techniques including domain decomposition techniques.

Another central issue during the conference was on domain decomposition on nonmatching grids where the subdomain problems are discretized individually requiring the realization of appropriate continuity constraints on the interfaces by means of Lagrange multipliers. these techniques also known as mortar element methods have been addressed both with regard to the development, analysis, and parallel implementation of efficient iterative solvers as well as concerning their application to problems as, e.g., in structural mechanics, fluid-structure interactions, flows in porous media, and wave propagation. A related technique, the so-called three fields approach which uses two types of multipliers on the interfaces has been presented in a stabilized version with emphasis on deriving optimal error estimates.
There was a special session on mortar element methods reflecting the history of this approach and very recent developments including the coupling of different types of triangulations and discretizations, sliding meshes, and extensions to mesh adaptivity. Also open problems such as general inf-sup conditions and the issue of anisotropy have been discussed.

Augsburg, May 1998 Ronald H.W. Hoppe

Collection of Abstracts

A Robin-Robin preconditioner for convection-diffusion problems

Yves Achdou (Rennes, France)

We propose a generalization of the Neumann-Neumann preconditioner for the Schur domain decomposition method applied to an advection-diffusion equation. Solving the preconditioner system consists of solving boundary value problems in the subdomains with suitable Robin conditions instead of Neumann problems.
For the case of two semi-infinite subdomains with uniform velocity, the preconditioner is the exact inverse of the Schur complement matrix.
A Fourier analysis is done in the case of strips which demonstrates the good properties of the preconditioner (the preconditioner is bounded and is the sum of an idempotent operator and of a small one). A coarse space solver is also investigated.
Finally, numerical tests assess the good behavior of the preconditioner.

Numerical simulation of wave propagation by non conforming mortar elements

Faker Ben Belgacem (Toulouse, France)

In this talk domain decomposition methods on nonmatching grids using mortar finite elements and appropriate implicit time discretizations are developed and analyzed for the numerical solution of wave equations.

Some problems in axisymmetric geometries and their spectral discretizations

Christine Bernardi (Paris, France)

When set in axisymmetric geometries, most three-dimensional problems arising from mechanics or physics can be reduced either to a problem on the meridian two-dimensional domain for axisymmetric data or to an amenable family of two-dimensional problems by Fourier series in general. Spectral discretizations are fully appropriate to handle the reduced problems, since the weighted formulations can be approximated thanks to suitable families of orthogonal polynomials and weighted Gauss-Lobatto type quadrature formulas and also because spectral techniques have the same infinite rate of accuracy as Fourier truncation.
The results are based on joint work with M. Azaiez, M. Dauge, and Y. Maday.

Industrial strength domain decomposition?

Petter Bjørstad (Bergen, Norway)

We review the PARASOL project to create a library of parallel, sparse solvers for large linear systems. The focus will be on domain decomposition algorithms and some of the trade-offs that seem unavoidable in a library code. The second part of the talk is a detailed analysis of a new coarse space algorithm with a previously considered space $V_0^{AUG} = V_{-1} + V_0$. We show that the formulation returns the essential convergence properties and even improves the previous approach. Finally, we give (yet another!!) example on the importance of computational feedback to theoretical analysis of these algorithms.

A multigrid algorithm for the mortar finite element method

Dietrich Braess (Bochum, Germany)

