Final Report
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Award Title: *Annual Copper Mountain Conferences*
on Multigrid and Iterative Methods,
Copper Mountain, Colorado

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Summary of the Project

This project supported the Copper Mountain Conference on Multigrid and Iterative Methods, held from 2007 to 2015, at Copper Mountain, Colorado. The subject of the Copper Mountain Conference Series alternated between Multigrid Methods in odd-numbered years and Iterative Methods in even-numbered years. Begun in 1983, the Series represents an important forum for the exchange of ideas in these two closely related fields. From 1983 until 2002, conferences in the Series were organized by the University of Colorado in cooperation with the Society of Industrial and Applied Mathematics (SIAM), with support provided by Front Range Scientific Computations, Inc. In 2003, 2005, and 2007, the conferences on Multigrid Methods were organized jointly by Van Emden Henson of Lawrence Livermore National Laboratory and Joel Dendy of Los Alamos National Laboratory. In 2009 and 2011 (and continuing forward in the odd numbered years), the conferences on Multigrid Methods were organized jointly by Van Emden Henson, as overall conference chairman, along with Ulrich Rüde of the Universität Erlangen (Nürnberg, Germany) and Irad Yavneh of the Technion – Israel Institute of Technology (Haifa, Israel), serving as conference Program co-Chairmen. Similarly, the 2004, 2006, and 2008 Copper Mountain Conferences on Iterative Methods were organized jointly by Howard Elman of the University of Maryland and Panayot Vassilevski of Lawrence Livermore National Laboratory. In 2010, Ray Tuminaro (Sandia National Laboratory) replaced Panayot Vassilevski as co-Chair, with Howard Elman, of the Iterative Conferences. In 2014, Michele Benzi (Emory University) replaced Howard Elman as Co-Chair, with Ray Tuminaro.

Final Report

This report describes the Copper Mountain Conference on Multigrid and Iterative Methods, 2007-2015. Information on the conference series is available at

I. MEETING DESCRIPTION

Begun in 1983 and alternating between Multigrid Methods (odd-numbered years) and Iterative Methods (even-numbered years), with substantial and increasing overlap in both programs, the Copper Mountain Conference Series is an important forum for exchange of ideas in these two closely related fields. The success of this series is measured not only by its continuing popularity among practitioners over the past 30 years, but also by the tangible scientific contributions that have resulted. Specifically, three major scientific journals have devoted a total of sixteen Special Issues to papers documenting transactions of the series. More difficult to document, but readily discernible through anecdotal evidence, are the numerous important scientific collaborations that have arisen out of planned and even chance encounters occurring at the conferences, the many publications that have resulted from these alliances, and the on-going resulting expansion of multigrid and iterative methods both as research fields and as tools used in an ever-widening array of applications.

An ongoing theme of the Copper Mountain Conferences is to engage and connect the mathematical sciences community and to continue to increase the number of participants from the mathematical sciences community. The conference series is notable in its emphasis on student participation; students typically account for more than one-third of the iterative conference attendees, with the smaller multigrid series garnering more than 40% this past year. But simply having students attend is only part of the strategy—students are strongly encouraged to participate fully at the conferences. Many of the students present papers at the meetings, encouraged by a student paper competition at each conference, and several tutorials that the series offers are designed to introduce newcomers, both students and established scientists, to the methods in these ever-expanding fields. For many years, participants who *first* attended these conferences as students have been asked to stand up at the conference banquet, and it is not unusual to see more than half of the audience on their feet. Furthermore, the conferences have made an effort to attract participation by women, foreign scientists, and other underrepresented groups. The most notable successes, to date, can be estimated by examining the percentages of women, minorities, and foreign students in attendance, often approaching half the total number of students. It is also noteworthy that three out of the four competition winners from the last Iterative meeting were women students. These signature characteristics of the conference series, of outreach and inclusion, show how well aligned the series is with NSF objectives and how significant its impact is on the sciences community.

The Copper Mountain series is the only regularly scheduled international meeting on multigrid methods held in the western hemisphere, and the most frequently held of all international multigrid conferences. The European multigrid conferences have been held on average about every third year, with the 2014 dates of September 9-12, in Leuven, Belgium. There are no regular international meetings on iterative methods. With the substantial research output, the focus on students, women, and underrepresented group participation, and the increasing attraction of foreign participants, the thriving Copper Mountain Conferences play a significant role in driving the progress and vitality of both multigrid and iterative methods and their

applications. Accordingly, the funds requested here are intended primarily to support attendance and participation by these groups.

