

Christel Baier
Holger Hermanns (Eds.)

LNCS 4137

CONCUR 2006 – Concurrency Theory

17th International Conference, CONCUR 2006
Bonn, Germany, August 2006
Proceedings



Springer

Christel Baier Holger Hermanns (Eds.)

CONCUR 2006 – Concurrency Theory

17th International Conference, CONCUR 2006
Bonn, Germany, August 27-30, 2006
Proceedings



Springer

Volume Editors

Christel Baier
Institute for Informatics I
University of Bonn
Römerstraße 164
53117 Bonn, Germany
E-mail: baier@cs.uni-bonn.de

Holger Hermanns
Dependable Systems and Software
Department of Computer Science
Saarland University
Campus, E1 3
66123 Saarbrücken, Germany
E-mail: hermanns@cs.uni-sb.de

Library of Congress Control Number: 2006930603

CR Subject Classification (1998): F.3, F.1, D.3, D.1, C.2

LNCS Sublibrary: SL 1 – Theoretical Computer Science and General Issues

ISSN	0302-9743
ISBN-10	3-540-37376-4 Springer Berlin Heidelberg New York
ISBN-13	978-3-540-37376-6 Springer Berlin Heidelberg New York

This work is subject to copyright. All rights are reserved, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, re-use of illustrations, recitation, broadcasting, reproduction on microfilms or in any other way, and storage in data banks. Duplication of this publication or parts thereof is permitted only under the provisions of the German Copyright Law of September 9, 1965, in its current version, and permission for use must always be obtained from Springer. Violations are liable to prosecution under the German Copyright Law.

Springer is a part of Springer Science+Business Media
springer.com

© Springer-Verlag Berlin Heidelberg 2006
Printed in Germany

Typesetting: Camera-ready by author, data conversion by Scientific Publishing Services, Chennai, India
Printed on acid-free paper SPIN: 11817949 06/3142 5 4 3 2 1 0

Commenced Publication in 1973

Founding and Former Series Editors:

