

Lecture Notes in Computer Science
Edited by G. Goos, J. Hartmanis, and J. van Leeuwen

2520

Springer

Berlin

Heidelberg

New York

Hong Kong

London

Milan

Paris

Tokyo

Manolis Koubarakis Timos Sellis
Andrew U. Frank Stéphane Grumbach
Ralf Hartmut Güting Christian S. Jensen
Nikos Lorentzos Yannis Manolopoulos
Enrico Nardelli Barbara Pernici
Hans-Jörg Schek Michel Scholl
Babis Theodoulidis Nectaria Tryfona (Eds.)

Spatio-Temporal Databases

The CHOROCHRONOS Approach



Springer

Series Editors

Gerhard Goos, Karlsruhe University, Germany
Juris Hartmanis, Cornell University, NY, USA
Jan van Leeuwen, Utrecht University, The Netherlands

Volume Editors

Manolis Koubarakis
Timos Sellis et al.
see page V

Cataloging-in-Publication Data applied for

A catalog record for this book is available from the Library of Congress

Bibliographic information published by Die Deutsche Bibliothek
Die Deutsche Bibliothek lists this publication in the Deutsche Nationalbibliographie;
detailed bibliographic data is available in the Internet at <<http://dnb.ddb.de>>.

CR Subject Classification (1998): H.2, J.1, H.3

ISSN 0302-9743

ISBN 3-540-40552-6 Springer-Verlag 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-Verlag. Violations are liable for prosecution under the German Copyright Law.

Springer-Verlag Berlin Heidelberg New York
a member of BertelsmannSpringer Science+Business Media GmbH

<http://www.springer.de>

© Springer-Verlag Berlin Heidelberg 2003
Printed in Germany

Typesetting: Camera-ready by author, data conversion by Christian Grosche, Hamburg
Printed on acid-free paper SPIN: 10873073 06/3142 5 4 3 2 1 0

Volume Editors

Andrew U. Frank

Dept. of Geoinformation
Technical University of Vienna
A-1040 Vienna, Austria
frank@geoinfo.tuwien.ac.at

Stéphane Grumbach

INRIA
Rocquencourt BP 105
78153 Le Chesnay Cedex
France
stephane.grumbach@inria.fr

Ralf Hartmut Güting

Praktische Informatik IV
FernUniversität Hagen
58084 Hagen, Germany
Ralf-Hartmut.Gueting
@FernUni-Hagen.de

Christian S. Jensen

Department of Computer Science
Aalborg University
DK-9220 Aalborg Øst
Denmark
csj@cs.auc.dk

Manolis Koubarakis

Dept. of Electronic
and Computer Engineering
Technical University of Crete
University Campus - Kounoupidiana
GR-73100 Chania, Crete, Greece
manolis@intelligence.tuc.gr

Nikos Lorentzos

Informatics Laboratory
Agricultural University of Athens
Iera Odos 75
GR-11855 Athens, Greece
lorentzos@aua.gr

Yannis Manolopoulos

Department of Informatics
Aristotle University
GR-54006 Thessaloniki, Greece
manolopo@csd.auth.gr

Enrico Nardelli

Dipartimento di Informatica
Università degli Studi di L'Aquila
I-67010 L'Aquila
Italy
Istituto di Analisi dei Sistemi
ed Informatica "Antonio Ruberti"
Consiglio Nazionale delle Ricerche
I-00185 Roma
Italy
nardelli@univaq.it

Barbara Pernici

Dip. Elettronica e Informazione
Politecnico di Milano
Piazza Leonardo da Vinci 32
I-20133 Milano
Italy
pernici@elet.polimi.it

Hans-Jörg Schek

ETH Zürich
Institute of Information Systems
ETH Zentrum, IFW C49.1
CH-8092 Zürich
Switzerland
schek@inf.ethz.ch