II. ORGANIZATION

Since 1990, the conferences have been organized and run by Front Range Scientific Computations, Inc., in cooperation with the University of Colorado and the Society of Industrial and Applied Mathematics (SIAM). Steve McCormick and Tom Manteuffel were co-Chairs from the beginning of the series in 1983 until 2003, when Joel Dendy (Los Alamos National Laboratory) and Van Emden Henson (Lawrence Livermore National Laboratory) replaced them as principal organizers and co-Chairs of the Copper Mountain Conferences on Multigrid Methods. Similarly, in 2004, Howard Elman (University of Maryland) and Panayot Vassilevski (Lawrence Livermore National Laboratory) became primary organizers and co-Chairs of the Copper Mountain Conferences on Iterative Methods. At the conclusion of the 2007 conference, Joel Dendy retired as co-Chair of the Multigrid Conferences, and Irad Yavneh (Technion) and Ulrich Rüde (University of Erlangen-Nüremberg) became joint Program Chairs. In 2010, Ray Tuminaro (Sandia National Laboratory) replaced Panayot Vassilevski as co-Chair, with Howard Elman, of the Iterative Conferences. In 2014, Michele Benzi (Emory University) replaced Howard Elman as Co-Chair, with Ray Tuminaro. In 2016, Rob Falgout (Lawrence Livermore Laboratory) and Luke Olson (University of Illinois) will co-Chair the Multigrid Conference.

Further information on the conference series is available at

<p style="text-align:center">http://grandmaster.colorado.edu/~copper/</p>

Current Iterative Methods Conference Organizational Structure

Co-Chairs

Michele Benzi	Emory University
Ray Tuminaro	Sandia National Laboratory

Organizing Committee:

Xiao-Chuan Cai	University of Colorado
Iain Duff	RAL and CERFACS
Howard Elman	University of Maryland
Kirk Jordan	IBM, Watson Research Center
Tim Kelley	North Carolina State University
Misha Kilmer	Tufts University
Dana Knoll	Los Alamos National Laboratory
Sven Leyffer	Argonne National Laboratory
Ira Livshits	Ball State University
Tom Manteuffel	University of Colorado at Boulder

Steve McCormick	University of Colorado at Boulder
James Nagy	Emory University
Luke Olson	University of Illinois at Urbana-Champaign
John Shadid	Sandia National Laboratory
David Silvester	University of Manchester
Andreas Stathopoulos	College of William and Mary
Homer Walker	Worchester Polytechnic
Karen Wilcox	MIT
Carol Woodward	Lawrence Livermore National Laboratory
Irad Yavneh	Technion

Current Multigrid Methods Conference Organizational Structure

Co-Chairs:

Robert Falgout	Lawrence Livermore National Laboratory
Luke Olson	University of Illinois at Urbana Champaign

Organizing Committee:

James Brannick	Pennsylvania State University
Susanne Brenner	University of South Carolina
Marian Brezina	University of Colorado at Boulder
Joel Dendy	Los Alamos National Laboratory
Hans De Sterck	University of Waterloo
Craig Douglas	University of Kentucky
Van Emden Henson	Lawrence Livermore National Laboratory
Jim Jones	Florida Institute of Technology
Kirk Jordan	IBM
Tom Manteuffel	University of Colorado at Boulder
Scott MacLachlan	Tufts University
Steve McCormick	University of Colorado at Boulder
David Moulton	Los Alamos National Laboratory
Kees Oosterlee	Delft University of Technology
Ulrich Rüde	Universität Erlangen
John Ruge	University of Colorado at Boulder
Klaus Stüben	GMD, Germany
Stefan Vandewalle	Katholieke Universiteit Leuven
Karen Wilcox	Massachusetts Institute of Technology
Ulrike Yang	Lawrence Livermore National Laboratory
Irad Yavneh	Technion, Israel

III. FORMAT AND SPEAKERS

Each conference is planned for five days, following a basic structure that has proved successful throughout the series. Morning and late afternoon sessions consist of individual talks of approximately 1/2 hour each. This structure accommodates about 60 talks in serial sessions, which has been adequate for the Multigrid Methods meetings, or about 120 talks in two parallel sessions, which has been necessary to accommodate the larger Iterative Methods meetings. As has been the tradition, the meetings have an egalitarian style with no invited talks, and student presentations are put on equal footing with all others.

The timing of the meetings coincides closely with term breaks in many countries and there has been very strong participation from Europe and other international locations. Based on discussions with possible attendees, these trends are expected to continue.

Both conference series have, since their inceptions, emphasized *conference themes* in their annual call for papers. In 1999, the multigrid conference was organized around the themes, with each day of the conference devoted to one specific theme. This innovation was very popular among the participants. Since then, both conferences promote conference themes, although without as much organizational formality as in 1999. The use of themes has proved to be highly successful both in attracting new attendees and in reinvigorating the discussion among longtime attendees.