The mortar finite element as a special domain decomposition method allows different kinds of discretization in the subdomains. One has to pay for this, and we consider the method in the framework of saddle point problems. We start from the assumption that the jumps over the interelement boundary T_{kl} belong to $H_{00}^{1/2}(T_{kl})$. The discretization by finite elements is more easily treated when we use mesh-dependent norms, especially $\|[v_h]\|_{H_{00}^{1/2}}$ is replaced by $h^{-1/2}\,\|[v_h]\|_0$ and $\|\lambda\|_{H_{00}^{-1/2}}$ by $h^{1/2}\,\|\lambda\|_0$. In this way we derive an L_2 error estimate.
The multigrid method is designed similarly as it was done for the Stefan problem. In contrast to other concepts we do not approximate the Schur complement. We rather use a u-dominant iteration for the smoothing operations in which the new iterates are independent of the Lagrange multiplier from the previous step. The smoothing property and the approximation property are established for the pairs $\|u - u^m\|_0$ (coarse topology) and $|||\, u - u^m \,|||_2$ with $|||\cdot|||_2 := \|Au + B^T\lambda - f\|_0$ (fine topology). Numerical results show the efficiency of the algorithm.

Lower bounds for domain decomposition preconditioners

Suzanne C. Brenner (Columbia, U.S.A.)

In this talk we present results which show that the condition number estimates for some well-known domain decomposition methods are sharp.

A stabilized three-fields approach to domain decomposition

Franco Brezzi (Pavia, Italy)

We propose a stabilization technique for a domain decomposition method which has been introduced by Brezzi and Marini in 1992. This is known as *Three Fields Method* and it is a completely mixed formulation of the well known techniques coming from the use of Steklov-Poincaré operators. The same level of parallelism is obtained and an easy preconditioning of the final interface problem is assured, but, on the other hand, two difficult inf-sup conditions are to be verified.
We use a finite element strategy in each sub-domain and we stabilize the single domain problem by means of particular bubble functions which are then eliminated by static condensation. A completely free choice of grids in different domains is possible and a good choice of bubbles allows us to obtain an optimal error estimate for the discrete solution.

A stabilization technique for the three-fields approach to domain decomposition

Annalisa Buffa (Pavia/Paris, Italy/France)

When dealing with the three-fields approach in domain decomposition methods, we have to solve ill-posed Dirichlet problems in mixed form. In general, the grids for the multipliers are finer than the triangulation of the subdomain. We present an analysis and error estimates for a stabilization technique by bubble functions and we show that the grids can be freely chosen.

Wavelet elements and applications

Claudio Canuto (Torino, Italy)

In this talk an overview is given on multiscale methods using wavelet elements for the numerical solution of elliptic problems. Further applications are also addressed.

Multilevel Schwarz methods for mortar finite element elliptic problems

Maksymilian Dryja (Warszaw, Poland)

In the talk multilevel Schwarz methods for solving linear systems of algebraic equations arising from a discretization of second order elliptic problems are discussed. The discretization is obtained by finite element methods on nonmatching triangulations using the mortar technique.
The methods are designed and analyzed using the special extension which preserves the mortar condition for functions of each level. Their complexity is optimal in each iteration and their rate of convergence is almost optimal.
The presented results are joint work with Olof Widlund.

The nonlinear domain decomposition method

Wolfgang Hackbusch (Kiel, Germany)

The subspace iteration for linear systems of equations is generalised to nonlinear systems. The asymptotic convergence speed of the nonlinear method is the same as the speed of the linear method applied to the linearised system. Under suitable conditions even global convergence can be proved.

Domain decomposition for eddy current problems

Ralf Hiptmair (Augsburg, Germany)

Many problems in the computation of electromagnetic fields lend themselves to a natural domain decomposition approach inspired by different physical regimes in different parts of the computational domain. In my talk I examine the A-V-model for eddy currents in a conducting bar which relies on a modified vector potential as unknown in the conducting region and a magnetic scalar potential in the surrounding air region. This amounts to primal-dual coupling where the solutions are only glued together at the interface through the weak form of the equations.
Discretization in space is done by means of conforming finite elements. Finally, we end up with a discrete saddle point problem. We aim to solve it iteratively making use of techniques developed in the framework of nonoverlapping domain decomposition methods with inexact solvers in the subdomains. This requires both good preconditioners for the discrete problems in the subdomains and the Schur complements. In both cases, multilevel methods turn out to be a promising choice.

