

1 Introduction

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1.1 Why Spatio-temporal Databases?

Time and space are ubiquitous aspects of reality. It is hard to imagine a day in our life going by without making use of temporal and spatial information. In today's digital world, there is hardly any information system where time, space or both need not be present as first-class concepts in order to effectively support the targeted application. The reader is invited to consider the information systems of such varied organizations as financial institutions, public administrations, factories, hospitals, environmental agencies, entertainment industries, the military, space agencies, schools or universities, to name a few.

Starting with Aristotle, philosophers, mathematicians and physicists have developed fascinating formal accounts of time and space culminating in Einstein's theory of general relativity [34,35,37,48,11]. In the last three decades, computer scientists took a strong interest in studying time and space from the point of view of various research areas and applications. There has been a lot of interesting work in temporal logic [30,31,18,4,3], computational geometry [33], databases [21,40,46,24,43,16,44,32,38], artificial intelligence [42,12,26,36], [14], geographic information systems [29,49,1], environmental information systems [22], multimedia information systems [17,8,2,45,13] and so on. Researchers in temporal and spatial databases in particular have been very productive, developing important techniques for the representation, and management of spatial information, together with prototype systems. All this work is nicely surveyed in [21,40,46,24,43,16,44,32,38].

Until the beginning of the nineties, it was quite noticeable that temporal and spatial databases were important but separate areas of database research, with their own specialized meetings and conferences [39,47,10,15,41,25]. However, researchers in both areas had felt that there were important connections in the problems addressed by each area, as well as in the techniques and tools used for their solution. Many papers in temporal databases at that time concluded with phrases such as "the ideas in this paper may be extended to spatial databases". Similarly, many papers in spatial databases suggested that techniques developed for spatial databases apply to temporal databases, by restricting attention to one dimension only. But with the exception of pioneering papers such as [20,9,50], little systematic interaction and synergy between these two areas had occurred. The project CHOROCHRONOS, initiated by the European Commission in August 1996, aimed to achieve exactly this kind of interaction and synergy. Two years earlier, in North America, the National Center for Geographic Informa-

tion and Analysis had started the initiative “Time in Geographic Space”, with somewhat similar goals.¹

1.2 CHOROCHRONOS

CHOROCHRONOS was established as a European Commission funded Training and Mobility of Researchers Network,² with the objective of studying the design, implementation, and application of spatio-temporal database management systems (STDBMS). The participants of the network were the following institutions: National Technical University of Athens (Timos Sellis), Aalborg University (Christian S. Jensen), FernUniversität Hagen (Ralf Güting), Università Degli Studi di L’Aquila (Enrico Nardelli), UMIST (Manolis Koubarakis and Babis Theodoulidis), Politecnico di Milano (Barbara Pernici), INRIA (Stéphane Grumbach and Michel Scholl), Aristotle University of Thessaloniki (Yannis Manolopoulos), Agricultural University of Athens (Nikos Lorentzos), Technical University of Vienna (Andrew Frank), and ETH Zürich (Hans-Jörg Schek). All these institutions had established research groups in spatial and temporal database systems, most of which had so far been working exclusively on spatial or temporal databases. CHOROCHRONOS enabled them to collaborate closely and to integrate their findings in their respective areas. The project was coordinated by Timos Sellis.

CHOROCHRONOS had the following main objectives:

- To stimulate research in the areas of spatial and temporal databases, paying particular attention to the many real-life problems that require spatio-temporal concepts that go *beyond* traditional research in spatial and temporal databases.
- To allow researchers working on spatial and temporal databases to improve their understanding of each other’s work, to integrate their results, and to avoid duplication of work. The joint design and partial implementation of one or many STDBMS prototypes would be a desirable outcome of this collaboration.
- To allow researchers working on temporal and spatial databases to cooperate with researchers from other disciplines (environmental sciences, multimedia, transportation etc.) that are faced with spatial and temporal information and that would benefit from spatio-temporal database technology.

To achieve these objectives, CHOROCHRONOS pursued an extensive research program, covering issues related to the ontology, structure, and represen-

¹ For more information, see

<http://www.spatial.maine.edu/~max/I10TechReport.html>.

² The objective of Training and Mobility of Researchers Networks funded under the ESPRIT programme of the European Commission was to pull together a significant amount of expertise in an area of interest, to push the frontiers of research in this area, and at the same time facilitate the training and mobility of young researchers in Europe.

tation of space and time; data models and query languages for STDBMS; graphical user interfaces for spatio-temporal information; query processing algorithms, storage structures and indexing techniques; and architectures and implementation techniques for STDBMSs.

1.3 Contributions

Put briefly, a spatio-temporal database embodies spatial, temporal, and spatio-temporal database concepts, and it captures simultaneously spatial and temporal aspects of data. All the individual spatial and temporal concepts (e.g., rectangle or time interval) must be considered. However, attention focuses on the area where the two classes of concepts intersect, which is challenging, as it represents inherently spatio-temporal concepts (e.g., velocity or acceleration) observed in objects that may be changing their spatial characteristics continuously (e.g., moving objects). Simply extending a spatial data model with a temporal dimension or vice versa will result in a temporal data model that may capture spatial data, or in a spatial data model that may capture time-referenced sequences of spatial data. However, this simple aggregation of space and time is inadequate for general spatio-temporal data management.

