Lecture Notes in Mathematics

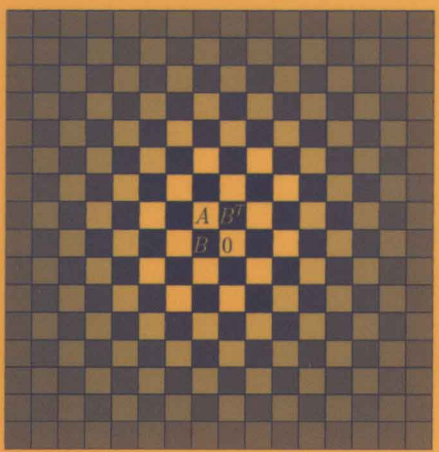
1939

Daniele Boffi
Franco Brezzi
Leszek F. Demkowicz
Ricardo G. Durán
Richard S. Falk
Michel Fortin

Mixed Finite Elements, Compatibility Conditions, and Applications

Cetraro, Italy 2006

Editors: D. Boffi, L. Gastaldi



Springer

FONDAZIONE CIME ROBERTO CONTI

Daniele Boffi · Franco Brezzi
Leszek F. Demkowicz · Ricardo G. Durán
Richard S. Falk · Michel Fortin

Mixed Finite Elements, Compatibility Conditions, and Applications

Lectures given at the
C.I.M.E. Summer School
held in Cetraro, Italy
June 26–July 1, 2006

Editors:
Daniele Boffi
Lucia Gastaldi

Springer

FONDAZIONE CIME ROBERTO CONTI

Lecture Notes in Mathematics 1939

FONDAZIONE
CIME
ROBERTO CONTI
CENTRO INTERNAZIONALE MATEMATICO ESTIVO
INTERNATIONAL MATHEMATICAL SUMMER CENTER

C.I.M.E. means Centro Internazionale Matematico Estivo, that is, International Mathematical Summer Center. Conceived in the early fifties, it was born in 1954 and made welcome by the world mathematical community where it remains in good health and spirit. Many mathematicians from all over the world have been involved in a way or another in C.I.M.E.'s activities during the past years.

So they already know what the C.I.M.E. is all about. For the benefit of future potential users and co-operators the main purposes and the functioning of the Centre may be summarized as follows: every year, during the summer, Sessions (three or four as a rule) on different themes from pure and applied mathematics are offered by application to mathematicians from all countries. Each session is generally based on three or four main courses (24–30 hours over a period of 6-8 working days) held from specialists of international renown, plus a certain number of seminars.

A C.I.M.E. Session, therefore, is neither a Symposium, nor just a School, but maybe a blend of both. The aim is that of bringing to the attention of younger researchers the origins, later developments, and perspectives of some branch of live mathematics.

The topics of the courses are generally of international resonance and the participation of the courses cover the expertise of different countries and continents. Such combination, gave an excellent opportunity to young participants to be acquainted with the most advance research in the topics of the courses and the possibility of an interchange with the world famous specialists. The full immersion atmosphere of the courses and the daily exchange among participants are a first building brick in the edifice of international collaboration in mathematical research.

C.I.M.E. Director
Pietro ZECCA
Dipartimento di Energetica "S. Stecco"
Università di Firenze
Via S. Marta, 3
50139 Florence
Italy
e-mail: zecca@unifi.it

C.I.M.E. Secretary
Elvira MASCOLO
Dipartimento di Matematica
Università di Firenze
viale G.B. Morgagni 67/A
50134 Florence
Italy
e-mail: mascolo@math.unifi.it

For more information see CIME's homepage: http://www.cime.unifi.it

CIME's activity is supported by:

- Istituto Nationale di Alta Mathematica "F. Severi"
- Ministero dell'Istruzione, dell'Università e delle Ricerca

Daniele Boffi
Dipartimento di Matematica
Università degli studi di Pavia
Via Ferrata 1, 27100 Pavia, Italy
daniele.boffi@unipv.it
http://www-dimat.unipv.it/boffi

Franco Brezzi
Istituto Universitario di Studi Superiori (IUSS)
and Istituto di Matematica Applicata e
Tecnologie Informatiche del C.N.R.
Via Ferrata 3, 27100 Pavia, Italy
brezzi@imati.cnr.it
http://www.imati.cnr.it/~brezzi

Leszek F. Demkowicz
Institute for Computational Engineering
and Sciences
The University of Texas at Austin
ACES 6.332, 105
Austin, TX 78712, USA
leszek@ices.utexas.edu
http://users.ices.utexas.edu/~leszek

Ricardo G. Durán
Departamento de Matemática
Facultad de Ciencias Exactas y Naturales
Universidad de Buenos Aires
Ciudad Universitaria. Pabellón I
1428 Buenos Aires, Argentina
rduran@dm.uba.ar
http://mate.dm.uba.ar/~rduran

Richard S. Falk
Department of Mathematics - Hill Center
Rutgers, The State University of New Jersey
110 Frelinghuysen Rd.
Piscataway, NJ 08854-8019, USA
falk@math.rutgers.edu
http://www.math.rutgers.edu/~falk

Michel Fortin
Département de mathématiques
et de statistique
Pavillon Alexandre-Vachon
Université Laval
1045, avenue de la Médecine
Québec (Québec)
G1V 0A6, Canada
mfortin@giref.ulaval.ca
http://www.mat.ulaval.ca

Lucia Gastaldi
Dipartimento di Matematica
Università degli Studi di Brescia
Via Valotti 9
25133 Brescia, Italy
gastaldi@ing.unibs.it
http://dm.ing.unibs.it/gastaldi

ISBN: 978-3-540-78314-5 e-ISBN: 978-3-540-78319-0
DOI: 10.1007/978-3-540-78319-0

Lecture Notes in Mathematics ISSN print edition: 0075-8434
ISSN electronic edition: 1617-9692

Library of Congress Control Number: 2008921921

Mathematics Subject Classification (2000): 65-02, 65N30, 65N12, 35M10, 74S05, 76M10, 78M10, 58A10, 58A12

Cover design: WMXDesign GmbH

Printed on acid-free paper

9 8 7 6 5 4 3 2 1

springer.com

Preface

This volume is a collection of the notes of the C.I.M.E. course "Mixed finite elements, compatibility conditions, and applications" held in Cetraro (CS), Italy, from June 26 to July 1, 2006.

