Encyclopedia of GIS

Shashi Shekar • Hui Xiong (Eds.)

Encyclopedia of GIS

With 723 Figures and 90 Tables

Springer

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To our families . . .

Foreword by Brian Berry

The publication of a definitive *Encyclopedia of GIS* that lays out many of the computer science/mathematics foundations of the field is a major event, the culmination of a half century of development. I was part of the earliest stirrings in the mid-1950s. A small group of geography graduate students at the University of Washington, William Garrison's "space cadets," began to assemble what became the foundations of contemporary spatial analysis and to refocus mathematical cartography while working with civil engineer Edgar Horwood on his attempts to use the printers of the time to produce grey-shaded maps. Our attention was captured by Sputnik, however, we didn't anticipate that the US's response, the rapid development of NASA and satellite systems, would be the key to the equally rapid development of remote sensing, or that global positioning would rewrite cartography. Among the innovations of the time were Torsten Hägerstrand's first simulation models of space-time diffusion processes and early econometric interest in spatial autocorrelation. Both themes are now central to spatial analysis.

The GIS focus shifted when Garrison, Marble and I relocated to the Chicago region. Garrison and I helped fund civil engineer Howard Fisher's first generation computer graphics software, SYMAP I, and Marble and I organized NSF workshops to spread the word and drew together an initial overview of the field in *Spatial Analysis*. Fisher took his ideas to the Ford Foundation and a subsequent grant to Harvard University, where he established the Laboratory for Computer Graphics. The Lab served as the focus for research in the field well into the 1970s, providing the spark to such innovators as Jack Dangermond, who subsequently established ESRI and created what became the world's most widely used computer graphics software. Meanwhile, hardware development proceeded apace, as did imaging and positioning capabilities created by the Department of Defense and NASA, facilitating the resulting emergence of digital cartography and the establishment of the first large-scale Geographic Information Systems such as the Canada Land Inventory. The rest, as they say, is history – albeit given a new dynamic by the Internet and the continued evolution of computing capabilities both on the desktop and in the supercomputer.

Fifty years after these beginnings, the result is a large and complex field spanning many disciplines, continuing to grow and to expand into an expanding array of applications. Cartographers have eschewed their pen-and-ink, and rudimentary mapmaking is at the fingertips of everyone with Internet access. Road atlases are fast giving way to satellite navigation systems. Congress continues to be concerned with the privacy issues raised by geographic information system capabilities, yet police and fire departments can no longer function effectively without GIS and Homeland Security without modern database and data mining capabilities. From city planning to store location, property taxation to highway building, disaster response to environmental management, there are few arenas in which GIS is not playing a significant role. What is important is the cross-cutting capability that was recognized when the NSF funded the Center for Spatially-Integrated Social Science (CSICC) at the University of California, Santa Barbara, or my own university's Ph.D. program, a joint venture of the School of Economic, Political and Policy Sciences, the School of Natural Sciences and Mathematics, and the School of Engineering and Computer Sciences.

I like to tell my colleagues that there are three levels of GIS education: "Driver's Ed," "Mr. Goodwrench," and "Design Team." Driver's Ed provides essential skills to the broad base of software users, the Mr. Goodwrenches of the world learn how to put together and maintain working software-hardware installations, while Design Teams create new and improved GIS capabilities. Most of the new data handling capabilities reside in the arenas of computer science/mathematics, while advances in inference are coming from innovations in the ability to handle space-time dynamics while simultaneously accounting for serial and spatial dependence.

The *Encyclopedia of GIS* provides an essential reference work for all three categories of users. In contrast to the current textbooks in the field, which are keyed to Driver's Ed, the *Encyclopedia* also provides a handy sourcebook for the Mr. Goodwrenches while defining the platform on which future Design Teams will build by focusing – more than existing works – on the computer science/mathematical foundations of the field. I know that the GIS community will value this important reference and guide, and I will cherish it as a milestone. It marks how far we have come – far beyond what our group of pioneers dreamed might be possible a half century ago. Professors Shekhar and Xiong and the considerable community of contributors to the collection have provided us with a comprehensive and authoritative treatment of the field, extensively cross-referenced with key citations and further readings. Importantly, it is available in both printed and XML online editions, the latter with hyperlinked citations. The GIS world will be indebted to them. No GIS bookshelf should, as they say, be without it.