Michel Scholl

INRIA
Rocquencourt BP 105
78153 Le Chesnay Cedex
France
michel.scholl@inria.fr

Timos Sellis

Dept. of Electrical
and Computer Engineering
National Technical
University of Athens
GR-15773 Zographou
Athens
Greece
timos@dblabb.ece.ntua.gr

Babis Theodoulidis

Dept. of Computation
UMIST, P.O. Box 88
Manchester, M60 1QD
United Kingdom
babis@co.umist.ac.uk

Nectaria Tryfona

Department of Computer Science
Aalborg University
DK-9220 Aalborg Øst, Denmark
tryfona@cs.auc.dk

Preface

This book is an introduction and source book for practitioners, graduate students, and researchers interested in the state of the art and practice in spatiotemporal databases. It collects the most important and representative research carried out in the project CHOROCHRONOS and presents it in a unified fashion. CHOROCHRONOS was a Training and Mobility Research Network funded by the European Commission with the objective to study the design, implementation, and application of spatiotemporal database management systems.

This book would never have been possible if it was not for the devoted work of many people. First and foremost, we would like to thank the authors of the nine chapters of this book for their hard work. We would also like to acknowledge the help of Christiane Bernard, our officer from the European Commission, who saw the project to its conclusion, working as hard as we did to make it a thorough success. The constructive comments and feedback of our reviewer Colette Roland (University of Paris-1) are also very much appreciated. Last, but not least, we would like to thank all the students and postdoctoral fellows who were trained during CHOROCHRONOS. We hope the time they spent at CHOROCHRONOS node institutions was rewarding and lots of fun!

March 2003

Timos Sellis
Manolis Koubarakis
Andrew Frank, Vienna
Stéphane Grumbach
Ralf Hartmut Güting
Christian Jensen
Nikos Lorentzos
Yannis Manolopoulos
Enrico Nardelli
Barbara Pernici
Babis Theodoulidis
Nectaria Tryfona
Hans-Jörg Schek
Michel Scholl

Table of Contents

| | |
|---|----|
| 1 Introduction | 1 |
| <i>Manolis Koubarakis, Timos Sellis</i> | |
| 1.1 Why Spatio-temporal Databases? | 1 |
| 1.2 CHOROCHRONOS | 2 |
| 1.3 Contributions | 3 |
| 1.4 Organization of the Book | 4 |
| References | 5 |
| 2 Ontology for Spatio-temporal Databases | 9 |
| <i>Andrew U. Frank</i> | |
| 2.1 Introduction | 9 |
| 2.1.1 Ontology to Drive Information System Design | 11 |
| 2.1.2 Ontological Problems of Geographic Information Systems and Other Spatio-temporal Information Systems | 12 |
| 2.1.3 Structure of the Chapter | 13 |
| 2.2 The Notion of Ontology | 13 |
| 2.2.1 Classical View | 13 |
| 2.2.2 Social Reality | 14 |
| 2.3 Application Domains | 15 |
| 2.3.1 Table-Top Situation | 16 |
| 2.3.2 Cityscape | 17 |
| 2.3.3 Geographic Landscape | 18 |
| 2.4 Model of Information Systems | 19 |
| 2.4.1 Information Systems as Vehicles of Exchange between Multiple Agents | 20 |
| 2.4.2 Correctness of Information System Related to Observations | 21 |
| 2.4.3 Semantics for Terms in Information Systems | 22 |
| 2.4.4 Grounding of Semantics in Physical Operations | 23 |
| 2.5 The Five Tiers of the Ontology | 24 |
| 2.5.1 Physical Reality Seen as an Ontology of a Four-Dimensional Field | 24 |
| 2.5.2 Observation of Physical Reality | 25 |
| 2.5.3 Operations and Ontology of Individuals | 26 |
| 2.5.4 Social Ontology | 29 |
| 2.5.5 Ontology of Cognitive Agents | 30 |
| 2.6 The Language to Describe the Ontology | 30 |
| 2.6.1 Tools to Implement Ontologies | 32 |
| 2.6.2 Multi-agent Systems and Formalization of Database Ontologies .. | 35 |
| 2.7 Ontological Tier 0: Ontology of the Physical Reality | 36 |
| 2.7.1 Properties | 37 |
| 2.7.2 Physical Space-Time Field | 38 |