Since the early 1970s, mixed finite elements have been the object of wide and deep study by the mathematical and engineering communities. The fundamental role of mixed methods for many application fields has been recognized worldwide and their use has been introduced in several commercial codes. An important feature of mixed finite elements is the interplay between theory and application: on the one hand, many schemes used for real life simulations have been cast in a rigorous framework, and on the other, the theoretical analysis makes it possible to design new schemes or to improve existing ones, based on their mathematical properties. Indeed, due to the compatibility conditions required by the discretization spaces to provide stable schemes, simple minded approximations generally do not work and the design of suitable stabilizations gives rise to challenging mathematical problems.

The course had two main goals. The first one was to review the rigorous setting of mixed finite elements and to revisit it after more than 30 years of practice; this resulted in developing a detailed a priori and a posteriori analysis. The second one was to show some examples of possible applications of the method.

We are confident this book will serve as a basic reference for people exploring the field of mixed finite elements. This "Lecture Notes" cover the theory of mixed finite elements and applications to Stokes problem, elasticity, and electromagnetism.

Ricardo G. Durán had the responsibility of reviewing the general theory. He started with the description of the mixed approximation of second-order elliptic problems (a priori and a posteriori estimates) and then extended the theory to general mixed problems, thus leading to the famous inf–sup conditions.

The second course on Stokes problem has been given by Daniele Boffi, Franco Brezzi, and Michel Fortin. From the basic application of the inf–sup theory to the linear Stokes system, stable Stokes finite elements have been analyzed, and general stabilization techniques have been described. Finally, some results on visco-elasticity have been presented.

Richard S. Falk has dealt with the mixed finite element approximation of the elasticity problem and, more particularly, of the Reissner–Mindlin plate problem. The corresponding notes are split into two parts: in the first one, recent results linking the de Rham complex to finite element schemes have been reviewed; in the second, classical Reissner–Mindlin plate elements have been presented, together with some discussion on quadrilateral meshes.

Leszek Demkowicz has given a general introduction to the exact sequence (de Rham complex) topic, which turns out to be a fundamental tool for the construction and analysis of mixed finite elements, and for the approximation of problems arising from electromagnetism. The results presented here use special characterization of traces for vector-valued functions in Sobolev spaces.

We thank all the lecturers and, in particular, Franco Brezzi, who laid the foundation for the analysis of mixed finite elements, for his active participation in this C.I.M.E. course.

Daniele Boffi, Pavia
Lucia Gastaldi, Brescia

LIST OF C.I.M.E. SEMINARS

Published by C.I.M.E

1954
1. Analisi funzionale
2. Quadratura delle superficie e questioni connesse
3. Equazioni differenziali non lineari

1955
4. Teorema di Riemann-Roch e questioni connesse
5. Teoria dei numeri
6. Topologia
7. Teorie non linearizzate in elasticità, idrodinamica, aerodinamic
8. Geometria proiettivo-differenziale

1956
9. Equazioni alle derivate parziali a caratteristiche reali
10. Propagazione delle onde elettromagnetiche automorfe
11. Teoria della funzioni di più variabili complesse e delle funzioni

1957
12. Geometria aritmetica e algebrica (2 vol.)
13. Integrali singolari e questioni connesse
14. Teoria della turbolenza (2 vol.)

1958
15. Vedute e problemi attuali in relatività generale
16. Problemi di geometria differenziale in grande
17. Il principio di minimo e le sue applicazioni alle equazioni funzionali

1959
18. Induzione e statistica
19. Teoria algebrica dei meccanismi automatici (2 vol.)
20. Gruppi, anelli di Lie e teoria della coomologia

1960
21. Sistemi dinamici e teoremi ergodici
22. Forme differenziali e loro integrali

1961
23. Geometria del calcolo delle variazioni (2 vol.)
24. Teoria delle distribuzioni
25. Onde superficiali

1962
26. Topologia differenziale
27. Autovalori e autosoluzioni
28. Magnetofluidodinamica

1963
29. Equazioni differenziali astratte
30. Funzioni e varietà complesse
31. Proprietà di media e teoremi di confronto in Fisica Matematica

1964
32. Relatività generale
33. Dinamica dei gas rarefatti
34. Alcune questioni di analisi numerica
35. Equazioni differenziali non lineari

1965
36. Non-linear continuum theories
37. Some aspects of ring theory
38. Mathematical optimization in economics

Published by Ed. Cremonese, Firenze

1966
39. Calculus of variations
40. Economia matematica
41. Classi caratteristiche e questioni connesse
42. Some aspects of diffusion theory

1967
43. Modern questions of celestial mechanics
44. Numerical analysis of partial differential equations
45. Geometry of homogeneous bounded domains

1968
46. Controllability and observability
47. Pseudo-differential operators
48. Aspects of mathematical logic

1969
49. Potential theory
50. Non-linear continuum theories in mechanics and physics and their applications
51. Questions of algebraic varieties

1970
52. Relativistic fluid dynamics
53. Theory of group representations and Fourier analysis
54. Functional equations and inequalities
55. Problems in non-linear analysis

1971
56. Stereodynamics
57. Constructive aspects of functional analysis (2 vol.)
58. Categories and commutative algebra

1972
59. Non-linear mechanics
60. Finite geometric structures and their applications
61. Geometric measure theory and minimal surfaces

1973
62. Complex analysis
63. New variational techniques in mathematical physics
64. Spectral analysis

1974
65. Stability problems
66. Singularities of analytic spaces
67. Eigenvalues of non linear problems

1975
68. Theoretical computer sciences
69. Model theory and applications
70. Differential operators and manifolds

Published by Ed. Liguori, Napoli

1976
71. Statistical Mechanics
72. Hyperbolicity
73. Differential topology

1977
74. Materials with memory
75. Pseudodifferential operators with applications
76. Algebraic surfaces

Published by Ed. Liguori, Napoli & Birkhäuser

1978
77. Stochastic differential equations
78. Dynamical systems

1979
79. Recursion theory and computational complexity
80. Mathematics of biology

1980
81. Wave propagation
82. Harmonic analysis and group representations
83. Matroid theory and its applications