Gerhard Goos, Juris Hartmanis, and Jan van Leeuwen

Editorial Board

David Hutchison

Lancaster University, UK

Takeo Kanade

Carnegie Mellon University, Pittsburgh, PA, USA

Josef Kittler

University of Surrey, Guildford, UK

Jon M. Kleinberg

Cornell University, Ithaca, NY, USA

Friedemann Mattern

ETH Zurich, Switzerland

John C. Mitchell

Stanford University, CA, USA

Moni Naor

Weizmann Institute of Science, Rehovot, Israel

Oscar Nierstrasz

University of Bern, Switzerland

C. Pandu Rangan

Indian Institute of Technology, Madras, India

Bernhard Steffen

University of Dortmund, Germany

Madhu Sudan

Massachusetts Institute of Technology, MA, USA

Demetri Terzopoulos

University of California, Los Angeles, CA, USA

Doug Tygar

University of California, Berkeley, CA, USA

Moshe Y. Vardi

Rice University, Houston, TX, USA

Gerhard Weikum

Max-Planck Institute of Computer Science, Saarbruecken, Germany

Lecture Notes in Computer Science

For information about Vols. 1–4024

please contact your bookseller or Springer

- Vol. 4144: T. Ball, R.B. Jones (Eds.), *Computer Aided Verification*. XV, 564 pages. 2006.
- Vol. 4139: T. Salakoski, F. Ginter, S. Pyysalo, T. Pahikkala (Eds.), *Advances in Natural Language Processing*. XIV, 771 pages. 2006. (Sublibrary LNAI).
- Vol. 4138: X. Cheng, W. Li, T. Znati (Eds.), *Wireless Algorithms, Systems, and Applications*. XVI, 709 pages. 2006.
- Vol. 4137: C. Baier, H. Hermanns (Eds.), *CONCUR 2006 - Concurrency Theory*. XIII, 525 pages. 2006.
- Vol. 4130: U. Furbach, N. Shankar (Eds.), *Automated Reasoning*. XV, 680 pages. 2006. (Sublibrary LNAI).
- Vol. 4127: E. Damiani, P. Liu (Eds.), *Data and Applications Security XX*. X, 319 pages. 2006.
- Vol. 4121: A. Biere, C.P. Gomes (Eds.), *Theory and Applications of Satisfiability Testing - SAT 2006*. XII, 438 pages. 2006.
- Vol. 4115: D.-S. Huang, K. Li, G.W. Irwin (Eds.), *Computational Intelligence and Bioinformatics, Part III*. XXI, 803 pages. 2006. (Sublibrary LNBI).
- Vol. 4114: D.-S. Huang, K. Li, G.W. Irwin (Eds.), *Computational Intelligence, Part II*. XXVII, 1337 pages. 2006. (Sublibrary LNAI).
- Vol. 4113: D.-S. Huang, K. Li, G.W. Irwin (Eds.), *Intelligent Computing, Part I*. XXVII, 1331 pages. 2006.
- Vol. 4112: D.Z. Chen, D. T. Lee (Eds.), *Computing and Combinatorics*. XIV, 528 pages. 2006.
- Vol. 4111: F.S. de Boer, M.M. Bonsangue, S. Graf, W.-P. de Roever (Eds.), *Formal Methods for Components and Objects*. VIII, 447 pages. 2006.
- Vol. 4109: D.-Y. Yeung, J.T. Kwok, A. Fred, F. Roli, D. de Ridder (Eds.), *Structural, Syntactic, and Statistical Pattern Recognition*. XXI, 939 pages. 2006.
- Vol. 4108: J.M. Borwein, W.M. Farmer (Eds.), *Mathematical Knowledge Management*. VIII, 295 pages. 2006. (Sublibrary LNAI).
- Vol. 4106: T.R. Roth-Berghofer, M.H. Göker, H. A. Güvenir (Eds.), *Advances in Case-Based Reasoning*. XIV, 566 pages. 2006. (Sublibrary LNAI).
- Vol. 4104: T. Kunz, S.S. Ravi (Eds.), *Ad-Hoc, Mobile, and Wireless Networks*. XII, 474 pages. 2006.
- Vol. 4099: Q. Yang, G. Webb (Eds.), *PRICAI 2006: Trends in Artificial Intelligence*. XXVIII, 1263 pages. 2006. (Sublibrary LNAI).
- Vol. 4098: F. Pfenning (Ed.), *Term Rewriting and Applications*. XIII, 415 pages. 2006.
- Vol. 4097: X. Zhou, O. Sokolsky, L. Yan, E.-S. Jung, Z. Shao, Y. Mu, D.C. Lee, D. Kim, Y.-S. Jeong, C.-Z. Xu (Eds.), *Emerging Directions in Embedded and Ubiquitous Computing*. XXVII, 1034 pages. 2006.
- Vol. 4096: E. Sha, S.-K. Han, C.-Z. Xu, M.H. Kim, L.T. Yang, B. Xiao (Eds.), *Embedded and Ubiquitous Computing*. XXIV, 1170 pages. 2006.
- Vol. 4094: O. H. Ibarra, H.-C. Yen (Eds.), *Implementation and Application of Automata*. XIII, 291 pages. 2006.
- Vol. 4093: X. Li, O.R. Zaïane, Z. Li (Eds.), *Advanced Data Mining and Applications*. XXI, 1110 pages. 2006. (Sublibrary LNAI).
- Vol. 4092: J. Lang, F. Lin, J. Wang (Eds.), *Knowledge Science, Engineering and Management*. XV, 664 pages. 2006. (Sublibrary LNAI).
- Vol. 4091: G.-Z. Yang, T. Jiang, D. Shen, L. Gu, J. Yang (Eds.), *Medical Imaging and Augmented Reality*. XIII, 399 pages. 2006.
- Vol. 4090: S. Spaccapietra, K. Aberer, P. Cudré-Mauroux (Eds.), *Journal on Data Semantics VI*. XI, 211 pages. 2006.
- Vol. 4088: Z.-Z. Shi, R. Sadananda (Eds.), *Agent Computing and Multi-Agent Systems*. XVII, 827 pages. 2006. (Sublibrary LNAI).
- Vol. 4085: J. Misra, T. Nipkow, E. Sekerinski (Eds.), *FM 2006: Formal Methods*. XV, 620 pages. 2006.
- Vol. 4079: S. Etalle, M. Truszczyński (Eds.), *Logic Programming*. XIV, 474 pages. 2006.
- Vol. 4077: M.-S. Kim, K. Shimada (Eds.), *Advances in Geometric Modeling and Processing*. XVI, 696 pages. 2006.
- Vol. 4076: F. Hess, S. Pauli, M. Pohst (Eds.), *Algorithmic Number Theory*. X, 599 pages. 2006.
- Vol. 4075: U. Leser, F. Naumann, B. Eckman (Eds.), *Data Integration in the Life Sciences*. XI, 298 pages. 2006. (Sublibrary LNBI).
- Vol. 4074: M. Burmester, A. Yasinac (Eds.), *Secure Mobile Ad-hoc Networks and Sensors*. X, 193 pages. 2006.
- Vol. 4073: A. Butz, B. Fisher, A. Krüger, P. Olivier (Eds.), *Smart Graphics*. XI, 263 pages. 2006.
- Vol. 4072: M. Harders, G. Székely (Eds.), *Biomedical Simulation*. XI, 216 pages. 2006.
- Vol. 4071: H. Sundaram, M. Naphade, J.R. Smith, Y. Rui (Eds.), *Image and Video Retrieval*. XII, 547 pages. 2006.
- Vol. 4070: C. Priami, X. Hu, Y. Pan, T.Y. Lin (Eds.), *Transactions on Computational Systems Biology V*. IX, 129 pages. 2006. (Sublibrary LNBI).
- Vol. 4069: F.J. Perales, R.B. Fisher (Eds.), *Articulated Motion and Deformable Objects*. XV, 526 pages. 2006.