Robust Schur-complement methods via nonoverlapping domain decomposition

Boris Khoromskij (Stuttgart, Germany)

Asymptotically optimal Schur-complement methods for solving elliptic equations with jumping coefficients will be presented. We consider scalar elliptic problems with jumping diffusion and anisotropy as well as the Stokes equation with piecewise constant viscosity. Robust interface preconditioners for anisotropic equations are based on the coefficient-dependent coarse mesh approximation associated with the domain decomposition and on a certain aggregation procedure in the edge-space.

In the case of the Stokes equation, we first discuss the direct Schur–complement method via domain decomposition which gives rise to a saddle-point problem for the velocity nodes on the subdomain boundaries and the mean values of the pressure on the subdomains. The analysis is essentially based on the two-level stabilization principle including the separate LBB conditions for each subdomain and a certain global inf-sup condition, but on the coarse level. The implementation only requires the solution of smaller discrete Stokes systems on the subdomains (e.g., by the multigrid methods) within the PCG iterations for the global interface equation posed in the constraints-free trace space. This method has the complexity $O(N^2 \log N)$, where N is the number of degrees of freedom on the interface.

An alternative method is oriented to a special case of rectangular substructures, where the direct sparse approximation to the local Schur-complements on subdomains is available. We analyze a mixed FE approximation to the Poincaré-Steklov operator on a subspace. The resultant interface equation is formulated w.r.t. to the trace of the pressure and the tangential velocity component on the skeleton. Under certain assumptions, an overall complexity is estimated by $O(N \log^3 N)$. The method may provide a robust interface preconditioning for the Lamé equation in the case of almost incompressible materials.

The results are based on joint work with Gabriel Wittum.

Domain decomposition methods with Lagrange multipliers for elasticity problems

Axel Klawonn (Münster, Germany)

In the last decade, a lot of research has been carried out on nonoverlapping domain decomposition methods with Lagrange multipliers. In these methods the original domain is decomposed into nonoverlapping subdomains. The intersubdomain continuity is then enforced by Lagrange multipliers across the interface defined by the subdomain boundaries. A computationally very efficient member of this class of methods is the Finite Element Tearing and Interconnecting (FETI) method introduced by Farhat and Roux. In a variant of the FETI method,

a Neumann and a Dirichlet problem per subdomain is solved exactly in each iteration.
A new domain decomposition method with Lagrange multipliers is introduced by reformulating the preconditioned system of the FETI algorithm as a saddle point problem with both primal and dual variables as unknowns. The resulting system is then solved using block-structured preconditioners in combination with a suitable Krylov space method. This approach avoids costly subdomain solvers and it also allows for more flexibility in the choice of preconditioners and inexact subdomain solvers. Good features of the FETI method such as scalability and efficiency are preserved.

Analysis and numerical methods for fluid structure interactions

Yvon Maday (Paris, France)

We are interested in applications when fluid structure interactions involve domains that vary little in time and are part of the unknowns. First of all, we present results about the wellposedness and existence of a solution in this frame. Then, starting from the basic fact that we want to use preexisting knowledge about the separated resolution of the fluid problem and the structure problem, we propose and analyze different ways of coupling these codes in order to simulate the coupled problem. This involves time stepping resolution and matching fluid and structure on different meshes.

Least squares methods for solving boundary value problems

Jean Francois Maitre (Ecully, France)

The presentation is concerned with a review about least squares methods: history, references, and work in progress with emphasis on ADN-founded least squares methods using the general estimates of Agmon-Douglis-Nirenberg (1964) for linear systems of partial differential equations. A list of recent applications is also given.