Published by Springer-Verlag

1981	84. Kinetic Theories and the Boltzmann Equation	(LNM 1048)
	85. Algebraic Threefolds	(LNM 947)
	86. Nonlinear Filtering and Stochastic Control	(LNM 972)
1982	87. Invariant Theory	(LNM 996)
	88. Thermodynamics and Constitutive Equations	(LNP 228)
	89. Fluid Dynamics	(LNM 1047)
1983	90. Complete Intersections	(LNM 1092)
	91. Bifurcation Theory and Applications	(LNM 1057)
	92. Numerical Methods in Fluid Dynamics	(LNM 1127)
1984	93. Harmonic Mappings and Minimal Immersions	(LNM 1161)
	94. Schrödinger Operators	(LNM 1159)
	95. Buildings and the Geometry of Diagrams	(LNM 1181)
1985	96. Probability and Analysis	(LNM 1206)
	97. Some Problems in Nonlinear Diffusion	(LNM 1224)
	98. Theory of Moduli	(LNM 1337)
1986	99. Inverse Problems	(LNM 1225)
	100. Mathematical Economics	(LNM 1330)
	101. Combinatorial Optimization	(LNM 1403)
1987	102. Relativistic Fluid Dynamics	(LNM 1385)
	103. Topics in Calculus of Variations	(LNM 1365)
1988	104. Logic and Computer Science	(LNM 1429)
	105. Global Geometry and Mathematical Physics	(LNM 1451)
1989	106. Methods of nonconvex analysis	(LNM 1446)
	107. Microlocal Analysis and Applications	(LNM 1495)
1990	108. Geometric Topology: Recent Developments	(LNM 1504)
	109. H_∞ Control Theory	(LNM 1496)
	110. Mathematical Modelling of Industrial Processes	(LNM 1521)
1991	111. Topological Methods for Ordinary Differential Equations	(LNM 1537)
	112. Arithmetic Algebraic Geometry	(LNM 1553)
	113. Transition to Chaos in Classical and Quantum Mechanics	(LNM 1589)
1992	114. Dirichlet Forms	(LNM 1563)
	115. D-Modules, Representation Theory, and Quantum Groups	(LNM 1565)
	116. Nonequilibrium Problems in Many-Particle Systems	(LNM 1551)
1993	117. Integrable Systems and Quantum Groups	(LNM 1620)
	118. Algebraic Cycles and Hodge Theory	(LNM 1594)
	119. Phase Transitions and Hysteresis	(LNM 1584)
1994	120. Recent Mathematical Methods in Nonlinear Wave Propagation	(LNM 1640)
	121. Dynamical Systems	(LNM 1609)
	122. Transcendental Methods in Algebraic Geometry	(LNM 1646)
1995	123. Probabilistic Models for Nonlinear PDE's	(LNM 1627)
	124. Viscosity Solutions and Applications	(LNM 1660)
	125. Vector Bundles on Curves. New Directions	(LNM 1649)
1996	126. Integral Geometry, Radon Transforms and Complex Analysis	(LNM 1684)
	127. Calculus of Variations and Geometric Evolution Problems	(LNM 1713)
	128. Financial Mathematics	(LNM 1656)

1997	129. Mathematics Inspired by Biology	(LNM 1714)
	130. Advanced Numerical Approximation of Nonlinear Hyperbolic Equations	(LNM 1697)
	131. Arithmetic Theory of Elliptic Curves	(LNM 1716)
	132. Quantum Cohomology	(LNM 1776)
1998	133. Optimal Shape Design	(LNM 1740)
	134. Dynamical Systems and Small Divisors	(LNM 1784)
	135. Mathematical Problems in Semiconductor Physics	(LNM 1823)
	136. Stochastic PDE's and Kolmogorov Equations in Infinite Dimension	(LNM 1715)
	137. Filtration in Porous Media and Industrial Applications	(LNM 1734)
1999	138. Computational Mathematics driven by Industrial Applications	(LNM 1739)
	139. Iwahori-Hecke Algebras and Representation Theory	(LNM 1804)
	140. Hamiltonian Dynamics - Theory and Applications	(LNM 1861)
	141. Global Theory of Minimal Surfaces in Flat Spaces	(LNM 1775)
	142. Direct and Inverse Methods in Solving Nonlinear Evolution Equations	(LNP 632)
2000	143. Dynamical Systems	(LNM 1822)
	144. Diophantine Approximation	(LNM 1819)
	145. Mathematical Aspects of Evolving Interfaces	(LNM 1812)
	146. Mathematical Methods for Protein Structure	(LNCS 2666)
	147. Noncommutative Geometry	(LNM 1831)
2001	148. Topological Fluid Mechanics	to appear
	149. Spatial Stochastic Processes	(LNM 1802)
	150. Optimal Transportation and Applications	(LNM 1813)
	151. Multiscale Problems and Methods in Numerical Simulations	(LNM 1825)
2002	152. Real Methods in Complex and CR Geometry	(LNM 1848)
	153. Analytic Number Theory	(LNM 1891)
	154. Inverse Problems and Imaging	(LNM 1943)
2003	155. Stochastic Methods in Finance	(LNM 1856)
	156. Hyperbolic Systems of Balance Laws	(LNM 1911)
	157. Symplectic 4-Manifolds and Algebraic Surfaces	(LNM 1938)
	158. Mathematical Foundation of Turbulent Viscous Flows	(LNM 1871)
2004	159. Representation Theory and Complex Analysis	(LNM 1931)
	160. Nonlinear and Optimal Control Theory	(LNM 1932)
	161. Stochastic Geometry	(LNM 1892)
2005	162. Enumerative Invariants in Algebraic Geometry and String Theory	to appear
	163. Calculus of Variations and Non-linear Partial Differential Equations	(LNM 1927)
	164. SPDE in Hydrodynamic. Recent Progress and Prospects	(LNM 1942)
2006	165. Pseudo-Differential Operators, Quantization and Signals	to appear
	166. Mixed Finite Elements, Compatibility Conditions, and Applications	(LNM 1939)
	167. Multiscale Problems in the Life Sciences. From Microscopic to Macroscopic	(LNM 1940)
	168. Quantum Transport: Modelling, Analysis and Asymptotics	to appear
2007	169. Geometric Analysis and Partial Differential Equations	to appear
	170. Nonlinear Optimization	to appear
	171. Arithmetic Geometry	to appear
2008	172. Nonlinear Partial Differential Equations and Applications	announced
	173. Holomorphic Dynamical Systems	announced
	174. Level Set and PDE based Reconstruction Methods: Applications to Inverse Problems and Image Processing	announced
	175. Mathematical models in the manufacturing of glass, polymers and textiles	announced