The conference series has a tradition of evening sessions that are devoted to panel discussions, workshops, and a *circus*. The circus provides a forum for participants to present their research on an *ad hoc* basis, allowing presentation of work-in-progress, late-breaking results, and open questions. The workshops and panel discussions are typically organized around specific themes, including the topics of special emphasis described below. Each member of the organizing committee is urged to speak and to arrange sessions, workshops, and panels on research that is of special interest to the community. A special effort is made to ensure that these sessions represent the most current developments and to encourage the participation of researchers from industry and government research laboratories whose work is focused on applications.

IV. PROGRAM

Topics of Emphasis

The meetings at Copper Mountain enjoy a special role in stimulating the iterative and multigrid communities. The sessions span the range of methods from highly theoretical to very practical and applied. The conference attracts participants from both academic and industrial communities. For many students and young researchers, they serve as an exciting initiation into the field. They cultivate a unique exchange of ideas from an impressive international collection of computational scientists. In addition to encouraging cross-fertilization across a wide range of multigrid and iterative method disciplines, the meetings also serve to introduce

many researchers to new trends, topics, and application areas. This is generally done by actively promoting special topics of emphasis. The topics reflect research areas that are particularly timely and have fostered increased attendance at recent conferences. Topics will be actively promoted by members of the program committee, including their solicitation of contributions and organization of special sessions built around the new themes. A conference format that includes one or two special daytime sessions and some evening workshops devoted to special topics has resounded well with conference attendees in the past, and the plan is to continue this line of organization. Here are the topics of emphasis for the three previous year's conferences:

2013 Highlighted Topics

- Algebraic multigrid (AMG)
- Aggregation methods: Smoothed and Unsmoothed/Accelerated
- Adaptive algebraic methods
- Multigrid for systems of PDEs
- Parallel multigrid (including AMG and SA)
- Multigrid for nonlinear problems
- Applications
- Hardware-aware multigrid
- Multigrid and multiscale modeling

2014 Highlighted Topics

- Stochastic PDEs and Uncertainty Quantification
- Scale-free/Small World Graphs, Page Rank and Markov Chains
- Multigrid and Other Iterative Schemes on GPU & Multicore Architectures
- Inverse Problems and Regularization
- Optimization of Complex Problems
- Nonlinear Solution Methods, Nonlinear Least-Squares
- Multigrid All-At-Once and Block Approaches to PDE Systems
- Coupled Multi-Physics Problems
- Time-Parallel Algorithms
- Krylov Accelerators
- Hybrid direct-iterative linear solvers
- Iterative Methods in Challenging Applications (e.g., Electromagnetics, Energy, Environmental, Data Assimilation, MHD, Neutronics, Transport/Reaction, Chemical Engineering)

2015 Highlighted Topics

- Uncertainty Quantification
- Optimization and Inverse Problems
- Data Mining, Large Graphs, and Markov Chains

- Nonsymmetric and Indefinite Problems
- Krylov Accelerators
- Hybrid Direct-Iterative Linear Solvers
- Reduced Communication for Parallel Implementation of Multilevel Algorithms
- Parallel Multigrid on Multicore Systems and Heterogeneous Architectures
- Time Parallel Methods
- Iterative Methods in Applications (e.g., Electromagnetics, Energy, Environmental, MHD, Neutronics, Transport/Reaction)

Tutorials

Beginning in 1999, because of the emerging critical need for new advances and new human resources in this field, the Conferences revived and updated the multigrid tutorials that were a staple of the early conferences. Bill Briggs of CU-Denver reprised his presentation of *A Multigrid Tutorial,* which was first given at the 1987 conference, and later written into Briggs' highly popular book of the same title (published by SIAM). Also in 1999, Van Emden Henson (Lawrence Livermore National Laboratory) first presented a tutorial on algebraic multigrid, and Jim Jones (then of Lawrence Livermore National Laboratory) presented a tutorial on multigrid for parallel computers. Based on the success of these tutorials, the tutorial series was continued and expanded for succeeding conferences. In each of the 2001, 2003, 2005, and 2007 conferences, Van Emden Henson presented a tutorial covering all the material of the 2001 revision and expansion of the book *A Multigrid Tutorial*, by Briggs, Henson, and McCormick. In addition, Craig Douglas (University of Wyoming), together with Ulrich Rüde (University of Erlangen-Nüremberg, Germany), presented a tutorial on cache-aware multigrid in 2001, 2003, 2005, and 2007, while Jim Jones (now at Florida Institute of Technology) presented an expanded tutorial on parallel multigrid in 2005. Since 2009, Irad Yavneh (Technion) has presented the basic tutorial while Van Henson has continued to cover the advanced topics. These tutorials have been well attended, and have received very high praise from many conference participants. As a result, the tutorial series is planned for continuation, with expansion and alterations of the content as the changing needs of the research community dictate.