Domain decomposition methods for bonded structures

Donatella Marini (Pavia, Italy)

We study numerically the bonding of two elastic bodies through a thin adhesive layer. By asymptotic analysis this problem is replaced by a limit problem where the layer has disappeared (geometrically) and is replacred by suitable transmission conditions at the interface. These conditions can be interpreted as Fourier-Robin conditions which are the starting point to build an iterative procedure between the two subdomains for which we prove convergence. The same algorithm is applied to the conforming piecewise linear finite element approximation of the problem. Convergence of the algorithm is proved as well as optimal error bounds for the approximation.

Approximation of retarded potentials in wave equations (acoustics and Maxwell)

Jean-Claude Nédélec (Palaiseau, France)

We present some numerical schemes using retarded integral equations and several numerical applications of these techniques.

Preconditioning for elliptic problems with bad parameters

Serguei Nepomnyashikh (Novosibirsk, Russia)

In this talk elliptic boundary value problems are considered in domains where the coefficients of the elliptic differential operators change discontinuously. Appropriate preconditioners for the finite element discretized problems are constructed and analyzed using arguments from the theory of fictitious domain methods.

Domain decomposition methods for time-dependent Stokes problems

Luca F. Pavarino (Pavia, Italy)

Time-dependent Stokes problems (also known as generalized Stokes problems) arise in incompressible fluid dynamics and in structural mechanics problems. Using implicit time stepping procedures and mixed finite elements for the space discretization, we have to solve at each time step a discrete saddle point problem. We consider the iterative solution of such a system based on domain decomposition techniques and block preconditioners.

Domain decomposition for flow problems with boundary elements

Alfio Quarteroni (Milano, Italy)

In this talk we formulate analogies among PDE's multidomain formulations, Steklov-Poincaré operators, and preconditioned iterative substructuring with special emphasis on heterogeneous problems. Some abstract convergence theorems are given.

Domain decomposition for interface problems in fluid flow in porous media

Jean Roberts (Rocquencourt, France)

We are concerned with the treatment of interface problems for fluid flow in porous media. Two cases are considered. In the first, the fluid is single-phase and the medium is fractured. The fracture, itself being a porous medium, is treated as an interface. The pressure is continuous at the interface, but the fluid ia allowed to flow into or out of the fracture. The pressure and the flow field in the fracture are themselves a solution to a differential equation in dimension n-1. In the second example, the fluid is two-phase and the interface is an interface between two rock types. Since a global pressure formulation is used, neither the pressure nor the saturation is continuous across the interface. In both cases, by the use of a Poincaré-Steklov operator, the problem is posed as a problem on the interface and numerical results are given.

Domain decomposition preconditioning in linear elasticity with nearly incompressible subdomains

Joachim Schöberl (Linz, Austria)

We consider the problem of linear elasticity with jumpi g coefficients. We are specially interested in the case of some nearly incompressible subdomains, i.e., $\nu \sim 1/2$.

We construct a non overlapping Dirichlet domain decomposition preconditioner with local robust multigrid preconditioners, local robust multigrid extension operators and robust Schur complement preconditioners. The Schur complement preconditioners split into a coarse-grid solver which has to capture the jumps of the coefficients and the nearly incompressibility in averaged form, and preconditiones for local trace spaces. The local trace preconditioners are realized by scalar preconditioners and projection operators into the subspace fulfilling $\int_{\gamma_1} u^T n ds$ for all faces γ_1 of the domain decomposition.

The result is an optimal preconditioner which is robust with respect to the jumps of the coefficients, $\nu \to 1/2$, and Korn's constant as long as the coarse grid has well-shaped elements and the local scalar preconditioners are optimal.

Multifield formulations and domain decomposition with boundary elements

Olaf Steinbach (Stuttgart, Germany)

In this talk we discuss boundary element discretizations of Steklov-Poincaré operators which play an important role in domain decomposition methods. Beside the symmetric approximation by means of the Calderon projection we consider mixed and hybrid formulations based on Symm's integral equation only. In this case a BBL-like stability condition is required to ensure the stability.