Lecture Notes in Mathematics

For information about earlier volumes
please contact your bookseller or Springer
LNM Online archive: springerlink.com

Vol. 1755: J. Azéma, M. Émery, M. Ledoux, M. Yor (Eds.), Séminaire de Probabilités XXXV (2001)
Vol. 1756: P. E. Zhidkov, Korteweg de Vries and Nonlinear Schrödinger Equations: Qualitative Theory (2001)
Vol. 1757: R. R. Phelps, Lectures on Choquet's Theorem (2001)
Vol. 1758: N. Monod, Continuous Bounded Cohomology of Locally Compact Groups (2001)
Vol. 1759: Y. Abe, K. Kopfermann, Toroidal Groups (2001)
Vol. 1760: D. Filipović, Consistency Problems for Heath-Jarrow-Morton Interest Rate Models (2001)
Vol. 1761: C. Adelmann, The Decomposition of Primes in Torsion Point Fields (2001)
Vol. 1762: S. Cerrai, Second Order PDE's in Finite and Infinite Dimension (2001)
Vol. 1763: J.-L. Loday, A. Frabetti, F. Chapoton, F. Goichot, Dialgebras and Related Operads (2001)
Vol. 1764: A. Cannas da Silva, Lectures on Symplectic Geometry (2001)
Vol. 1765: T. Kerler, V. V. Lyubashenko, Non-Semisimple Topological Quantum Field Theories for 3-Manifolds with Corners (2001)
Vol. 1766: H. Hennion, L. Hervé, Limit Theorems for Markov Chains and Stochastic Properties of Dynamical Systems by Quasi-Compactness (2001)
Vol. 1767: J. Xiao, Holomorphic Q Classes (2001)
Vol. 1768: M. J. Pflaum, Analytic and Geometric Study of Stratified Spaces (2001)
Vol. 1769: M. Alberich-Carramiñana, Geometry of the Plane Cremona Maps (2002)
Vol. 1770: H. Gluesing-Luerssen, Linear Delay-Differential Systems with Commensurate Delays: An Algebraic Approach (2002)
Vol. 1771: M. Émery, M. Yor (Eds.), Séminaire de Probabilités 1967-1980. A Selection in Martingale Theory (2002)
Vol. 1772: F. Burstall, D. Ferus, K. Leschke, F. Pedit, U. Pinkall, Conformal Geometry of Surfaces in S^4 (2002)
Vol. 1773: Z. Arad, M. Muzychuk, Standard Integral Table Algebras Generated by a Non-real Element of Small Degree (2002)
Vol. 1774: V. Runde, Lectures on Amenability (2002)
Vol. 1775: W. H. Meeks, A. Ros, H. Rosenberg, The Global Theory of Minimal Surfaces in Flat Spaces. Martina Franca 1999. Editor: G. P. Pirola (2002)
Vol. 1776: K. Behrend, C. Gomez, V. Tarasov, G. Tian, Quantum Comohology. Cetraro 1997. Editors: P. de Bartolomeis, B. Dubrovin, C. Reina (2002)
Vol. 1777: E. García-Río, D. N. Kupeli, R. Vázquez-Lorenzo, Osserman Manifolds in Semi-Riemannian Geometry (2002)
Vol. 1778: H. Kiechle, Theory of K-Loops (2002)
Vol. 1779: I. Chueshov, Monotone Random Systems (2002)
Vol. 1780: J. H. Bruinier, Borcherds Products on O(2,1) and Chern Classes of Heegner Divisors (2002)
Vol. 1781: E. Bolthausen, E. Perkins, A. van der Vaart, Lectures on Probability Theory and Statistics. Ecole d' Eté de Probabilités de Saint-Flour XXIX-1999. Editor: P. Bernard (2002)
Vol. 1782: C.-H. Chu, A. T.-M. Lau, Harmonic Functions on Groups and Fourier Algebras (2002)
Vol. 1783: L. Grüne, Asymptotic Behavior of Dynamical and Control Systems under Perturbation and Discretization (2002)
Vol. 1784: L. H. Eliasson, S. B. Kuksin, S. Marmi, J.-C. Yoccoz, Dynamical Systems and Small Divisors. Cetraro, Italy 1998. Editors: S. Marmi, J.-C. Yoccoz (2002)
Vol. 1785: J. Arias de Reyna, Pointwise Convergence of Fourier Series (2002)
Vol. 1786: S. D. Cutkosky, Monomialization of Morphisms from 3-Folds to Surfaces (2002)
Vol. 1787: S. Caenepeel, G. Militaru, S. Zhu, Frobenius and Separable Functors for Generalized Module Categories and Nonlinear Equations (2002)
Vol. 1788: A. Vasil'ev, Moduli of Families of Curves for Conformal and Quasiconformal Mappings (2002)
Vol. 1789: Y. Sommerhäuser, Yetter-Drinfel'd Hopf algebras over groups of prime order (2002)
Vol. 1790: X. Zhan, Matrix Inequalities (2002)
Vol. 1791: M. Knebusch, D. Zhang, Manis Valuations and Prüfer Extensions I: A new Chapter in Commutative Algebra (2002)
Vol. 1792: D. D. Ang, R. Gorenflo, V. K. Le, D. D. Trong, Moment Theory and Some Inverse Problems in Potential Theory and Heat Conduction (2002)
Vol. 1793: J. Cortés Monforte, Geometric, Control and Numerical Aspects of Nonholonomic Systems (2002)
Vol. 1794: N. Pytheas Fogg, Substitution in Dynamics, Arithmetics and Combinatorics. Editors: V. Berthé, S. Ferenczi, C. Mauduit, A. Siegel (2002)
Vol. 1795: H. Li, Filtered-Graded Transfer in Using Noncommutative Gröbner Bases (2002)
Vol. 1796: J.M. Melenk, hp-Finite Element Methods for Singular Perturbations (2002)
Vol. 1797: B. Schmidt, Characters and Cyclotomic Fields in Finite Geometry (2002)
Vol. 1798: W.M. Oliva, Geometric Mechanics (2002)
Vol. 1799: H. Pajot, Analytic Capacity, Rectifiability, Menger Curvature and the Cauchy Integral (2002)
Vol. 1800: O. Gabber, L. Ramero, Almost Ring Theory (2003)
Vol. 1801: J. Azéma, M. Émery, M. Ledoux, M. Yor (Eds.), Séminaire de Probabilités XXXVI (2003)
Vol. 1802: V. Capasso, E. Merzbach, B. G. Ivanoff, M. Dozzi, R. Dalang, T. Mountford, Topics in Spatial Stochastic Processes. Martina Franca, Italy 2001. Editor: E. Merzbach (2003)