V. DISSEMINATION

Special Journal Issue

Each speaker is invited to submit a paper to a special issue of a major scientific journal. Special Issues of *Electronic Transactions in Numerical Analysis (ETNA)* were devoted to the 1997, 1999, and 2001 Multigrid conferences. The 2003, 2005, 2007, 2009, 2011, and 2013 Multigrid conferences resulted in special issues of *Numerical Linear Algebra with Applications* (with an issue for the 2015 meeting in progress). The Iterative conferences have produced a

special issue of the *SIAM Journal of Scientific Computing* every even year since 1990. The conference papers are subjected to the same rigorous refereeing process as regular submissions to these journals, and submission to the special issue is also open to the general community.

Each of the conferences, since the beginning in 1983, have produced either a special issue (as is the case for the later conferences) or published refereed proceedings. All of the special issues are available on-line; those published in ETNA and NLAA are accessible through links on the Copper Mountain Conference series web page:

http://grandmaster.colorado.edu/~copper/index.html

VI. HUMAN RESOURCES

One of the main purposes of this proposal is for funding to enhance the participation in this meeting by students, women, post docs, junior faculty, and minority mathematicians. This participation is accomplished through two mechanisms: a student paper competition and a special fund to augment travel support for students and for women, post docs, junior faculty, and minority mathematicians.

The organizing committees recognize the value to students of the opportunity to meet and interact with experts in the field. Just as important, the committees recognize the critical importance to the field of computational science that young scientists be engaged as early as possible in their careers. To affect these outcomes, the meetings will continue to feature a student paper competition. Students are invited to submit a 10-page paper describing original research due *primarily* to the student. The program committee will select the winners, each of whom will receive a travel award. The conference will pay their travel expenses, lodging, and registration fee. The student winners will present a talk on their research at a special session of the meeting. To the extent possible, the conference will provide lodging expenses and registration fees to the other students who have submitted papers.

Based on availability of funds, lodging and registration support should be extended to as many students as possible, with a special effort made to encourage women and minority students. Support for students has been a priority of past conferences. Below is a table of available data on the total number of students, including the number of female students and foreign students, as well as the total number of conference attendees.

	2015	2014	2013	2012	2011	2010	2009
Students:							
total	31	55	38	61	43	55	39
female	5	19	11	31	12	11	4
foreign	7	11	10	20	16	17	13
All Attendees	76	160	100	182	91	187	95
Student %	**41%**	**34%**	**38%**	**34%**	**47%**	**29%**	**41%**

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Fem. Student %	16%	35%	29%	51%	28%	20%	10%

	2008	2007	2006	2005	2004	2003	2002
Students:							
total	49	30	55	36	50	38	29
female	27	4	10	3	6	8	7
foreign	37	21	15	17	26	19	11
All Attendees	162	69	175	111	185	91	160
Student %	30%	43%	31%	32%	27%	42%	18%
Fem. Student %	55%	13%	18%	8%	12%	21%	24%

	2001	2000	1999	1998	1997	1996	1995
Students:							
total	31	42	28	25	24	31	21
female	1	9	5	4	2	6	3
foreign	14	25	8	-	-	-	-
All Attendees	110	189	100	190	98	-	-
Student %	28%	22%	28%	13%	24%		
Fem. Student %	3%	21%	18%	16%	8%		

While the Conference series has been remarkably successful in attracting students, post docs, and junior faculty, the percent of women and minority students oscillated around national averages. This improved noticeable during the 2011-2014 timeframe, with the help of an NSF grant that provided particularly generous support to encourage women and minority mathematicians. In those years, we aggressively announced the possibility of financial support in the call for papers and registration process leading to a notable number of travel awards. During this 2011-2014 period, the female student percentage jumped to the 28-50% range (we only track/ask gender information of the students, as the general population may be reluctant to supply this). Unfortunately, last year's female student percentage was lower. This may be due to several factors, including a scheduling conflict with the large SIAM Computational Science and Engineering meeting and less funding available to encourage attendance from under-represented groups. We are not satisfied with this level of participation and are re-doubling our efforts towards improving representation from these groups. We also note that we do not anticipate scheduling conflicts between future Copper meetings and SIAM Computational Science and Engineering meetings. While we have not tracked minority attendance over the years, we do feel our efforts to attract minority attendees are starting to pay dividends.