Parallel adaptive solution of problems due to approximations on nonmatching grids

Yuri Vassilevski (Moscow, Russia)

For the efficient parallel adaptive solution of symmetric elliptic problems we apply the conception of domain decomposition with nonmatching grids. Given a parallel computational system with N_p processors, we construct an adaptive domain decomposition, N_p being essentially smaller than the number m of subdomains. The decomposition is a solution-adapted coarse triangulation of the computational domain and refines where future adapted meshes are needed. Then we generate in parallel quasi-hierarchical adaptive meshes in each subdomain regardless of meshing in neighboring subdomains. The subdomain meshes do not match at the interfaces. We apply the macro-hybrid formulation to discretize the elliptic problem on the nonmatching meshes. For the solution of the arising algebraic saddle-point problem we use the generalized Lanczos method with a block diagonal preconditioner that is in some sense spectrally equivalent to the saddle-point matrix. The preconditioner consists of blocks for preconditioning the subdomain problems and the interface problem.
In order to provide an appropriate load balancing, in the parallel implementation of the method we merge the subdomains into clusters, each of them corresponding to a process, and reallocate the subtasks on the basis of known arithmetical complexity. We measure the arithmetical complexity in terms of subtask execution time.
As an illustrative example we present the results of parallel adaptive solutions of model potential flow problems.

Solution of a biomedical problem by a domain decomposition method

Marina Vidrascu (Rocquencourt, France)

Laparoscopic techniques reduce operating time and morbidity. Students have to practice this novel technique. One can either use living animals or cadavers or numerical simulation. A surgery simulator was designed in the project EPIDAURE at INRIA (N. Ayache, H. Delingueter, S. Cotin). The geometrical model is built from medical images. The real time computations are based on a linear model and include a force feedback. The aim of a present multi-action project including several teams at INRIA and medical doctors from IRCAD (Strasbourg) is to improve the simulator and to check its accuracy. The aim of our project MOSTRAIMSN (P. LeTallec, A. Thiriel and myself) is to use the most apprpriate finite element nonlinear model to compute the deformations of the liver and compare solutions to those obtained by the simulator. The chosen model is nonlinear hyperelasticity using Ogden type constitutive enrgy for isotropic incompressible materials. A total Lagrangian form is used. The problem is discretized by using P2-P0 elements and is solved by a Newton-Euler continuation algorithm with automatic time-stepping. The main step in this algorithm is the solution of a large scale linear problem which is sparse and ill conditioned. The problem is solved using a domain decomposition method with a generalized Neumann-Neumann preconditioner. This is a particular case of the additive Schwarz method and it can handle irregular decompositions using unstructured finite elements. After eliminating the internal nodes, the interface problem is solved by a GMRES preconditioned algorithm. We construct the preconditioner of the initial tangent stiffness matrix and use it for several Newton iterations. Numerical tests are performed on a cluster of workstations in parallel. The domain is split into 20 subdomains. The first results demonstrate the ability of this algorithm to solve real life problems.

Domain decomposition methods for subsurface and surface flow problems

Mary F. Wheeler (Austin, U.S.A.)

In this talk we discuss parallel and accurate algorithms for solving subsurface and surface flow. Both computationally rough techniques (number of computations per element changes with space and time) and computationally smooth ones are presented. For subsurface problems, a locally conservative expanded mixed finite element method for nonmatching grids is defined and convergence results are given. This formulation is presented for both single and multiphase flow. Numerical results are presented for a multicomponent bio-geochemical problem and for two-phase flows. The grid partitioning algorithm based on space-filling curves is also defined and results for a Cheseapeake Bay surface flow problem are discussed.