Vol. 1803: G. Dolzmann, Variational Methods for Crystalline Microstructure – Analysis and Computation (2003)
Vol. 1804: I. Cherednik, Ya. Markov, R. Howe, G. Lusztig, Iwahori-Hecke Algebras and their Representation Theory. Martina Franca, Italy 1999. Editors: V. Baldoni, D. Barbasch (2003)
Vol. 1805: F. Cao, Geometric Curve Evolution and Image Processing (2003)
Vol. 1806: H. Broer, I. Hoveijn. G. Lunther, G. Vegter, Bifurcations in Hamiltonian Systems. Computing Singularities by Gröbner Bases (2003)
Vol. 1807: V. D. Milman, G. Schechtman (Eds.), Geometric Aspects of Functional Analysis. Israel Seminar 2000-2002 (2003)
Vol. 1808: W. Schindler, Measures with Symmetry Properties (2003)
Vol. 1809: O. Steinbach, Stability Estimates for Hybrid Coupled Domain Decomposition Methods (2003)
Vol. 1810: J. Wengenroth, Derived Functors in Functional Analysis (2003)
Vol. 1811: J. Stevens, Deformations of Singularities (2003)
Vol. 1812: L. Ambrosio, K. Deckelnick, G. Dziuk, M. Mimura, V. A. Solonnikov, H. M. Soner, Mathematical Aspects of Evolving Interfaces. Madeira, Funchal, Portugal 2000. Editors: P. Colli, J. F. Rodrigues (2003)
Vol. 1813: L. Ambrosio, L. A. Caffarelli, Y. Brenier, G. Buttazzo, C. Villani, Optimal Transportation and its Applications. Martina Franca, Italy 2001. Editors: L. A. Caffarelli, S. Salsa (2003)
Vol. 1814: P. Bank, F. Baudoin, H. Föllmer, L.C.G. Rogers, M. Soner, N. Touzi, Paris-Princeton Lectures on Mathematical Finance 2002 (2003)
Vol. 1815: A. M. Vershik (Ed.), Asymptotic Combinatorics with Applications to Mathematical Physics. St. Petersburg, Russia 2001 (2003)
Vol. 1816: S. Albeverio, W. Schachermayer, M. Talagrand, Lectures on Probability Theory and Statistics. Ecole d'Eté de Probabilités de Saint-Flour XXX-2000. Editor: P. Bernard (2003)
Vol. 1817: E. Koelink, W. Van Assche (Eds.), Orthogonal Polynomials and Special Functions. Leuven 2002 (2003)
Vol. 1818: M. Bildhauer, Convex Variational Problems with Linear, nearly Linear and/or Anisotropic Growth Conditions (2003)
Vol. 1819: D. Masser, Yu. V. Nesterenko, H. P. Schlickewei, W. M. Schmidt, M. Waldschmidt, Diophantine Approximation. Cetraro, Italy 2000. Editors: F. Amoroso, U. Zannier (2003)
Vol. 1820: F. Hiai, H. Kosaki, Means of Hilbert Space Operators (2003)
Vol. 1821: S. Teufel, Adiabatic Perturbation Theory in Quantum Dynamics (2003)
Vol. 1822: S.-N. Chow, R. Conti, R. Johnson, J. Mallet-Paret, R. Nussbaum, Dynamical Systems. Cetraro, Italy 2000. Editors: J. W. Macki, P. Zecca (2003)
Vol. 1823: A. M. Anile, W. Allegretto, C. Ringhofer, Mathematical Problems in Semiconductor Physics. Cetraro, Italy 1998. Editor: A. M. Anile (2003)
Vol. 1824: J. A. Navarro González, J. B. Sancho de Salas, C^∞ – Differentiable Spaces (2003)
Vol. 1825: J. H. Bramble, A. Cohen, W. Dahmen, Multiscale Problems and Methods in Numerical Simulations, Martina Franca, Italy 2001. Editor: C. Canuto (2003)
Vol. 1826: K. Dohmen, Improved Bonferroni Inequalities via Abstract Tubes. Inequalities and Identities of Inclusion-Exclusion Type. VIII, 113 p, 2003.