- Vol. 4068: H. Schärfe, P. Hitzler, P. Øhrstrøm (Eds.), *Conceptual Structures: Inspiration and Application*. XI, 455 pages. 2006. (Sublibrary LNAI).
- Vol. 4067: D. Thomas (Ed.), *ECOOP 2006 – Object-Oriented Programming*. XIV, 527 pages. 2006.
- Vol. 4066: A. Rensink, J. Warmer (Eds.), *Model Driven Architecture – Foundations and Applications*. XII, 392 pages. 2006.
- Vol. 4065: P. Perner (Ed.), *Advances in Data Mining*. XI, 592 pages. 2006. (Sublibrary LNAI).
- Vol. 4064: R. Büschkes, P. Laskov (Eds.), *Detection of Intrusions and Malware & Vulnerability Assessment*. X, 195 pages. 2006.
- Vol. 4063: I. Gorton, G.T. Heineman, I. Crnkovic, H.W. Schmidt, J.A. Stafford, C.A. Szyperski, K. Wallnau (Eds.), *Component-Based Software Engineering*. XI, 394 pages. 2006.
- Vol. 4062: G. Wang, J.F. Peters, A. Skowron, Y. Yao (Eds.), *Rough Sets and Knowledge Technology*. XX, 810 pages. 2006. (Sublibrary LNAI).
- Vol. 4061: K. Miesenberger, J. Klaus, W. Zagler, A. Karshmer (Eds.), *Computers Helping People with Special Needs*. XXIX, 1356 pages. 2006.
- Vol. 4060: K. Futatsugi, J.-P. Jouannaud, J. Meseguer (Eds.), *Algebra, Meaning, and Computation*. XXXVIII, 643 pages. 2006.
- Vol. 4059: L. Arge, R. Freivalds (Eds.), *Algorithm Theory – SWAT 2006*. XII, 436 pages. 2006.
- Vol. 4058: L.M. Batten, R. Safavi-Naini (Eds.), *Information Security and Privacy*. XII, 446 pages. 2006.
- Vol. 4057: J.P.W. Pluim, B. Likar, F.A. Gerritsen (Eds.), *Biomedical Image Registration*. XII, 324 pages. 2006.
- Vol. 4056: P. Flocchini, L. Gasieniec (Eds.), *Structural Information and Communication Complexity*. X, 357 pages. 2006.
- Vol. 4055: J. Lee, J. Shim, S.-g. Lee, C. Bussler, S. Shim (Eds.), *Data Engineering Issues in E-Commerce and Services*. IX, 290 pages. 2006.
- Vol. 4054: A. Horváth, M. Telek (Eds.), *Formal Methods and Stochastic Models for Performance Evaluation*. VIII, 239 pages. 2006.
- Vol. 4053: M. Ikeda, K.D. Ashley, T.-W. Chan (Eds.), *Intelligent Tutoring Systems*. XXVI, 821 pages. 2006.
- Vol. 4052: M. Bugliesi, B. Preneel, V. Sassone, I. Wegener (Eds.), *Automata, Languages and Programming, Part II*. XXIV, 603 pages. 2006.
- Vol. 4051: M. Bugliesi, B. Preneel, V. Sassone, I. Wegener (Eds.), *Automata, Languages and Programming, Part I*. XXIII, 729 pages. 2006.
- Vol. 4049: S. Parsons, N. Maudet, P. Moraitis, I. Rahwan (Eds.), *Argumentation in Multi-Agent Systems*. XIV, 313 pages. 2006. (Sublibrary LNAI).
- Vol. 4048: L. Goble, J.-J.C. Meyer (Eds.), *Deontic Logic and Artificial Normative Systems*. X, 273 pages. 2006. (Sublibrary LNAI).
- Vol. 4047: M. Robshaw (Ed.), *Fast Software Encryption*. XI, 434 pages. 2006.
- Vol. 4046: S.M. Astley, M. Brady, C. Rose, R. Zwiggelaar (Eds.), *Digital Mammography*. XVI, 654 pages. 2006.
- Vol. 4045: D. Barker-Plummer, R. Cox, N. Swoboda (Eds.), *Diagrammatic Representation and Inference*. XII, 301 pages. 2006. (Sublibrary LNAI).
- Vol. 4044: P. Abrahamsson, M. Marchesi, G. Succi (Eds.), *Extreme Programming and Agile Processes in Software Engineering*. XII, 230 pages. 2006.
- Vol. 4043: A.S. Atzeni, A. Liroy (Eds.), *Public Key Infrastructure*. XI, 261 pages. 2006.
- Vol. 4042: D. Bell, J. Hong (Eds.), *Flexible and Efficient Information Handling*. XVI, 296 pages. 2006.
- Vol. 4041: S.-W. Cheng, C.K. Poon (Eds.), *Algorithmic Aspects in Information and Management*. XI, 395 pages. 2006.
- Vol. 4040: R. Reulke, U. Eckardt, B. Flach, U. Knauer, K. Polthier (Eds.), *Combinatorial Image Analysis*. XII, 482 pages. 2006.
- Vol. 4039: M. Morisio (Ed.), *Reuse of Off-the-Shelf Components*. XIII, 444 pages. 2006.
- Vol. 4038: P. Ciancarini, H. Wiklicky (Eds.), *Coordination Models and Languages*. VIII, 299 pages. 2006.
- Vol. 4037: R. Gorrieri, H. Wehrheim (Eds.), *Formal Methods for Open Object-Based Distributed Systems*. XVII, 474 pages. 2006.
- Vol. 4036: O. H. Ibarra, Z. Dang (Eds.), *Developments in Language Theory*. XII, 456 pages. 2006.
- Vol. 4035: T. Nishita, Q. Peng, H.-P. Seidel (Eds.), *Advances in Computer Graphics*. XX, 771 pages. 2006.
- Vol. 4034: J. Münch, M. Vierimaa (Eds.), *Product-Focused Software Process Improvement*. XVII, 474 pages. 2006.
- Vol. 4033: B. Stiller, P. Reichl, B. Tuffin (Eds.), *Performatibility Has its Price*. X, 103 pages. 2006.
- Vol. 4032: O. Etzion, T. Kuflik, A. Motro (Eds.), *Next Generation Information Technologies and Systems*. XIII, 365 pages. 2006.
- Vol. 4031: M. Ali, R. Dapoigny (Eds.), *Advances in Applied Artificial Intelligence*. XXIII, 1353 pages. 2006. (Sublibrary LNAI).
- Vol. 4029: L. Rutkowski, R. Tadeusiewicz, L.A. Zadeh, J.M. Zurada (Eds.), *Artificial Intelligence and Soft Computing – ICAISC 2006*. XXI, 1235 pages. 2006. (Sublibrary LNAI).
- Vol. 4028: J. Kohlas, B. Meyer, A. Schiper (Eds.), *Dependable Systems: Software, Computing, Networks*. XII, 295 pages. 2006.
- Vol. 4027: H.L. Larsen, G. Pasi, D. Ortiz-Arroyo, T. Andreassen, H. Christiansen (Eds.), *Flexible Query Answering Systems*. XVIII, 714 pages. 2006. (Sublibrary LNAI).
- Vol. 4026: P.B. Gibbons, T. Abdelzaher, J. Aspnes, R. Rao (Eds.), *Distributed Computing in Sensor Systems*. XIV, 566 pages. 2006.
- Vol. 4025: F. Eliassen, A. Montresor (Eds.), *Distributed Applications and Interoperable Systems*. XI, 355 pages. 2006.