For the last few years, the conference has been successful in disseminating its announcements through electronic newsletters and services. The conference call, the call for papers, and other announcements have been issued via several such electronic media, including NANet, MGNet,

SciComp, SIAM Unwrapped, and several other special interest groups on multigrid, supercomputing, and linear algebra. The conference will make every effort to expand this electronic dissemination process to include underrepresented groups.

The following table shows the students who have won the student paper competitions in the past twenty-three years. We were especially pleased to have three women winners in the 2014 competition.

2015	Simon Baumann	Universitat München
	Fei Cao	Penn State University
	Markus Hüber	Technische Universitat München
2014	Jessica Bosch	Max Planck Institute
	Sarah Gaaf	Eindhoven
	Scott Ladenheim	Temple University
	Manda Winlaw	University of Waterloo
2013	Siegfried Cools	University of Antwerp
	Stephanie Friedhoff	Tufts University
	Deylan Kalchev	LLNL
2012	Jennifer Pestana	University of Oxford
	Umberto Villa	Emory University
	Minghao Wu	University of Maryland
2011	Yao Chen	Penn State University
	Lei Tang	University of Colorado
	Eran Treister	Israel Institute of Technology
2010	Tyrone Rees	University of Oxford
	Artem Napov	Université Libre de Bruxelles
	Donghui Chen	Tufts University
	Andrew Gordon	University of Manchester
2009	Killian Miller	University of Waterloo
	Eran Treister	Israel Institute of Technology

	Liuqiang Zhong	Xiangtang University, China
2008	Melina Freitag	University of Bath
	Fei Xue	University of Maryland
	Stefan Wild	Cornell University
	Andrew Barker	University of Colorado
2007	Hengguang Li	Penn State
	Christian Mense	Tech Univ. of Berlin
	Hisham Zubair	Delft University
2006	Sue Dollar	Oxford University
	Elena Virnick	Technical University of Berlin
	Haim Waisman	Renssalaer Polytechnic Institute
2005	Bram Metsch	Universität Bonn
	Haim Waisman	Rensselaer Polytechnic Institute
	Michael Bronstein	Technion
2004	Andrei Drăgănescu	University of Chicago
	Ruth Holland	Oxford University
	Yair Koren	Technion
2003	Rima Gandlin	Weizmann Institute
	Gregory Dardyk	Technion
	Oren Livne	Weizmann Institute
2002	Tim Chartier	University of Colorado
	Michael Hochstenbach	Utrecht University
	Julien Langou	CERFACS
2001	Avraham Kenigsberg	Technion
	Malik Silva	University of Columbo

	Markus Kowarschik	University of Erlangen
	Chisup Kim	Texas A & M University
2000	Judith Vogel	Temple University
	Johannes Korsawe	University of Essen
	Michiel Hochstenbach	Utrecht University
1999	Roman Wienands	GMD
	Jonathan Rochez	Lawrence Livermore National Laboratory
	Shuhua Chen	Purdue
	Jonathan Hu	University of Kentucky
1998	Mark Adams	University of California at Berkeley
	Wai Ki Ching	Hong Kong University
	Daniel Loghin	Oxford University
	Chih-Jen Lin	University of Michigan
1997	Boris Diskin	Weizmann Institute of Science
	Jule Kouatchou	George Washington University
	Marc Kuther	University of Freiburg
	Xaviar Vassuer	Ecole Centrale de Nantes
	Erik Sterner	Department of Scientific Computing
	Hubertus Oswald	University of Heidelburg
	Wing-Lok Wan	University of California Los Angeles
1996	Axel Klawonn	University of Muenster
	Mark Horn	Wichita State University
	Stefan Knapek	Universität München
1995	Dexuan Xie	University of Houston
	J.R. Phillips	Massachusetts Institute of Technology
1994	Qing He	Arizona State

	Lina Hemmingsson	Uppsala University
	Johannes Tausch	Colorado State University
1993	Kenneth Brachenridge	Oxford University
	Chang Ock Lee	University of Wisconsin
	Mark Reichelt	MIT
1992	Andrew Lumsdaine	Massachusetts Institute of Technology
	Marlis Hochbruck	Universität Karlsruhe
	Xhang-Zhong Guo	University of Maryland
1991	M. R. Hanisch	Cornell University
	Yong Huang	University of Cincinatti
	Daniel Quinlan & Max Lemke	University of Colorado at Denver
1990	Barry Smith	Courant Institute
	Douglas James	University of North Carolina
	Sverker Holmgren & Kurt Otto	Uppsala University