Vol. 1827: K. M. Pilgrim, Combinations of Complex Dynamical Systems. IX, 118 p, 2003.
Vol. 1828: D. J. Green, Gröbner Bases and the Computation of Group Cohomology. XII, 138 p, 2003.
Vol. 1829: E. Altman, B. Gaujal, A. Hordijk, Discrete-Event Control of Stochastic Networks: Multimodularity and Regularity. XIV, 313 p, 2003.
Vol. 1830: M. I. Gil', Operator Functions and Localization of Spectra. XIV, 256 p, 2003.
Vol. 1831: A. Connes, J. Cuntz, E. Guentner, N. Higson, J. E. Kaminker, Noncommutative Geometry, Martina Franca, Italy 2002. Editors: S. Doplicher, L. Longo (2004)
Vol. 1832: J. Azéma, M. Émery, M. Ledoux, M. Yor (Eds.), Séminaire de Probabilités XXXVII (2003)
Vol. 1833: D.-Q. Jiang, M. Qian, M.-P. Qian, Mathematical Theory of Nonequilibrium Steady States. On the Frontier of Probability and Dynamical Systems. IX, 280 p, 2004.
Vol. 1834: Yo. Yomdin, G. Comte, Tame Geometry with Application in Smooth Analysis. VIII, 186 p, 2004.
Vol. 1835: O.T. Izhboldin, B. Kahn, N.A. Karpenko, A. Vishik, Geometric Methods in the Algebraic Theory of Quadratic Forms. Summer School, Lens, 2000. Editor: J.-P. Tignol (2004)
Vol. 1836: C. Năstăsescu, F. Van Oystaeyen, Methods of Graded Rings. XIII, 304 p, 2004.
Vol. 1837: S. Tavaré, O. Zeitouni, Lectures on Probability Theory and Statistics. Ecole d'Eté de Probabilités de Saint-Flour XXXI-2001. Editor: J. Picard (2004)
Vol. 1838: A.J. Ganesh, N.W. O'Connell, D.J. Wischik, Big Queues. XII, 254 p, 2004.
Vol. 1839: R. Gohm, Noncommutative Stationary Processes. VIII, 170 p, 2004.
Vol. 1840: B. Tsirelson, W. Werner, Lectures on Probability Theory and Statistics. Ecole d'Eté de Probabilités de Saint-Flour XXXII-2002. Editor: J. Picard (2004)
Vol. 1841: W. Reichel, Uniqueness Theorems for Variational Problems by the Method of Transformation Groups (2004)
Vol. 1842: T. Johnsen, A. L. Knutsen, K_3 Projective Models in Scrolls (2004)
Vol. 1843: B. Jefferies, Spectral Properties of Noncommuting Operators (2004)
Vol. 1844: K.F. Siburg, The Principle of Least Action in Geometry and Dynamics (2004)
Vol. 1845: Min Ho Lee, Mixed Automorphic Forms, Torus Bundles, and Jacobi Forms (2004)
Vol. 1846: H. Ammari, H. Kang, Reconstruction of Small Inhomogeneities from Boundary Measurements (2004)
Vol. 1847: T.R. Bielecki, T. Björk, M. Jeanblanc, M. Rutkowski, J.A. Scheinkman, W. Xiong, Paris-Princeton Lectures on Mathematical Finance 2003 (2004)
Vol. 1848: M. Abate, J. E. Fornaess, X. Huang, J. P. Rosay, A. Tumanov, Real Methods in Complex and CR Geometry, Martina Franca, Italy 2002. Editors: D. Zaitsev, G. Zampieri (2004)
Vol. 1849: Martin L. Brown, Heegner Modules and Elliptic Curves (2004)
Vol. 1850: V. D. Milman, G. Schechtman (Eds.), Geometric Aspects of Functional Analysis. Israel Seminar 2002-2003 (2004)
Vol. 1851: O. Catoni, Statistical Learning Theory and Stochastic Optimization (2004)
Vol. 1852: A.S. Kechris, B.D. Miller, Topics in Orbit Equivalence (2004)
Vol. 1853: Ch. Favre, M. Jonsson, The Valuative Tree (2004)