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Foreword by Michael Goodchild

Geographic Information Systems date from the 1960s, when computers were mostly seen as devices for massive computation. Very significant technical problems had to be solved in those early days: how did one convert the contents of a paper map to digital form (by building an optical scanner from scratch); how did one store the result on magnetic tape (in the form of a linear sequence of records representing the geometry of each boundary line as sequences of vertices); and how did one compute the areas of patches (using an elegant algorithm involving trapezia). Most of the early research was about algorithms, data structures, and indexing schemes, and, thus, had strong links to emerging research agendas in computer science.

Over the years, however, the research agenda of GIS expanded away from computer science. Many of the technical problems of computation were solved, and attention shifted to issues of data quality and uncertainty; the cognitive principles of user interface design; the costs and benefits of GIS; and the social impacts of the technology. Academic computer scientists interested in GIS wondered if their research would be regarded by their colleagues as peripheral – a marginally interesting application – threatening their chances of getting tenure. Repeated efforts were made to have GIS recognized as an ACM Special Interest Group, without success, though the ACM GIS conferences continue to attract excellent research.

The entries in this encyclopedia should finally lay any lingering doubts to rest about the central role of computer science in GIS. Some research areas, such as spatiotemporal databases, have continued to grow in importance because of the fundamental problems of computer science that they address, and are the subject of several respected conference series. Geospatial data mining has attracted significant attention from computer scientists as well as spatial statisticians, and it is clear that the acquisition, storage, manipulation, and visualization of geospatial data are special, requiring substantially different approaches and assumptions from those in other domains.

At the same time, GIS has grown to become a very significant application of computing. Sometime around 1995, the earlier view of GIS as an assistant performing tasks that the user found too difficult, complex, tedious, or expensive to do by hand, was replaced by one in which GIS became the means by which humans communicate what they know about the surface of Earth, with which they collectively make decisions about the management of land, and by which they explore the effects of alternative plans. A host of new issues suddenly became important: how to support processes of search, assessment, and retrieval of geospatial data; how to overcome lack of interoperability between systems; how to manage large networks of fixed or mobile sensors providing flows of real-time geographic data; how to offer useful services on the very limited platform of a cell phone; and how to adapt and evolve the technology in order to respond to emergencies and to provide useful intelligence. A revitalized research agenda for computer science emerged that shows no sign of diminishing, and is reflected in many of the topics addressed in this encyclopedia.

For example, computer scientists are engaged in the development of data structures, algorithms, and indexing schemes to support the hugely popular virtual globes (Google Earth, Microsoft's Virtual Earth, NASA's World Winds) that have emerged in the past few years and are stimulating a whole new generation of applications of geospatial technology. Research is ongoing on sensor networks, and the complex protocols that are needed to handle flows of real-time data from massive numbers of devices distributed over the Earth's surface, in areas of scientific interest such as the sea floor, in vehicles acquiring data on traffic movement, and in battlefields. Semantic interoperability, or the ability of systems to share not only data but the meaning of data, remains a thorny problem that will challenge the research community for many years to come.

As a collection of well-written articles on this expanding field, this encyclopedia is a welcomed addition to the GIS bookshelf. The fact that its compilers have chosen to emphasize the links between GIS and computer science is especially welcome. GIS is in many ways a *boundary object*, to use a term common in the community of science historians: a field that has emerged between two existing and recognized fields, in this case computer science and geography, and which has slowly established its own identity. As it does so, contributions such as this will help to keep those links alive, and to ensure that GIS continues to attract the interest of leading researchers in computer science.

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Preface

Interest in Geographic Information Systems, Science, and Services (GIS) has tremendously grown in recent years in many different ways. Researchers from a variety of academic disciplines are using spatial thinking and GIS tools to develop spatially-explicit models. Broad public interest in this subject is being fuelled by popular applications like Google maps, personal navigation devices, MapQuest, etc. Web-based software developers are increasingly exploring "mash-ups" integrating different information sources to web-based maps, such as Google Earth and MS Virtual Earth. Therefore, there is a need to bring key GIS concepts and results to a diverse audience as current GIS literature (e. g., textbooks, journals, conference-proceedings, trade-books) largely caters to either GIS specialists or end-users of popular GIS software.