Fast solvers for groundwater flow problems

Gabriel Wittum (Stuttgart, Germany)

Efficient soultion strategies are crucial for the simulation of large application problems. We present a combination of adaptivity, multigrid and parallelism combined in the software package "ug". A special tool for parallelization of general graph structures, DDD, is presented too. These strategies are applied to complex application problems in groundwater flow: flow around a saltdome and two-phase flow. Both problems are very important for applications. The saltdome problem has a highly complex geometry which requires millions of nodes. The problem can hardly be resolved, even on the largest available computer. In the two-phase flow problem, we were able to compute capillary effects which could not be computed up to now. This shows the benefit of fast solvers to real-life problems.

A priori and a posteriori estimates and parallelization by two-grid discretization

Jinchao Xu (University Park, U.S.A.)

A new two-grid technique is used to parallelize finite element computations. With a coarse grid to capture global components of the solution, the finite element solution on a much finer grid can be obtained locally without loss of accuracy. This technique is based on some new local a priori estimates for finite element solutions on general shape-regular non-uniform grids. Some new local a posteriori estimates are also presented and they are used to design a new parallel adaptive method and efficiently realize the aforement two-grid parallel algorithm.

List of E-mail addresses:

Yves Achdou	Yves.Achdou@insa-rennes.fr
Ove Axelsson	axelsson@sci.kun.nl
Randolph E. Bank	rbank@ucsd.edu
Faker Ben Belgacem	belgacem@mip.ups-tlse.fr
Christine Bernardi	bernardi@ann.jussieu.fr
Petter E. Bjørstad	petter.ii.uib.no
Dietrich Braess	braess@num.ruhr-uni-bochum.de
Suzanne Brenner	brenner@math.sc.edu
Franco Brezzi	brezzi@dragon.ian.pv.cnr.it
AnnaLuisa Buffa	abuffa@asci.fr
Claudio Canuto	ccanuto@polito.it
Peter Deuflhard	deuflhard@zib-berlin.de
Jim Douglas	douglas@math.purdue.edu
Maksymilian Dryja	dryja@hydra.mimuw.edu.pl
Richard E. Ewing	ewing@math.tamu.edu
Wolfgang Hackbusch	wh@numerik.uni-kiel.de
Ralf Hiptmair	hiptmair@math.uni-augsburg.de
Ronald H.W. Hoppe	hoppe@math.uni-augsburg.de
Boris Khoromskij	khorom@ica3.uni-stuttgart.de
Axel Klawonn	klawonn@escher.uni-muenster.de
Ralf Kornhuber	kornhuber@mathematik.uni-stuttgart.de
Yuri A. Kuznetsov	kuz@math.uh.edu
Ulrich Langer	ulanger@miraculix.numa.uni-linz.ac.at
Raytcho Lazarov	lazarov@math.tamu.edu
Yvon Maday	maday@ann.jussieu.fr
Jean-Francois Maitre	maitre@cc.ec-lyon.fr
Donatella Marini	marini@dradon.ian.pv.cnr.it
Jean-Claude Nedelec	nedelec@cmapx.polytechnique.fr
Serguei Nepomnyashikh	ict@nsk.su
Alexander Padij	padij@sci.kun.nl
Luca Pavarino	pavarino@dragon.ian.pv.cnr.it
Alfio Quarteroni	alfqua@ipmma1.polimi
Rolf Rannacher	rannacher@gaia.iwr.uni-heidelberg.de
Jean Roberts	jean.roberts@inria.fr
Joachim Schöberl	schoeberl@miraculix.numa.uni-linz.ac.at
Olaf Steinbach	steinbach@mathematik.uni-stuttgart.de
Pasi Tarvainen	tarvainen@tarzan.math.jyu.fi
Jean-Marie Thomas	jean-marie.thomas@univ-pau.fr
Yuri Vassilevski	vasilevs@humpty.inm.ras.ru
Marina Vidrascu	marina.vidrascu@inria.fr
Wolfgang L. Wendland	wendland@mathematik.uni-stuttgart.de