Preface

This volume contains the proceedings of the 17th International Conference on Concurrency Theory (CONCUR) held in Bonn, Germany, August 27–30, 2006.

The purpose of the CONCUR conference series is to bring together researchers, developers and students in order to advance the theory of concurrency and promote its applications. Interest in this topic is continuously growing, as a consequence of the importance and ubiquity of concurrent systems and their applications and the scientific relevance of their foundations. The scope of CONCUR covers all areas of semantics, logics, and verification techniques for concurrent systems. Topics include basic models and logics of concurrent and distributed computation (such as process algebras, Petri nets, domain theoretic or game theoretic models, modal and temporal logics), specialized models or classes of systems (such as circuits, synchronous systems, real-time and hybrid systems, stochastic systems, databases, mobile and migrating systems, parametric protocols, security protocols), related verification techniques and tools (such as state-space exploration, model-checking, synthesis, abstraction, automated deduction, testing), and related programming models (such as distributed, constraint- or object-oriented, graph rewriting, as well as associated type systems, static analyses, abstract machines, and environments).

This volume starts with five invited papers covering the invited lectures and tutorials of the conference. The remaining 29 papers were selected by the Programme Committee out of 101 submissions after a very intensive reviewing and discussion phase. We would like to thank the members of the Programme Committee and the external reviewers for their excellent and hard work.

The conference programme contained three invited lectures and two invited tutorials. The invited talks were given by Edward A. Lee (University of California at Berkeley, USA), Jan Willem Klop, (Free University of Amsterdam, The Netherlands) and Orna Kupferman (Hebrew University, Israel), and the invited tutorials by Uwe Nestmann (Technical University of Berlin, Germany) and Roberto Segala (University of Verona, Italy).