Research in CHOROCHRONOS concentrated on the following six tasks:

- *Ontology, structure, and representation of space and time.* This involved the study of temporal and spatial ontologies, including their interrelations and their utility in STDBMS. As explained above, particular emphasis was put on concepts that are clearly spatio-temporal and cannot be obtained by a simple aggregation of temporal and spatial dimensions.
- *Models and languages for STDBMS.* The focus here was on three topics: (i) the study of languages for spatio-temporal relations, (ii) the development of models and query languages for spatio-temporal databases, and (iii) the provision of techniques for designing spatio-temporal databases. This work built on previous proposals and covered relational, object-oriented and constraint databases.
- *Graphical user interfaces for spatio-temporal information.* Research in this area had two goals: (i) to extend graphical interfaces for temporal and spatial databases, and (ii) to develop better visual interfaces for specific applications (e.g., VRML for time-evolving spaces).
- *Storage structures, indexing techniques, and query processing algorithms for spatio-temporal databases.* Techniques for the efficient evaluation of queries were the focus of this area. These techniques included high-level algebraic optimizations, new indexing techniques, and low-level strategies for page/object management.
- *Architectures for STDBMS.* The study of alternative architectures and implementation techniques for STDBMS was of high interest. As a result, several prototype STDBMS were developed in the project to demonstrate the innovations of more theoretical work.

- *Applications of STDBMS.* Finally, applying STDBMS in realistic problem settings guided our research throughout the project. We were particularly interested in applying our concepts and techniques not only to traditional target applications (e.g., GIS), but also to more advanced ones where the connection to a standard database approach was not obvious.

In summary, CHOROCHRONOS was a very exciting project. New ideas came out and collaboration among the specific teams has brought a lot of new and interesting issues to work on. The participating teams were very enthusiastic about this collaboration, and a lot of high-quality work was produced. Many joint papers in major conferences and journals were published, and various prototype STDBMS and related systems were developed. Several dissemination activities were held including an Intensive Workshop in Austria [19], a seminar at Schloss Dagstuhl [23] and an International Workshop in Edinburgh [7]. In all these events there was lively participation of researchers from other disciplines faced with temporal and spatial information. Last but not least, the project enabled many talented young researchers (pre-docs and post-docs) to remain in Europe and contribute to the research area of spatio-temporal databases.

1.4 Organization of the Book

The present book collects important and representative research carried out in CHOROCHRONOS and presents it in a unified fashion. The various chapters have been written in a tutorial way making the research contributions of the project accessible to a new generation of researchers interested in spatio-temporal information.

After this introductory chapter, Chapter 2 sets the stage for our contributions to the field of spatio-temporal databases, with a far-reaching study of the role of ontologies in spatio-temporal databases and information systems. Ontology and the related term “semantics” have recently gained increased attention in the database community particularly with the emphasis on ontology-based information integration [27] and the Semantic Web efforts [6,5]. Compared with traditional DBMS, STDBMS must be prepared to make stronger ontological commitments to capture the rich meaning of space and time. Such an ontology is necessarily more involved and the connection to the application area stronger. Moreover, the designer of a database application has to reconcile the ontological concepts from the application area, with the ontology built into the STDBMS. Optimally, an STDBMS involves in its built-in ontology a minimal commitment on how space and time is structured and is thus most open for application specific refinements. Exploring the minimal set of ontological commitment is the goal of Chapter 2.

Chapter 3 concentrates on conceptual database models for spatio-temporal information systems, and presents two related frameworks: the Spatio-Temporal Entity Relationship Model and the Extended Spatio-Temporal Unified Modeling Language. The emphasis in this chapter is on expressing application requirements in high-level conceptual notations, so that designs become understandable

to application stakeholders and users, and can be translated easily into the logical spatio-temporal models to be developed in Chapter 4.

Chapters 4 and 5 present CHOROCHRONOS' main contributions in terms of logical models for STDBMS. These chapters develop data models and query languages to deal with geometries changing over time. In contrast to most of the earlier work on this subject, these models and languages are capable of handling continuously changing geometries, or moving objects. These chapters focus on two basic abstractions called moving point and moving region. A moving point can represent an entity for which only the position in space is relevant. A moving region captures moving as well as growing or shrinking regions.

Chapter 4 takes a data type oriented approach. The idea is to view moving points and moving regions as three- or higher-dimensional entities whose structure and behavior is captured by modeling them as abstract data types. These data types can then be integrated as attribute types into relational, object-oriented, or other DBMS data models; they can be implemented as extension packages for suitable extensible DBMSs. Chapter 5 takes a different approach and explores extensions of the constraint database model [28] for the representation of geometries changing. The benefits of this approach is that the main concepts of the relational model are kept intact, and at the same time, one has powerful constructs to express infinite or indefinite phenomena.

Chapter 6 discusses index structures and query evaluation algorithms for STDBMS. The discussion in this chapter is far-reaching going from simple extensions of well-understood index structures for temporal and spatial databases, to very innovative recent proposals especially designed for moving object databases.

Chapter 7 is devoted to architectural and implementation aspects of spatio-temporal database management systems. This chapter gives a general introduction to architectures and commercial approaches to extending databases by spatio-temporal features. Then several prototype systems developed by CHOROCHRONOS researchers are discussed together with their intended applications.

Chapter 8 is devoted to the study of how the techniques developed in earlier chapters of this book can be put to use in applications that cannot be characterized as traditional database applications, but where there is a strong spatio-temporal emphasis. The application chosen is that of composing interactive multimedia presentations where a strong spatio-temporal connection is evident.

Chapter 9 is the epilogue to this book. The readers are challenged with the discussion of three important application areas (mobile and wireless computing, data warehousing and mining, and the Semantic Web) and the role that ideas from spatio-temporal databases can play in these.

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