Mary Fanett Wheeler	mfw@ticam.utexas.edu
Olof B. Widlund	widlund@cs.nyu.edu
Gabriel Wittum	gabriel@ica3.uni-stuttgart.de
Barbara Wohlmuth	wohlmuth@cs.nyu.edu
Konstanze Wulf	wulfk@malaga.math.uni-augsburg.de
Jinchao Xu	xu@math.psu.edu

Tagungsteilnehmer

Prof.Dr. Yves Achdou
Departement de Mathematiques
Universite de Rennes I
Campus de Beaulieu

F-35042 Rennes Cedex

Prof.Dr. Petter E. Bjorstad
Department of Informatics
University of Bergen
Hoyteknologisenteret

N-5020 Bergen

Prof.Dr. Owe Axelsson
Mathematisch Instituut
Katholieke Universiteit Nijmegen
Toernooiveld 1

NL-6525 ED Nijmegen

Prof.Dr. Dietrich Braess
Institut f. Mathematik
Ruhr-Universität Bochum
Gebäude NA

44780 Bochum

Prof.Dr. Randolph E. Bank
Dept. of Mathematics
University of California, San Diego

La Jolla , CA 92093-0112
USA

Dr. Susanne C. Brenner
Dept. of Mathematics
University of South Carolina

Columbia , SC 29208
USA

Prof.Dr. Faker Ben Belgacem
Mathematiques
Universite Paul Sabatier
118, route de Narbonne

F-31062 Toulouse Cedex

Prof.Dr. Franco Brezzi
I. A. N. del C. N. R.
Corso C. Alberto, 5

I-27100 Pavia

Prof.Dr. Christine Bernardi
Laboratoire d'Analyse Numerique,
Tour 55-65
Universite P. et M. Curie(Paris VI)
4, Place Jussieu

F-75252 Paris Cedex 05

Dr. Annalisa Buffa
c/o Prof. Yvon Maday
Lab. d'Analyse Numerique
Univ. Pierre et Marie Curie
4, place Jussieu

F-75252 Paris Cedex

Prof.Dr. Claudio Canuto
Dipartimento di Matematica
Politecnico di Torino
Corso Duca degli Abruzzi, 24

I-10129 Torino

Prof.Dr. Wolfgang Hackbusch
Max-Planck-Institut für Mathematik
in den Naturwissenschaften
Inselstr. 22 - 26

04103 Leipzig

Prof.Dr. Peter Deuflhard
Konrad-Zuse-Zentrum für
Informationstechnik Berlin (ZIB)
Takustr. 7

14195 Berlin

Dr. Ralf Hiptmair
Lehrstuhl für Angewandte
Mathematik I
Universität Augsburg
Universitätsstr. 14

86159 Augsburg

Prof.Dr. Jim Douglas
Dept. of Mathematics
Purdue University

West Lafayette , IN 47907-1395
USA

Prof.Dr. Ronald H.W. Hoppe
Lehrstuhl für Angewandte
Mathematik I
Universität Augsburg
Universitätsstr. 14

86159 Augsburg

Prof.Dr. Maksymilian Dryja
Institute of Mathematics
University of Warsaw
Banacha 2

02-097 Warszawa
POLAND

Dr. Boris Khoromskij
Joint Institute for Nuclear
Research
Dubna Head Post Office
P.O. Box 79

101000 Moscow
RUSSIA

Prof.Dr. Richard E. Ewing
Institute for Scient. Computation
Texas A&M University

College Station , TX 77843-3404
USA

Dr. Axel Klawonn
Institut für Numerische und
Instrumentelle Mathematik
Universität Münster
Einsteinstr. 62

48149 Münster

Prof.Dr. Ralf Kornhuber
Institut für Informatik
Freie Universität Berlin
Arnimallee 2 - 6

14195 Berlin

Prof.Dr. Jean-Francois Maitre
Departement M. I. S.
CNRS/Ecole Centrale de Lyon
B. P. 163