Eleven workshops are affiliated to CONCUR 2006:

- Formal Methods for Industrial Critical Systems (FMICS) organized by Lubos Brim and Martin Leucker
- Verification of Infinite-State Systems (INFINITY) organized by Ahmed Bouajjani
- Expressiveness in Concurrency (EXPRESS) organized by Roberto Amadio and Iain Phillips
- Structural Operational Semantics (SOS) organized by Rob van Glabbeek and Peter D. Mosses
- Geometric and Topological Methods in Concurrency (GETCO) organized by Eric Goubault

- German Verification Day (GVD), organized by Werner Damm and Wolfgang Paul
- Foundations of Coordination Languages and Software Architectures (FO-CLASA) organized by Carlos Canal and Mirko Viroli
- Parallel and Distributed Model Checking (PDMC) organized by Boudewijn Haverkort and Jaco van de Pol
- Security Issues in Coordination Models, Languages, and Systems (SecCo) organized by Dieter Gollmann and Peter Ryan
- Control and Observation of Real-Time Open Systems (CORTOS) organized by Franck Cassez
- Graph Transformation for Verification and Concurrency (GT-VC) organized by Arend Rensink

We would like to thank the CONCUR Steering Committee, the workshop organizers, the authors, and all Organizing Committee members for their contributions to the success of the conference. Finally, we gratefully acknowledge the generous support received from the Deutsche Forschungsgemeinschaft (DFG) and from the European Research Consortium for Informatics and Mathematics (ERCIM).

June 2006

Christel Baier and Holger Hermanns

Organization

Steering Committee

Roberto Amadio	University of Paris 7, France
Jos Baeten	Eindhoven University of Technology, The Netherlands
Eike Best	University of Oldenburg, Germany
Kim Larsen	Aalborg University, Denmark
Ugo Montanari	University of Pisa, Italy
Scott Smolka	SUNY, Stony Brook, USA

Programme Committee

Parosh Abdulla	Uppsala University, Sweden
Luca Aceto	Reykjavík University, Iceland
Luca De Alfaro	University of California, Santa Cruz, USA
Roberto Amadio	University of Paris 7, France
Jos Baeten	Eindhoven University of Technology, The Netherlands
Christel Baier	University of Bonn, Germany
Patricia Bouyer	École Normale Supérieure de Cachan, France
Franck van Breugel	York University, Canada
Kousha Etessami	University of Edinburgh, UK
Wan Fokkink	Free University of Amsterdam, The Netherlands
Philippa Gardner	Imperial College London, UK
Rob van Glabbeek	National ICT Australia, Sydney, Australia
Holger Hermanns	Saarland University, Germany
Barbara Koenig	University of Duisburg-Essen, Germany
Antonín Kučera	Masaryk University in Brno, Czech Republic
Kim Larsen	Aalborg University, Denmark
Gerald Luetzgen	University of York, UK
Nancy Lynch	Massachusetts Institute of Technology, USA
Massimo Merro	University of Verona, Italy
Ugo Montanari	University of Pisa, Italy
Anca Muscholl	University of Paris 7, France
Catuscia Palamidessi	INRIA Futurs Saclay, France
Wojciech Penczek	ICS PAS and Podlasie Academy, Poland
Corrado Priami	University of Trento, Italy
Jean-Francois Raskin	Université Libre de Bruxelles, Belgium
Jan Rutten	Centre for Mathematics and Computer Science (CWI), The Netherlands
P.S. Thiagarajan	National University of Singapore, Singapore

Organizing Committee

Tobias Blechmann
 Frank Ciesinski
 Marcus Gröber (Workshop Chair)
 Martina Janssen
 Joachim Klein
 Sascha Klüppelholz
 Jörn Ossowski
 Reza Pulungan
 Christa Schäfer

Referees

Samy Abbes	Fabrice Chevalier	Dilian Gurov
Rajeev Alur	Yannick Chevalier	Cristian Haack
Farhad Arbab	Federica Ciocchetta	Bjørn Haagenzen
Pedro D'Argenio	D. Clarke	Jonathan Hayman
Eugene Asarin	Hubert Comon-Lundh	Keijo Heljanko
Michael Backes	Giovanni Conforti	Claudio Hermida
Eric Badouel	D. Costa	Thomas Hildebrandt
Massimo Bartoletti	Mads Dam	Jane Hillston
Twan Basten	Philippe Darondeau	Florian Horn
Marek Bednarczyk	Giorgio Delzanno	Hans Hüttel
Emmanuel Beffara	Yuxin Deng	Samuel Hym
Laurent Van Begin	Rocco De Nicola	Anna Ingolfssdottir
Gerd Behrmann	Laurent Doyen	Florent Jacquemard
Nick Benton	Dominic Duggan	Radha Jagadeesan
Nathalie Bertrand	Claudio Eccher	Michael Jenkin
Inge Bethke	Dirk Fahland	E. Johnsen
Andreas Blass	Harald Fecher	Bengt Jonsson
Peter Bodorik	Cédric Fournet	Marcin Jurdzinski
Michele Boreale	Sibylle Froeschle	S. Kemper
Johannes Borgström	Pierre Ganty	Astrid Kiehn
Ahmed Bouajjani	Paul Gastin	Jetty Kleijn
Mario Bravetti	Gilles Geeraerts	Josva Kleist
Tomáš Brázdil	Blaise Genest	Barbara Klunder
Roberto Bruni	Hugo Gimbert	Beata Konikowska
Nadia Busi	Jens Chr. Godskesen	Maciej Koutny
Diletta R. Cacciagrano	Georges Gonthier	Steve Kremer
Nestor Catano	Andy Gordon	Jean Krivine
Didier Caucal	Jan Friso Groote	Morten Kühnrich
Matteo Cavaliere	Dan Grossman	K. Narayan Kumar
Samarjit Chakraborty	Maria L. Guerriero	Clemens Kupke