Vol. 1854: O. Saeki, Topology of Singular Fibers of Differential Maps (2004)
Vol. 1855: G. Da Prato, P.C. Kunstmann, I. Lasiecka, A. Lunardi, R. Schnaubelt, L. Weis, Functional Analytic Methods for Evolution Equations. Editors: M. Iannelli, R. Nagel, S. Piazzera (2004)
Vol. 1856: K. Back, T.R. Bielecki, C. Hipp, S. Peng, W. Schachermayer, Stochastic Methods in Finance, Bressanone/Brixen, Italy, 2003. Editors: M. Fritelli, W. Runggaldier (2004)
Vol. 1857: M. Émery, M. Ledoux, M. Yor (Eds.), Séminaire de Probabilités XXXVIII (2005)
Vol. 1858: A.S. Cherny, H.-J. Engelbert, Singular Stochastic Differential Equations (2005)
Vol. 1859: E. Letellier, Fourier Transforms of Invariant Functions on Finite Reductive Lie Algebras (2005)
Vol. 1860: A. Borisyuk, G.B. Ermentrout, A. Friedman, D. Terman, Tutorials in Mathematical Biosciences I. Mathematical Neurosciences (2005)
Vol. 1861: G. Benettin, J. Henrard, S. Kuksin, Hamiltonian Dynamics – Theory and Applications, Cetraro, Italy, 1999. Editor: A. Giorgilli (2005)
Vol. 1862: B. Helffer, F. Nier, Hypoelliptic Estimates and Spectral Theory for Fokker-Planck Operators and Witten Laplacians (2005)
Vol. 1863: H. Führ, Abstract Harmonic Analysis of Continuous Wavelet Transforms (2005)
Vol. 1864: K. Efstathiou, Metamorphoses of Hamiltonian Systems with Symmetries (2005)
Vol. 1865: D. Applebaum, B.V. R. Bhat, J. Kustermans, J. M. Lindsay, Quantum Independent Increment Processes I. From Classical Probability to Quantum Stochastic Calculus. Editors: M. Schürmann, U. Franz (2005)
Vol. 1866: O.E. Barndorff-Nielsen, U. Franz, R. Gohm, B. Kümmerer, S. Thorbjønsen, Quantum Independent Increment Processes II. Structure of Quantum Lévy Processes, Classical Probability, and Physics. Editors: M. Schürmann, U. Franz, (2005)
Vol. 1867: J. Sneyd (Ed.), Tutorials in Mathematical Biosciences II. Mathematical Modeling of Calcium Dynamics and Signal Transduction. (2005)
Vol. 1868: J. Jorgenson, S. Lang, $\mathrm{Pos}_n(\mathrm{R})$ and Eisenstein Series. (2005)
Vol. 1869: A. Dembo, T. Funaki, Lectures on Probability Theory and Statistics. Ecole d'Eté de Probabilités de Saint-Flour XXXIII-2003. Editor: J. Picard (2005)
Vol. 1870: V.I. Gurariy, W. Lusky, Geometry of Müntz Spaces and Related Questions. (2005)
Vol. 1871: P. Constantin, G. Gallavotti, A.V. Kazhikhov, Y. Meyer, S. Ukai, Mathematical Foundation of Turbulent Viscous Flows, Martina Franca, Italy, 2003. Editors: M. Cannone, T. Miyakawa (2006)
Vol. 1872: A. Friedman (Ed.), Tutorials in Mathematical Biosciences III. Cell Cycle, Proliferation, and Cancer (2006)
Vol. 1873: R. Mansuy, M. Yor, Random Times and Enlargements of Filtrations in a Brownian Setting (2006)
Vol. 1874: M. Yor, M. Émery (Eds.), In Memoriam Paul-André Meyer - Séminaire de Probabilités XXXIX (2006)
Vol. 1875: J. Pitman, Combinatorial Stochastic Processes. Ecole d'Eté de Probabilités de Saint-Flour XXXII-2002. Editor: J. Picard (2006)
Vol. 1876: H. Herrlich, Axiom of Choice (2006)
Vol. 1877: J. Steuding, Value Distributions of L-Functions (2007)
Vol. 1878: R. Cerf, The Wulff Crystal in Ising and Percolation Models, Ecole d'Eté de Probabilités de Saint-Flour XXXIV-2004. Editor: Jean Picard (2006)
Vol. 1879: G. Slade, The Lace Expansion and its Applications, Ecole d'Eté de Probabilités de Saint-Flour XXXIV-2004. Editor: Jean Picard (2006)
Vol. 1880: S. Attal, A. Joye, C.-A. Pillet, Open Quantum Systems I, The Hamiltonian Approach (2006)
Vol. 1881: S. Attal, A. Joye, C.-A. Pillet, Open Quantum Systems II, The Markovian Approach (2006)
Vol. 1882: S. Attal, A. Joye, C.-A. Pillet, Open Quantum Systems III, Recent Developments (2006)
Vol. 1883: W. Van Assche, F. Marcellàn (Eds.), Orthogonal Polynomials and Special Functions, Computation and Application (2006)
Vol. 1884: N. Hayashi, E.I. Kaikina, P.I. Naumkin, I.A. Shishmarev, Asymptotics for Dissipative Nonlinear Equations (2006)
Vol. 1885: A. Telcs, The Art of Random Walks (2006)
Vol. 1886: S. Takamura, Splitting Deformations of Degenerations of Complex Curves (2006)
Vol. 1887: K. Habermann, L. Habermann, Introduction to Symplectic Dirac Operators (2006)
Vol. 1888: J. van der Hoeven, Transseries and Real Differential Algebra (2006)
Vol. 1889: G. Osipenko, Dynamical Systems, Graphs, and Algorithms (2006)
Vol. 1890: M. Bunge, J. Funk, Singular Coverings of Toposes (2006)
Vol. 1891: J.B. Friedlander, D.R. Heath-Brown, H. Iwaniec, J. Kaczorowski, Analytic Number Theory, Cetraro, Italy, 2002. Editors: A. Perelli, C. Viola (2006)
Vol. 1892: A. Baddeley, I. Bárány, R. Schneider, W. Weil, Stochastic Geometry, Martina Franca, Italy, 2004. Editor: W. Weil (2007)
Vol. 1893: H. Hanßmann, Local and Semi-Local Bifurcations in Hamiltonian Dynamical Systems, Results and Examples (2007)
Vol. 1894: C.W. Groetsch, Stable Approximate Evaluation of Unbounded Operators (2007)
Vol. 1895: L. Molnár, Selected Preserver Problems on Algebraic Structures of Linear Operators and on Function Spaces (2007)
Vol. 1896: P. Massart, Concentration Inequalities and Model Selection, Ecole d'Été de Probabilités de Saint-Flour XXXIII-2003. Editor: J. Picard (2007)
Vol. 1897: R. Doney, Fluctuation Theory for Lévy Processes, Ecole d'Été de Probabilités de Saint-Flour XXXV-2005. Editor: J. Picard (2007)
Vol. 1898: H.R. Beyer, Beyond Partial Differential Equations, On linear and Quasi-Linear Abstract Hyperbolic Evolution Equations (2007)
Vol. 1899: Séminaire de Probabilités XL. Editors: C. Donati-Martin, M. Émery, A. Rouault, C. Stricker (2007)
Vol. 1900: E. Bolthausen, A. Bovier (Eds.), Spin Glasses (2007)
Vol. 1901: O. Wittenberg, Intersections de deux quadriques et pinceaux de courbes de genre 1, Intersections of Two Quadrics and Pencils of Curves of Genus 1 (2007)
Vol. 1902: A. Isaev, Lectures on the Automorphism Groups of Kobayashi-Hyperbolic Manifolds (2007)
Vol. 1903: G. Kresin, V. Maz'ya, Sharp Real-Part Theorems (2007)
Vol. 1904: P. Giesl, Construction of Global Lyapunov Functions Using Radial Basis Functions (2007)