The GIS research community is enthusiastically embracing encyclopedias, i. e., collections of articles on numerous topics in a field, as a tool to bring key ideas from a field to a general audience. This is not only evident from the preparation of multiple encyclopedias of GIS in the 2007–2008 time-frame, but also from the generous time commitments from GIS researchers contributing to the encyclopedia projects as authors, field editors and reviewers. The concurrent development of multiple GIS encyclopedias helped us define a focus, given the multi-disciplinary nature of the field. This encyclopedia focuses on computational aspects of a variety of GIS concepts for a variety of reasons. First, computational advances are making GIS available to a wide variety of end-users, software developers and researchers. Second, many geo-spatial datasets are large and growing rapidly due to advances in cyber-infrastructure, including sensor and data management technologies. This will make computational issues even more critical in the coming years. Finally, computational technologies are advancing at a rapid pace, making new capabilities possible every few years. While the recent advances, e. g., Google Earth and Microsoft Virtual Earth, look impressive, we are likely to see even bigger advances due to growing computing power in the years to come.

Despite the focus on computational aspects of GIS, it was still challenging to narrow down the list of possible articles in order to explain the key software, datasets, and processes used by geographers and computational scientists. After all, our goal was to provide a comprehensive and authoritative treatment of GIS, providing easy access to the field. We reviewed the topics in calls-for-papers for conferences and journals along with the keywords in relevant books and model curricula. We also consulted various leaders in the GIS area. Additionally, we tried to balance the set of topics to reflect the interests of industry, government and academia. For example, topics such as GIS standards as well as examples of GIS software from industry and the public domain were included in the topic list. Similarly, we included topics like crime mapping, evacuation planning and location-based services. Naturally, the list includes a variety of academic topics ranging from "Spatial Cognition" to "Statistical Modeling."

The next major challenge was to identify suitable field editors and authors representing the world leaders in selected topic areas. Many researchers usually focus on conference and journal papers. Yet, we were pleasantly surprised by the generosity of time and expertise received from so many enthusiastic GIS colleagues for this encyclopedia project. Field editors went beyond their call of duty to identify and invite potential authors, and review contributions in order to ensure technical quality while working with Springer project managers to keep the project on schedule. This is a wonderful sign of the energy and collegiality of the computational GIS research community.

Springer's encyclopedia group provided thoughtful guidelines for the entries. Typical entries are 3000 words and provide balance among definition, scientific fundamentals, application domains, and future trends. Many include short definitional entries cross-referenced to related regular entries in order to discuss specific terms and concepts such as the Global Positioning System, Digital Elevation/Terrain Model, and Remote Sensing. Regular entries include key citations and a list of recommended reading regarding the literature, and (online) internal hyperlinks to definitional entries and current standards. This Encyclopedia is also simultaneously available as an XML online reference with hyperlinked citations, cross-references, four-color art, links to Web-based maps, and other interactive features.

Key Features at a Glance

- Immediate point of entry into the field for researchers
- A–Z format allows easy, intuitive access for newcomers to the field
- Many headers for easy skimming and navigation of topics
- Includes coverage of GIS standards in development by ISO
- Cross-referenced entries
- Internationally renowned editorial board, both scientifically and geographically diverse
- Hundreds of contributors ensure balanced coverage
- Interactive features add to convenience, ease of use and understanding
- Peer-reviewed entries assure researchers that information is vetted
- eReference is available at springerlink.com

Content Organization

The encyclopedia is divided into 41 fields, each one an important sub-area within GIS. These fields include: Basic Concepts; Basic Storage and Retrieval Structure; Cartography and Visualization; Commercial GIS; Commercial Spatial Databases; Critical Evaluation of Standard Proposals; Data Exchange and Interoperability; Digital Road Map; Emergency Evacuations; Evacuation Planning and Operations; Geosensor Networks; GeoSpatial Semantic Web; GIS in Business Intelligence, Routing; GIS Issues and Applications; Indoor Positioning; Information Collection Using Sensor Network; Open Source GIS Software; Photogrammetry; Representation of Inexact Spatial Information; Road Network Databases; Security and Privacy in Geospatial Information Systems; Spatial Analysis; Spatial Aspects of Bioinformatics; Spatial Aspects of Distributed Computing; Spatial Aspects of Mobile Computing; Spatial Association Discovery; Spatial Co-location Rule Mining; Spatial Constraint Databases; Spatial Data Warehousing and Decision Support; Spatial Database Modeling for Applications; Spatial Indexing; Spatial Outlier Detection; Spatial Prediction; Spatial Thinking; Spatial Time Series; Spatial Uncertainty and Imprecision; Spatio-Temporal Data Modeling; Spatio-Temporal Databases; Statistical Modeling for Spatial Data; Tesselation Data Models; and Use of Spatial Data for Simulation.

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We would like to thank the members of the spatial database research group in the Computer Science Department at the University of Minnesota. They contributed in many different ways including providing literature surveys, organizing topics, and reviewing articles. We would also like to thank some of the students enrolled in Csci 8701 and Csci 8715 for contributing articles.