F-69131 Ecully Cedex

Prof.Dr. Yuri A. Kuznetsov
Department of Mathematics
University of Houston

Houston , TX 77204-3476
USA

Dr. Donatella Marini
Dipartimento di Matematica
Universita di Pavia
Via Abbiategrasso 209

I-27100 Pavia

Prof.Dr. Ulrich Langer
Institut für Analysis und Numerik
Universität Linz
Altenbergstr. 69

A-4040 Linz

Prof.Dr. Jean-Claude Nedelec
Centre de Mathematiques Appliquees
Ecole Polytechnique
U. R. A. - C. N. R. S. 169

F-91128 Palaiseau Cedex

Prof.Dr. Rajco D. Lazarov
Department of Mathematics
Texas A & M University

College Station , TX 77843-3368
USA

Dr. Sergei Nepomnyaschikh
Computing Center
Siberian Division of the Russian
Academy of Sciences
ul. Lavrentieva 6

630090 Novosibirsk
RUSSIA

Prof.Dr. Yvon Maday
Laboratoire d'Analyse Numerique,
Tour 55-65
Universite P. et M. Curie(Paris VI)
4, Place Jussieu

F-75252 Paris Cedex 05

Prof.Dr. Alexander Padiy
Mathematisch Instituut
Katholieke Universiteit Nijmegen
Toernooiveld 1

NL-6525 ED Nijmegen

Joachim Schöberl
Institut für Mathematik
Universität Linz
Altenberger Str. 69

A-4040 Linz

Dr. Luca F. Pavarino
Dipartimento di Matematica
Universita di Pavia
Via Abbiategrasso 215

I-27100 Pavia

Olaf Steinbach
Mathematisches Institut A
Universität Stuttgart
Pfaffenwaldring 57

70569 Stuttgart

Prof.Dr. Alfio Quarteroni
Dipartimento di Matematica
Politecnico di Milano
Via Bonardi 9

I-20133 Milano

Dr. Pasi Tarvainen
Dept. of Mathematics
University of Jyväskylä
P.O.Box 35

SF-40351 Jyväskylä

Prof.Dr. Rolf C. Rannacher
Institut für Angewandte Mathematik
Universität Heidelberg
Im Neuenheimer Feld 293

69120 Heidelberg

Prof.Dr. Jean-Marie Thomas
Lab. Math. Appliquees
UPRESA 5033
IPRA
Av. de l`Université

F-64000 Pau

Prof.Dr. Jean Roberts
INRIA Rocquencourt
Domaine de Voluceau
B. P. 105

F-78153 Le Chesnay Cedex

Dr. Yuri V. Vassilevski
CDCSP
Universite Claude Bernard Lyon 1
ISTIL - Batiment 101
43, BD du 11 Novembre 1918

F-68622 Villeurbanne Cedex

Dr. Marina Vidrascu
INRIA Rocquencourt
Domaine de Voluceau
B. P. 105

F-78153 Le Chesnay Cedex

Dr. Barbara Wohlmuth
Courant Institute of
Mathematical Sciences
New York University
251, Mercer Street

New York , NY 10012
USA

Prof.Dr.-Ing. Wolfgang L. Wendland
Mathematisches Institut A
Universität Stuttgart

70550 Stuttgart

Dr Konstanze Wulf
Institut für Mathematik
Universität Augsburg
Universitätsstr. 14

86159 Augsburg

Prof.Dr. Mary Fanett Wheeler
TICAM
TAY 2.400
University of Texas

Austin , TX 78712

Prof.Dr. Jinchao Xu
Department of Mathematics
Pennsylvania State University
218 McAllister Building

University Park , PA 16802
USA

Prof.Dr. Olof Widlund
Courant Institute of
Mathematical Sciences
New York University
251, Mercer Street

New York , NY 10012-1110
USA

Prof.Dr. Gabriel Wittum
Institut für Computeranwendungen
Numerik für Höchstleistungsrechner
Universität Stuttgart

70550 Stuttgart