Vol. 1905: C. Prévôt, M. Röckner, A Concise Course on Stochastic Partial Differential Equations (2007)
Vol. 1906: T. Schuster, The Method of Approximate Inverse: Theory and Applications (2007)
Vol. 1907: M. Rasmussen, Attractivity and Bifurcation for Nonautonomous Dynamical Systems (2007)
Vol. 1908: T.J. Lyons, M. Caruana, T. Lévy, Differential Equations Driven by Rough Paths, Ecole d'Été de Probabilités de Saint-Flour XXXIV-2004 (2007)
Vol. 1909: H. Akiyoshi, M. Sakuma, M. Wada, Y. Yamashita, Punctured Torus Groups and 2-Bridge Knot Groups (I) (2007)
Vol. 1910: V.D. Milman, G. Schechtman (Eds.), Geometric Aspects of Functional Analysis. Israel Seminar 2004-2005 (2007)
Vol. 1911: A. Bressan, D. Serre, M. Williams, K. Zumbrun, Hyperbolic Systems of Balance Laws. Cetraro, Italy 2003. Editor: P. Marcati (2007)
Vol. 1912: V. Berinde, Iterative Approximation of Fixed Points (2007)
Vol. 1913: J.E. Marsden, G. Misiołek, J.-P. Ortega, M. Perlmutter, T.S. Ratiu, Hamiltonian Reduction by Stages (2007)
Vol. 1914: G. Kutyniok, Affine Density in Wavelet Analysis (2007)
Vol. 1915: T. Bıyıkoğlu, J. Leydold, P.F. Stadler, Laplacian Eigenvectors of Graphs. Perron-Frobenius and Faber-Krahn Type Theorems (2007)
Vol. 1916: C. Villani, F. Rezakhanlou, Entropy Methods for the Boltzmann Equation. Editors: F. Golse, S. Olla (2008)
Vol. 1917: I. Veselić, Existence and Regularity Properties of the Integrated Density of States of Random Schrödinger (2008)
Vol. 1918: B. Roberts, R. Schmidt, Local Newforms for GSp(4) (2007)
Vol. 1919: R.A. Carmona, I. Ekeland, A. Kohatsu-Higa, J.-M. Lasry, P.-L. Lions, H. Pham, E. Taflin, Paris-Princeton Lectures on Mathematical Finance 2004. Editors: R.A. Carmona, E. Çinlar, I. Ekeland, E. Jouini, J.A. Scheinkman, N. Touzi (2007)
Vol. 1920: S.N. Evans, Probability and Real Trees. Ecole d'Été de Probabilités de Saint-Flour XXXV-2005 (2008)
Vol. 1921: J.P. Tian, Evolution Algebras and their Applications (2008)
Vol. 1922: A. Friedman (Ed.), Tutorials in Mathematical BioSciences IV. Evolution and Ecology (2008)
Vol. 1923: J.P.N. Bishwal, Parameter Estimation in Stochastic Differential Equations (2008)
Vol. 1924: M. Wilson, Littlewood-Paley Theory and Exponential-Square Integrability (2008)
Vol. 1925: M. du Sautoy, L. Woodward, Zeta Functions of Groups and Rings (2008)
Vol. 1926: L. Barreira, V. Claudia, Stability of Nonautonomous Differential Equations (2008)
Vol. 1927: L. Ambrosio, L. Caffarelli, M.G. Crandall, L.C. Evans, N. Fusco, Calculus of Variations and Non-Linear Partial Differential Equations. Cetraro, Italy 2005. Editors: B. Dacorogna, P. Marcellini (2008)
Vol. 1928: J. Jonsson, Simplicial Complexes of Graphs (2008)
Vol. 1929: Y. Mishura, Stochastic Calculus for Fractional Brownian Motion and Related Processes (2008)
Vol. 1930: J.M. Urbano, The Method of Intrinsic Scaling. A Systematic Approach to Regularity for Degenerate and Singular PDEs (2008)
Vol. 1931: M. Cowling, E. Frenkel, M. Kashiwara, A. Valette, D.A. Vogan, Jr., N.R. Wallach, Representation Theory and Complex Analysis. Venice, Italy 2004. Editors: E.C. Tarabusi, A. D'Agnolo, M. Picardello (2008)
Vol. 1932: A.A. Agrachev, A.S. Morse, E.D. Sontag, H.J. Sussmann, V.I. Utkin, Nonlinear and Optimal Control Theory. Cetraro, Italy 2004. Editors: P. Nistri, G. Stefani (2008)
Vol. 1933: M. Petkovic, Point Estimation of Root Finding Methods (2008)
Vol. 1934: C. Donati-Martin, M. Émery, A. Rouault, C. Stricker (Eds.), Séminaire de Probabilités XLI (2008)
Vol. 1935: A. Unterberger, Alternative Pseudodifferential Analysis (2008)
Vol. 1936: P. Magal, S. Ruan (Eds.), Structured Population Models in Biology and Epidemiology (2008)
Vol. 1937: G. Capriz, P. Giovine, P.M. Mariano (Eds.), Mathematical Models of Granular Matter (2008)
Vol. 1938: D. Auroux, F. Catanese, M. Manetti, P. Seidel, B. Siebert, I. Smith, G. Tian, Symplectic 4-Manifolds and Algebraic Surfaces. Cetraro, Italy 2003. Editors: F. Catanese, G. Tian (2008)
Vol. 1939: D. Boffi, F. Brezzi, L. Demkowicz, R.G. Durán, R.S. Falk, M. Fortin, Mixed Finite Elements, Compatibility Conditions, and Applications. Cetraro, Italy 2006. Editors: D. Boffi, L. Gastaldi (2008)
Vol. 1940: J. Banasiak, V. Capasso, M.A.J. Chaplain, M. Lachowicz, J. Miękisz, Multiscale Problems in the Life Sciences. From Microscopic to Macroscopic. Będlewo, Poland 2006. Editors: V. Capasso, M. Lachowicz (2008)
Vol. 1941: S.M.J. Haran, Arithmetical Investigations. Representation Theory, Orthogonal Polynomials, and Quantum Interpolations (2008)
Vol. 1942: S. Albeverio, F. Flandoli, Y.G. Sinai, SPDE in Hydrodynamic. Recent Progress and Prospects. Cetraro, Italy 2005. Editors: G. Da Prato, M. Röckner (2008)
Vol. 1943: L.L. Bonilla (Ed.), Inverse Problems and Imaging. Martina Franca, Italy 2002 (2008)
Vol. 1944: A. Di Bartolo, G. Falcone, P. Plaumann, K. Strambach, Algebraic Groups and Lie Groups with Few Factors (2008)

Recent Reprints and New Editions

Vol. 1702: J. Ma, J. Yong, Forward-Backward Stochastic Differential Equations and their Applications. 1999 – Corr. 3rd printing (2007)
Vol. 830: J.A. Green, Polynomial Representations of GL_n, with an Appendix on Schensted Correspondence and Littelmann Paths by K. Erdmann, J.A. Green and M. Schoker 1980 – 2nd corr. and augmented edition (2007)
Vol. 1693: S. Simons, From Hahn-Banach to Monotonicity (Minimax and Monotonicity 1998) – 2nd exp. edition (2008)
Vol. 470: R.E. Bowen, Equilibrium States and the Ergodic Theory of Anosov Diffeomorphisms. With a preface by D. Ruelle. Edited by J.-R. Chazottes. 1975 – 2nd rev. edition (2008)
Vol. 523: S.A. Albeverio, R.J. Høegh-Krohn, S. Mazzucchi, Mathematical Theory of Feynman Path Integral. 1976 – 2nd corr. and enlarged edition (2008)

Contents

Polynomial Exact Sequences and Projection-Based Interpolation with Application to Maxwell Equations