| | |
|---|-----------|
| 2.8 Ontological Tier 1: Our Limited Knowledge of the World | |
| through Observations of Reality | 38 |
| 2.8.1 Observations | 38 |
| 2.8.2 Measurement Units | 40 |
| 2.8.3 Classification of Values | 41 |
| 2.8.4 Special Observations: Points in Space and Time | 42 |
| 2.8.5 Approximate Location | 44 |
| 2.8.6 Discretization and Sampling | 46 |
| 2.8.7 Virtual Datasets: Validity of Values | 47 |
| 2.9 Ontological Tier 2: Representation – World of Individual Objects | 48 |
| 2.9.1 Objects Are Defined by Uniform Properties | 49 |
| 2.9.2 Geometry of Objects | 49 |
| 2.9.3 Properties of Objects | 52 |
| 2.9.4 Geographic Objects Are not Solid Bodies | 52 |
| 2.9.5 Objects Endure in Time | 52 |
| 2.9.6 Temporal, but A-Spatial Objects | 56 |
| 2.10 Ontological Tier 3: Socially Constructed Reality | 57 |
| 2.10.1 Social Reality Is Real within a Context | 57 |
| 2.10.2 Names | 58 |
| 2.10.3 Institutional Reality | 59 |
| 2.11 Ontological Tier 4: Modeling Cognitive Agents | 61 |
| 2.11.1 Logical Deduction | 61 |
| 2.11.2 Two Time Perspectives | 62 |
| 2.11.3 Sources of Knowledge | 63 |
| 2.12 Ontological Commitments Necessary for a Spatio-temporal Database | 64 |
| 2.12.1 Existence of a Single Reality | 64 |
| 2.12.2 Values for Properties Can Be Observed | 64 |
| 2.12.3 Assume Space and Time | 64 |
| 2.12.4 Observations Are Necessarily Limited | 64 |
| 2.12.5 Processes Determine Objects | 65 |
| 2.12.6 Names of Objects | 65 |
| 2.12.7 Social, Especially Institutionally Constructed Reality | 65 |
| 2.12.8 Knowledge of an Agent Is Changing in Time | 65 |
| 2.13 Conclusions | 66 |
| References | 67 |
| 3 Conceptual Models for Spatio-temporal Applications | 79 |
| <i>Nectaria Tryfona, Rosanne Price, Christian S. Jensen</i> | |
| 3.1 Motivation | 79 |
| 3.2 Spatio-temporal Foundations | 80 |
| 3.3 Spatio-temporal Entity-Relationship Model | 82 |
| 3.3.1 Extending the ER with Spatio-temporal Constructs | 82 |
| 3.3.2 A Textual Notation for STER | 91 |
| 3.3.3 Example of Usage of STER | 93 |