Mirosław Kurkowski	Jan Obdržálek	Jiri Srba
Slawomir Lasota	Edward Ochmański	Ian Stark
Paola Lecca	Simona Orzan	Oldřich Stražovský
James Leifer	Michiel van Osch	Maciej Szereter
Marina Lenisa	Joel Ouaknine	Nathalie Sznajder
Michael Leuschel	Pawel Pączkowski	Simone Tini
Cédric Lhoussaine	Richard Paige	Salvatore La Torre
Alberto Lluch Lafuente	Radek Pelánek	Tayssir Touili
Etienne Lozes	Detlef Plump	Nikola Trčka
Bas Luttik	Agata Pólróla	Ashutosh Trivedi
Ian Mackie	Alexis Potrounias	Frank D. Valencia
P. Madhusudan	Damien Pous	Daniele Varacca
Sergio Maffeis	Davide Prandi	Bjorn Victor
Louis Mandel	Jacob I. Rasmussen	Maria G. Vigliotti
Sebastian Maneth	Julian Rathke	Walter Vogler
Luc Maranget	Michel Reniers	Tomas Vojnar
Radu Mardare	Arend Rensink	Marc Voorhoeve
Nicolas Markey	Pierre-Alain Reynier	Vojtěch Řehák
Jasen Markovski	Bill Roscoe	Igor Walukiewicz
Sjouke Mauw	Andrey Rybalchenko	Andrzej Wasowski
Richard Mayr	Davide Sangiorgi	Thomas Wilke
Joycee Mekié	Arnaud Sangnier	Mark Winands
Hernan Melgratti	Vladamiro Sassone	Jozef Winkowski
Michael Mendler	Zdeněk Sawa	James Worrell
Carroll Morgan	Ivan Scagnetto	Bożena Woźna
Larry Moss	Mark Schaefer	Peng Wu
Laurent Mounier	Philippe Schnoebelen	Martin De Wulf
J. Tobias Muehlberg	Stefan Schwoon	Wang Yi
Madhavan Mukund	Koushik Sen	Hans Zantema
Uwe Nestmann	Olivier Serre	Francesco Zappa Nardelli
Mogens Nielsen	Yang Shaofa	Gianluigi Zavattaro
Artur Niewiadomski	Mihaela Sighireanu	Marc Zeitoun
Gethin Norman	Radu Siminiceanu	Wiesław Zielonka
Dirk Nowotka	Pawel Sobocinski	Silvano Dal Zilio

Table of Contents

Invited Contributions

Modeling Timed Concurrent Systems	1
<i>Xiaojun Liu, Eleftherios Matsikoudis, Edward A. Lee</i>	
Some Remarks on Definability of Process Graphs	16
<i>Clemens Grabmayer, Jan Willem Klop, Bas Luttik</i>	
Sanity Checks in Formal Verification	37
<i>Orna Kupferman</i>	

Invited Tutorials

Welcome to the Jungle: A Subjective Guide to Mobile Process Calculi	52
<i>Uwe Nestmann</i>	
Probability and Nondeterminism in Operational Models of Concurrency	64
<i>Roberto Segala</i>	

Model Checking

A Livelock Freedom Analysis for Infinite State Asynchronous Reactive Systems	79
<i>Stefan Leue, Alin Ștefănescu, Wei Wei</i>	
Proving Liveness by Backwards Reachability	95
<i>Parosh Aziz Abdulla, Bengt Jonsson, Ahmed Rezine, Mayank Saxena</i>	
Model Checking Quantified Computation Tree Logic	110
<i>Arend Rensink</i>	

Process Calculi

Liveness, Fairness and Impossible Futures	126
<i>Rob van Glabbeek, Marc Voorhoeve</i>	
Checking a Mutex Algorithm in a Process Algebra with Fairness	142
<i>Flavio Corradini, Maria Rita Di Berardini, Walter Vogler</i>	

A Complete Axiomatic Semantics for the CSP Stable-Failures Model	158
<i>Yoshinao Isobe, Markus Roggenbach</i>	

Transition Systems of Elementary Net Systems with Localities	173
<i>Maciej Koutny, Marta Pietkiewicz-Koutny</i>	

Minimization and Equivalence Checking

Operational Determinism and Fast Algorithms	188
<i>Henri Hansen, Antti Valmari</i>	

Minimization, Learning, and Conformance Testing of Boolean Programs	203
<i>Viraj Kumar, P. Madhusudan, Mahesh Viswanathan</i>	

A Capability Calculus for Concurrency and Determinism	218
<i>Tachio Terauchi, Alex Aiken</i>	

