Contributions of GIScience over the Past Twenty Years

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Abstract: This paper summarizes the discussions related to the panel "Contributions of GIScientists (or GIScience) over the past Twenty Years" at the 2015 Vespucci Institute. Reflections about the past not only provide an account of what occurred, but also may serve as a basis for comparison when in the future somehow related scenarios arise. Such histories may be detailed enumerations of chronological events or, more analytically, analyses of interactions that enabled or caused specific developments. The purpose of this paper is to account for some key developments in the academic field of geographic information science over the past twenty years (i.e., since 1995) and to assess some of the impact of these developments. The panel in Bar Harbor, moderated by David Coleman, included two invited presentations (by Max Egenhofer and Keith Clarke), and responses by two early career panelists (Song Gao and Teriitutea Quesnot), and by two senior panelists (Randolph Franklin and May Yuan).

Keywords: Emergence of GIScience; short recent history; outlets of GIScience research; publication ranking; selected highlights of GIScience research; contributions to other disciplines; research topics that have disappeared; recently emerging topics.

1 Introduction

Geographic information system (GIS) as the term and concept preceded geographic information science. The term geographic information system is widely attributed to Roger Tomlinson's Canadian Geographic Information System [88]. The concept spread over its first twenty years to sizeable software systems whose principal goal was to perform computerized mapping.

The first Big Book [64] included a chapter by Coppock and Rhind [10], entitled "The History of GIS," which described primarily the roles of different organizations in developing computerized mapping systems. To contrast this history's focus on vector representations, Foresman [28] provided a complementary history of GIS from the raster perspective. A third approach—The GIS History Project [62]—aimed at a critical examination of the history of GIS. All these efforts highlight that a single history about geographic information is unlikely to represent fully the many different facets and linkages that geographic information systems have.

As this paper focuses on developments since the two International Early Career Summer Institutes in Geographic Information [11, 12], the examination and reflection on geographic information science is limited here to new insights gained since the mid 1990s.

This chapter summarizes the main ideas and remarks that emerged from both the panelists (i.e., the authors) and the audience during the first panel session. Specifically, this panel reviewed the emergence of GIScience (Section 2), its recent history (Section 3). Panelists analyzed the proliferation of the terms GIS and GIScience throughout the literature (Section 4) and examined the journal and competitive conferences that are dedicated to GIScience (Section 5) and the most frequently cited articles in some outlets (Section 6). Selected research highlights and contributions to other disciplines are discussed in Sections 7 and 8, respectively. Finally, the change of topics in the research landscape (Section 9) and recently emerging topics (Section 10) are discussed. The chapter closes with conclusions in Section 11.

2 The Emergence of Geographic Information Science

The term *Geographic Information Science* emerged in the early 1990s. Goodchild's keynote address at the Fourth International Symposium on Spatial Data Handling introduced ideas of some science behind the systems [32]. This approach was very much in response to concerns expressed by Abler [1] that geographic information systems were theory-poor, yet in the long term the success of such a field would require strong theoretical underpinnings.

The introduction of a term that distinguished the systems from the science marked the start of this transition. While Goodchild's initial choice was *Spatial* Information Science (possibly in line with the Symposium's name), the longer version of the essay published in the *International Journal of Geographical Information Systems (IJGIS)*, replaced *spatial* with *geographical* information science [34]. The minor discrepancy between geographical and geographic had already been addressed by Abler [1] during the emergence of the NCGIA, attributing the difference to the British (geographical) vs. US (geographic) linguistic intricacies and the IJGIS's preferences (Goodchild's 1991 keynote at EGIS had used the term Geographic Information Science [33]). Goodchild [36] reflects on twenty years of progress, including these historical accounts in Geographic Information Science. The twenty-one research initiatives of the National Center fro Geographic Information and Analysis (NCGIA), which fuelled much research publication in the GIS field between 1988 and 1996, can be seen as a first comprehensive GIS research agenda (www.ncgia.ucsb.edu/research/initiatives.html).

Geographic Information Science was quickly adopted as a popular term in academia, as it promotes scientific endeavors beyond technological GIS applications. The broader adoption of geographic information science was evident by the establishment of the (US) university consortium for geographic information science (UCGIS). In 1997, the flagship journal, IJGIS, changed its name from the International Journal of Geographical Information Systems to the International Journal of Geographical Information Science.