| | |
|--|------------|
| 3.4 Spatio-temporal Unified Modeling Language | 95 |
| 3.4.1 Using UML Core Constructs for Spatio-temporal Data | 95 |
| 3.4.2 Overview of Extended Spatio-temporal UML | 99 |
| 3.4.3 Basic Constructs: Spatial, Temporal, Thematic | 99 |
| 3.4.4 Additional Constructs: Specification Box, Existence Time, and Groups | 109 |
| 3.4.5 Example of Usage | 110 |
| 3.5 Related Work | 111 |
| 3.6 Conclusions | 114 |
| References | 114 |
| | |
| 4 Spatio-temporal Models and Languages: An Approach Based on Data Types | 117 |
| <i>Ralf Hartmut Güting, Michael H. Böhlen, Martin Erwig, Christian S. Jensen, Nikos Lorentzos, Enrico Nardelli, Markus Schneider, Jose R.R. Viqueira</i> | |
| 4.1 Introduction | 117 |
| 4.2 The Data Type Approach | 119 |
| 4.2.1 Motivation | 119 |
| 4.2.2 Modeling | 121 |
| 4.2.3 Some Example Queries | 123 |
| 4.2.4 Some Basic Issues | 125 |
| 4.3 An Abstract Model: A Foundation for Representing and Querying Moving Objects | 129 |
| 4.3.1 Spatio-temporal Data Types | 129 |
| 4.3.2 Language Embedding of Abstract Data Types | 133 |
| 4.3.3 Overview of Data Type Operations | 134 |
| 4.3.4 Operations on Non-temporal Types | 135 |
| 4.3.5 Operations on Temporal Types | 140 |
| 4.3.6 Application Example | 145 |
| 4.3.7 Summary | 146 |
| 4.4 A Discrete Model: Data Structures for Moving Objects Databases | 146 |
| 4.4.1 Overview | 146 |
| 4.4.2 Definition of Discrete Data Types | 149 |
| 4.5 Outlook | 160 |
| 4.5.1 Spatio-temporal Predicates and Developments | 160 |
| 4.5.2 Spatio-temporal Partitions | 164 |
| 4.5.3 On a Spatio-temporal Relational Model Based on Quanta | 167 |
| 4.5.4 Spatio-temporal Statement Modifiers | 170 |
| References | 174 |

| | |
|---|-----|
| 5 Spatio-temporal Models and Languages: An Approach Based on Constraints | 177 |
| <i>Stéphane Grumbach, Manolis Koubarakis, Philippe Rigaux, Michel Scholl, Spiros Skiadopoulos</i> | |
| 5.1 Introduction | 177 |
| 5.2 Representing Spatio-temporal Information Using Constraints | 179 |
| 5.2.1 An Algebra for Relations with Constraints | 181 |
| 5.3 Indefinite Information in Spatio-temporal Databases | 183 |
| 5.3.1 Querying Indefinite Information | 186 |
| 5.4 Beyond Flat Constraint Relations: The DEDALE Approach | 190 |
| 5.4.1 The DEDALE Algebra | 192 |
| 5.5 The User Query Language of DEDALE | 194 |
| 5.5.1 The Syntax | 195 |
| 5.5.2 Example Queries | 196 |
| 5.6 Conclusions | 198 |
| References | 199 |
| 6 Access Methods and Query Processing Techniques | 203 |
| <i>Adriano Di Pasquale, Luca Forlizzi, Christian S. Jensen, Yannis Manolopoulos, Enrico Nardelli, Dieter Pfoser, Guido Proietti, Simonas Šaltenis, Yannis Theodoridis, Theodoros Tzouramanis, Michael Vassilakopoulos</i> | |
| 6.1 Introduction | 203 |
| 6.2 R-Tree-Based Methods | 204 |
| 6.2.1 Preliminary Approaches | 204 |
| 6.2.2 The Spatio-bitemporal R-Tree | 207 |
| 6.2.3 The Time-Parameterized R-Tree | 212 |
| 6.2.4 Trajectory Bundle | 217 |
| 6.3 Quadtree-Based Methods | 221 |
| 6.3.1 The MOF-Tree | 222 |
| 6.3.2 The MOF ⁺ -Tree | 225 |
| 6.3.3 Overlapping Linear Quadtrees | 227 |
| 6.3.4 Multiversion Linear Quadtree | 231 |
| 6.4 Data Structures and Algorithms for the Discrete Model | 236 |
| 6.4.1 Data Structures | 236 |
| 6.4.2 Two Example Algorithms | 239 |
| 6.5 Benchmarking and Data Generation | 244 |
| 6.5.1 Benchmarking | 244 |
| 6.5.2 Data Generation | 246 |
| 6.6 Distribution and Optimization Issues | 248 |
| 6.6.1 Distributed Indexing Techniques | 248 |
| 6.6.2 Query Optimization | 251 |
| 6.7 Related Work | 253 |
| 6.8 Conclusions | 255 |
| References | 255 |