Types

A New Type System for Deadlock-Free Processes	233
<i>Naoki Kobayashi</i>	

Sortings for Reactive Systems	248
<i>Lars Birkedal, Søren Debois, Thomas Hildebrandt</i>	

Dynamic Access Control in a Concurrent Object Calculus	263
<i>Avik Chaudhuri</i>	

Semantics

Concurrent Rewriting for Graphs with Equivalences	279
<i>Paolo Baldan, Fabio Gadducci, Ugo Montanari</i>	

Event Structure Semantics for Nominal Calculi	295
<i>Roberto Bruni, Hernán Melgratti, Ugo Montanari</i>	

Encoding CDuce in the $\mathbb{C}\pi$ -Calculus	310
<i>Giuseppe Castagna, Mariangiola Dezani-Ciancaglini, Daniele Varacca</i>	

Probability

A Complete Axiomatisation of Branching Bisimulation for Probabilistic Systems with an Application in Protocol Verification	327
<i>Suzana Andova, Jos C.M. Baeten, Tim A.C. Willemse</i>	

Probabilistic I/O Automata: Theories of Two Equivalences	343
<i>Eugene W. Stark, Rance Cleaveland, Scott A. Smolka</i>	

Reachability in Recursive Markov Decision Processes	358
<i>Tomáš Brázdil, Václav Brožek, Vojtěch Forejt, Antonín Kučera</i>	
Strategy Improvement for Stochastic Rabin and Streett Games	375
<i>Krishnendu Chatterjee, Thomas A. Henzinger</i>	

Bisimulation and Simulation

Weak Bisimulation Up to Elaboration	390
<i>Damien Pous</i>	
Generic Forward and Backward Simulations	406
<i>Ichiro Hasuo</i>	
On Finite Alphabets and Infinite Bases III: Simulation	421
<i>Taolue Chen, Wan Fokkink</i>	

Real Time

Inference of Event-Recording Automata Using Timed Decision Trees	435
<i>Olga Grinchtein, Bengt Jonsson, Paul Pettersson</i>	
Controller Synthesis for MTL Specifications	450
<i>Patricia Bouyer, Laura Bozzelli, Fabrice Chevalier</i>	
On Interleaving in Timed Automata	465
<i>Ramzi Ben Salah, Marius Bozga, Oded Maler</i>	

Formal Languages

A Language for Task Orchestration and Its Semantic Properties	477
<i>David Kitchin, William R. Cook, Jayadev Misra</i>	
Finding Shortest Witnesses to the Nonemptiness of Automata on Infinite Words	492
<i>Orna Kupferman, Sarai Sheinvald-Faragy</i>	
Second-Order Simple Grammars	509
<i>Colin Stirling</i>	

Modeling Timed Concurrent Systems

Xiaojun Liu¹, Eleftherios Matsikoudis², and Edward A. Lee²

¹ Sun Microsystems, Inc.

xiaojun.liu@sun.com

² University of California, Berkeley

{ematsi, eal}@eecs.berkeley.edu

Abstract. Timed concurrent systems are widely used in concurrent and distributed real-time software, modeling of hybrid systems, design of hardware systems (using hardware description languages), discrete-event simulation, and modeling of communication networks. They consist of concurrent components that communicate using timed signals, that is, sets of (semantically) time-stamped events. The denotational semantics of such systems is traditionally formulated in a metric space, wherein causal components are modeled as contracting functions. We show that this formulation excessively restricts the models of time that can be used. In particular, it cannot handle super-dense time, commonly used in hardware description languages and hybrid systems modeling, finite time lines, and time with no origin. Moreover, if we admit continuous-time and mixed signals (essential for hybrid systems modeling) or certain Zeno signals, then causality is no longer equivalent to its formalization in terms of contracting functions. In this paper, we offer an alternative semantic framework using a generalized ultrametric that overcomes these limitations.

1 Introduction

This paper focuses on timed concurrent systems modeling. Timed concurrent systems are collections of concurrent components that communicate by use of timed signals. We will define this formally, but intuitively timed signals are functions of a globally defined time. They consist of either continuously evolving values or discrete events or some combination of the two. Semantically, time is a globally shared concept, and causality is intrinsically bound to chronological ordering.

Timed concurrent systems have a wide range of application. They are used in concurrent and distributed real-time software, modeling of hybrid systems, design of hardware systems (using hardware description languages), discrete-event simulation, and modeling of communication networks.

The importance of precise mathematical models for such systems cannot be overemphasized. In short, they establish canonical denotational definitions of timed programming languages, thereby providing the means for reasoning about the correctness of individual implementations, as well as allowing hidden commonalities of seemingly different timed systems to emerge.

Unfortunately, timed systems are not amenable to standard order-theoretic denotational semantic approaches as they may realize non-monotonic functions over the sequences of observable actions [25]. Yet interesting results have been obtained by imposing a fixed lower bound on the reaction time of the involved components, effectively precluding Zeno behavior, where an infinite number of actions takes place over a finite interval of time. This has permitted the successful employment of traditional metric-space theory in the construction of well-defined mathematical models for these constrained classes of timed concurrent systems [23,25,11,2,4,6].