Finally, special thanks are due to many people at Springer for their enthusiasm, advice, and support. In particular, we would like to thank Susan Lagerstrom-Fife, Oona Schmid, Jennifer Carlson, Andrea Schmidt, Simone Tavenrath, Sharon Palleschi, and Yana Lambert, who at different times have played key roles in the development of this book.

August, 2007 Shashi Shekhar and Hui Xiong

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Professor Shekhar was elected as an IEEE Fellow and received the IEEE Technical Achievement Award for contributions to spatial database storage methods, data mining, and Geographic Information Systems (GIS). He has a distinguished academic record that includes 200+ refereed papers and two books including a textbook on Spatial Databases (Prentice Hall, 2003). He is serving as a member of the mapping science committee of the NRC/NAS (National Research Council National Academy of Sciences) (2004-2009), and the steering committee of the ACM Symposium on GIS. He is also serving as a co-Editor-in-Chief of Geo-Informatica: An International Journal on Advances of Computer Science for GIS. He has served as a member of the NRC/NAS Committee, reviewing basic and applied research at the National Geo-spatial-Intelligence Agency (NGA), the Board of Directors of the University Consortium on GIS (2003-2004), the editorial boards of IEEE Transactions on Knowledge and Data Engineering as well as the IEEE-CS Computer Science & Engineering Practice Board. He also served as a program co-chair for the ACM International Workshop on Advances in GIS (1996).

Professor Shekhar is a leading researcher in the area of spatial databases and spatial data mining, an interdisciplinary area at the intersection of Computer Science and GIS. A major goal of his research is to understand the computational structure of very large spatial computations (e. g., data analysis via spatial querying and spatial data mining) needed by social and physical sciences as well as engineering disciplines. Earlier, his research developed core technologies behind in-vehicle navigation devices as well as web-based routing services, revolutionizing outdoor navigation in the urban environment in the last decade. His research results are now playing a critical role in evacuation route planning for homeland security and were recognized via the CTS partnership award (2006) for significantly impacting transportation.

Professor Shekhar's general area of research includes data and knowledge engineering with a focus on storage, management and analysis of scientific and geographic data, information and knowledge. Major contributions in data engineering and database systems include the Connectivity-Clustered Access Method (CCAM), a new storage and access method for spatial networks which outperforms traditional indexes (e. g., R-tree family) in carrying out network computations. Other contributions are related to semantic query optimization and high performance geographic databases. In knowledge engineering, his work focuses on spatial data mining and neural networks. Major contributions include the notion of "co-location" patterns in spatial datasets, characterization of the computational structure of "spatial outlier" detection, faster algorithms for estimating parameters for the spatial auto-regression model as well one of the most scalable parallel formulations of the back-propagation learning algorithms for neural networks.

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Professor Xiong received his Ph.D. in computer science from the University of Minnesota in 2005. He is currently an assistant professor in the Management Science and Information Systems Department at Rutgers, the State University of New Jersey. His general area of research is data and knowledge engineering, with a focus on developing effective and efficient data analysis techniques for emerging data intensive applications. He has published prolifically in refereed journals and conference proceedings, such as IEEE Transactions on Knowledge and Data Engineering, the VLDB Journal, the Data Mining and Knowledge Discovery Journal, ACM SIGKDD International Conference on Knowledge Discovery and Data Mining (KDD), SIAM International Conference on Data Mining (SDM), IEEE International Conference on Data Mining (ICDM), and ACM International Symposium on Advances in Geographic Information Systems (ACM GIS). He is the co-editor of Clustering and Information Retrieval (Kluwer Academic Publishers, 2003) and the author of Hyperclique Pattern Discovery: Algorithms and Applications (ProQuest Information and Learning, 2006). He has served regularly in the organization committees and the program committees of a number of international conferences and workshops. Furthermore, he has been a reviewer for the leading academic journals in his fields. He is a member of the IEEE Computer Society, the Sigma Xi, and the ACM. Professor Xiong was the recipient of the Junior Faculty Teaching Excellence Award at the Rutgers Business School in 2007.

Professor Xiong is a well-known researcher in the field of data mining. A major goal of his research is to understand the computational structure of very large computations needed in science, business, and engineering disciplines. His major research contributions include the notion of hyperclique patterns, characterization of the computational structure of the phi correlation coefficient, enhancing data analysis with noise removal, a systematic study of clustering validation measures from a data distribution perspective, and the development of local decomposition for rare class analysis.

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