| | |
|---|-----|
| 7 Architectures and Implementations of Spatio-temporal Database Management Systems | 263 |
| <i>Martin Breunig, Can Türker, Michael H. Böhlen, Stefan Dieker, Ralf Hartmut Güting, Christian S. Jensen, Lukas Relly, Philippe Rigaux, Hans-Jörg Schek, Michel Scholl</i> | |
| 7.1 Introduction | 263 |
| 7.2 Architectural Aspects | 263 |
| 7.2.1 The Layered Architecture | 264 |
| 7.2.2 The Monolithic Architecture | 266 |
| 7.2.3 The Extensible Architecture | 266 |
| 7.2.4 Commercial Approaches to Spatial-temporal Extensions | 267 |
| 7.3 The Concert Prototype System | 270 |
| 7.3.1 Introduction | 270 |
| 7.3.2 Architecture | 270 |
| 7.3.3 Spatio-temporal Extensions | 272 |
| 7.3.4 Implementation Details | 275 |
| 7.3.5 Case Studies | 276 |
| 7.4 The Secondo Prototype System | 279 |
| 7.4.1 Introduction | 279 |
| 7.4.2 Second-Order Signature | 280 |
| 7.4.3 Architecture | 283 |
| 7.4.4 Implementing Spatio-temporal Algebra Modules | 288 |
| 7.5 The Dedale Prototype System | 290 |
| 7.5.1 Introduction | 290 |
| 7.5.2 Interpolation in the Constraint Model: Representation of Moving Objects | 291 |
| 7.5.3 Architecture | 292 |
| 7.5.4 Implementation Details | 293 |
| 7.5.5 Example of Query Evaluation | 294 |
| 7.6 The Tiger Prototype System | 297 |
| 7.6.1 Introduction | 297 |
| 7.6.2 Architecture | 297 |
| 7.6.3 Spatio-temporal Extensions | 298 |
| 7.6.4 TIGER's Implementation | 300 |
| 7.6.5 Processing Queries Using External Modules—Case Study | 302 |
| 7.7 The GeoToolKit Prototype System | 303 |
| 7.7.1 Introduction | 303 |
| 7.7.2 Architecture | 304 |
| 7.7.3 Spatio-temporal Extensions | 305 |
| 7.7.4 Implementation Details | 308 |
| 7.7.5 Case Studies | 309 |
| 7.8 Conclusions | 310 |
| References | 313 |

8 Advanced Uses:
Composing Interactive Spatio-temporal Documents 319
Isabelle Mirbel, Barbara Pernici, Babis Theodoulidis, Alex Vakaloudis, Michalis Vazirgiannis

8.1 Introduction 319

8.2 Interactive Presentations and Spatio-temporal Databases 320

8.3 Modeling the Components of Spatio-temporal Interactive Documents . . 321

 8.3.1 Particularities of 3D-Spatio-temporal Modeling
 for Scenario Components 321

 8.3.2 Meta-modeling 322

 8.3.3 Temporal Semantics 325

 8.3.4 3D-Spatial Semantics 327

 8.3.5 3D-Spatio-temporal Semantics 328

8.4 Modeling of Spatio-temporal Behavior 330

 8.4.1 Modeling Interaction with Events 330

8.5 Database Support for Scenario Components 335

 8.5.1 Querying and Accessing Stored Components 336

 8.5.2 A Global Architecture 338

8.6 Examples of Applications 338

8.7 Related Work 340

8.8 Conclusions 343

References 344

9 Spatio-temporal Databases in the Years Ahead 345
Manolis Koubarakis, Yannis Theodoridis, Timos Sellis

9.1 Introduction 345

9.2 Mobile and Wireless Computing 345

9.3 Data Warehousing and Mining 346

9.4 The Semantic Web 346

9.5 Conclusions 346

References 347

List of Contributors 349