In this paper, we expose a number of limitations in the traditional metric-space approach that hinder generalization to broader classes of timed concurrent systems. We then proceed to develop the fundamentals of a semantic framework for timed concurrent systems that is more broadly applicable. The underlying assumption is that a timed concurrent system can be modeled as a single system function, and that the behavior of the system corresponds to a fixed point of that function. In practice, to obtain this function, we have to be concerned about composition. That is, given the functions for the interconnected components, we need to be able to compose them to obtain the system function. The techniques given in this paper facilitate such composition.

This paper begins with a brief review of metric spaces, a definition of timed signals, and a review of a metric-space semantics for timed concurrent systems. During this review, we point out several limitations in this traditional approach. We then develop an alternative based on generalized ultrametric spaces, and discuss how it overcomes these limitations.

2 Mathematical Preliminaries

A *metric space* (X, d) is a set X with a *metric distance function* $d: X \times X \rightarrow \mathbb{R}_0$ such that for all $x, y, z \in X$,

1. $d(x, y) = 0$ if and only if $x = y$,
2. $d(x, y) = d(y, x)$, and
3. $d(x, z) \leq d(x, y) + d(y, z)$.

If the metric distance function d also satisfies

4. $d(x, z) \leq \max(d(x, y), d(y, z))$

for all $x, y, z \in X$, then (X, d) is an *ultrametric space* and d an *ultrametric distance function*.

The value $d(x, y)$ quantifies how closely x approximates y . An element $x \in X$ is the *limit* of a sequence $\{x_k\}_{k \in \mathbb{N}}$, where $\mathbb{N}$ is the set of all natural numbers $\{0, 1, 2, \dots\}$, iff for all $\epsilon > 0$, there exists $n \in \mathbb{N}$ such that for all $k \geq n$, $d(x_k, x) < \epsilon$. The sequence is then said to *converge* to x , denoted by $x_k \rightarrow x$. A sequence $\{x_k\}_{k \in \mathbb{N}}$ is *Cauchy* iff for all $\epsilon > 0$, there exists $n \in \mathbb{N}$ such that for all $k, l \geq n$, $d(x_k, x_l) < \epsilon$. A metric space (X, d) is *complete* iff every Cauchy sequence converges to some $x \in X$.

If $B_\delta(x)$ is the set $\{y \in X \mid d(y, x) < \delta\}$, then the collection of such sets $\{B_\delta(x) \mid x \in X, \delta \in \mathbb{R}_+\}$ is a basis of a *topology* on X . This topology is called the *metric topology* induced by d .

Let (X, d) and (X', d') be metric spaces. A function $f: X \rightarrow X'$ is *continuous* iff $x_k \rightarrow x$ implies $f(x_k) \rightarrow f(x)$. It is *contracting* iff for all $x, y \in X$,

$$d'(f(x), f(y)) \leq d(x, y).$$

It is *strictly contracting* iff for all $x, y \in X$,

$$x \neq y \implies d'(f(x), f(y)) < d(x, y).$$

It is a δ -*contraction* iff there exists $\delta \in (0, 1)$ such that for all $x, y \in X$,

$$d'(f(x), f(y)) \leq \delta d(x, y).$$

From the theory of metric spaces, the key result used in programming language semantics is the Banach fixed-point theorem [7].

Theorem 1 (Banach). *Let (X, d) be a complete metric space. If the function $f: (X, d) \rightarrow (X, d)$ is a δ -contraction, then f has a unique fixed point in X , denoted by $\text{fix } f$, and for all $x \in X$, $f^k(x) \rightarrow \text{fix } f$.*

3 Timed Signals

In this paper, we are interested in concurrent components that communicate via *timed signals*. We model these using the tagged-signal model [12], where the communication between two components is represented by a set of events. Formally, let $\mathcal{T}$ be a non-empty set of *tags*, and $\mathcal{V}$ a non-empty set of *values*. An *event* is a pair (t, v) in $\mathcal{T} \times \mathcal{V}$. A *signal* is a set of events that typically represents the sum total of the communication between two components along some communication path. For the systems we are interested in, these sets are very likely infinite. Most applications of the tagged-signal model impose structure on the tag set $\mathcal{T}$ and study the consequences of that structure. For example, $\mathcal{T}$ might represent causality properties, time, or activation orders.

3.1 Models of Time

In general, in the tagged signal model, $\mathcal{T}$ is a partially ordered set. In this paper, $\mathcal{T}$ represents time. Our framework admits several models of time, but in all cases, $\mathcal{T}$ will be totally ordered.

Perhaps the most natural choice for $\mathcal{T}$ is the set of non-negative real numbers $\mathbb{R}_0$, reflecting a Newtonian physical view of time. The fact that we include only the non-negative reals implies that our timed concurrent networks have a starting point.