Then editor-in-chief Peter Fisher highlighted that the name change was only after the 24th character (not counting blanks) so that future volumes would still be most likely shelved in libraries in close proximity, when sorted alphabetically. A few years later, the journal *Cartography and Geographic Information Systems* also adopted the science term, changing to *Cartography and Geographic Information Science*. With the initiation of the International Conference on Geographic Information Science in 2000, the term Geographic Information Science gained further prominence within the scientific community, as this biennial conference series caters on the many components of this interdisciplinary field and its intricacies. The conference series' acronym (GIScience) became a popular way to refer to the field, distinguishing it from its systems (GISs).

3 A Short Recent History of Geographic Information Science

Depending on when one wants to pinpoint the birth of geographic information science, any of its histories may start between 1990 and 1992. The reflection on the early 1990s through mid 2010s captured in this section develops from an earlier focus on a somewhat longer time frame [18] during which the *game changers* contributed to the formation of geographic information science, such as Vannevar Bush's *As We May Think* [5], Tomlinson's Canadian Geographic Information Systems [88], Tobler's Computer Movie Simulating Urban Growth [86], Hägerstrand's Time Geography [46], Dutton's Symposium on Data Structures for Geographic Information Systems [15], Pat Hayes's Naive Physics Manifesto [48], Peucker's TINs [73], Tomlin's Map Algebra [87], Guttmann's R-tree [45], and Abler's vision about the US National Center for Geographic Information and Analysis [1].

Although held only a week prior to Goodchild's 1990 keynote [32], the NATO Advanced Study Institute on Cognitive and Linguistic Aspects of Geographic Space [66] became the foundation of the cognitive and computational aspects of geographic information science. Together with the *Conference on Spatial Information Theory* (COSIT) series and the *Journal of Spatial Cognition and Computation*, a subfield was created that had high impact on geographic information science overall. Twenty-five years later the critique as to whether Las Navas's Lakoffian credo was more an advancement or an impediment to bringing other approaches on board [7] is up for debate.

By 1992 the first traces of micro-sensors started to make an impact on the field as not only GPS-based location (albeit crude at that time) emerged. The Active Badge Location Systems [91] pioneered sensor-based location techniques to track people movement in building complexes. Coupled with the advent of the World-Wide Web, location data can be quickly disseminated across space. Negroponte's visionary account of a Being Digital [72] within a society started a novel perspective, also on sharing spatial data digitally, instantaneously. Only shortly afterwards, the visions of location sensors, the Web, and novel space-time interactions came together in the concept of Digital Earth [41]. Access to scientific and cultural data with respect to the sphere would enable global collaboration.

In addition, the virtual reality, augmented reality, and visualization technologies more broadly pushed for immersive digital environments. The Virtual LA project [51] added the facet that the traditional map based conveyance of geographic information could be accomplished in a way that allows users to experience space more like they were immersed in that space. In addition, the opportunity of combining photo-realistic renderings of infrastructure with simulations about non-static objects and events started to bring the community outside of its confines.

The setting of networked sensors [24] provided the backbone for real-time data collections of distributed phenomena. Geosensor networks [82] highlight the particular challenges that arise with static and mobile sensor colonies that are spatially distributed. The amount, complexity, and diversity of datasets that arise within such geosensor networks have fuelled the contemporary focus on spatial big data [79].

At the beginning of the millennium, the focus shifted towards the meaning of data. The Semantic Web [4] provided a vision that the Web also needs logic in order to make automatic inferences about the data. A critical role in this setting is reserved for ontologies—specifications of conceptualizations [43]. Semantics and ontologies were further specified within the context of geographic information, yielding such concepts as the Geospatial Semantic Web [17] and Ontology-Driven GIS [27].

A new development in the recent history of geographic information science is the concept of volunteered geographic information [35], which puts a focus on spatial data collections that are community-driven rather than conducted and controlled by a single authority. As such volunteered data sets do not necessarily follow a prescribed format, they have the potential of great variability (e.g., quantitative vs. qualitative) and accuracy. Volunteered datasets to which masses of users contribute have the enormous prospectus of timely, up-to-date access to spatial information about phenomena that undergo rapid change.

4 Proliferation of the Terms GIS and GIScience

The terms *GIS* and *GIScience* have become increasingly popular within the scientific world, not only within its own field. In order to quantify such a development, we used Scopus, the abstract and citation database of peer-reviewed literature to query the number of publications that contain the keyword GIS or GIScience between 1991 and 2015 (Figure 1). The annual summary counts reveal for phases:

1. Up to 1995, annual counts were less than 1,000.
2. Between 1996 and 2000 the use of the two terms increases modestly to just below 1,300.
3. Between 2001 and 2010, the counts essentially quadrupled to rough 6,000 occurrences annually.
4. Since 2010, this count has plateaued at roughly 6,000 annual occurrences of the terms GIS and GIScience.

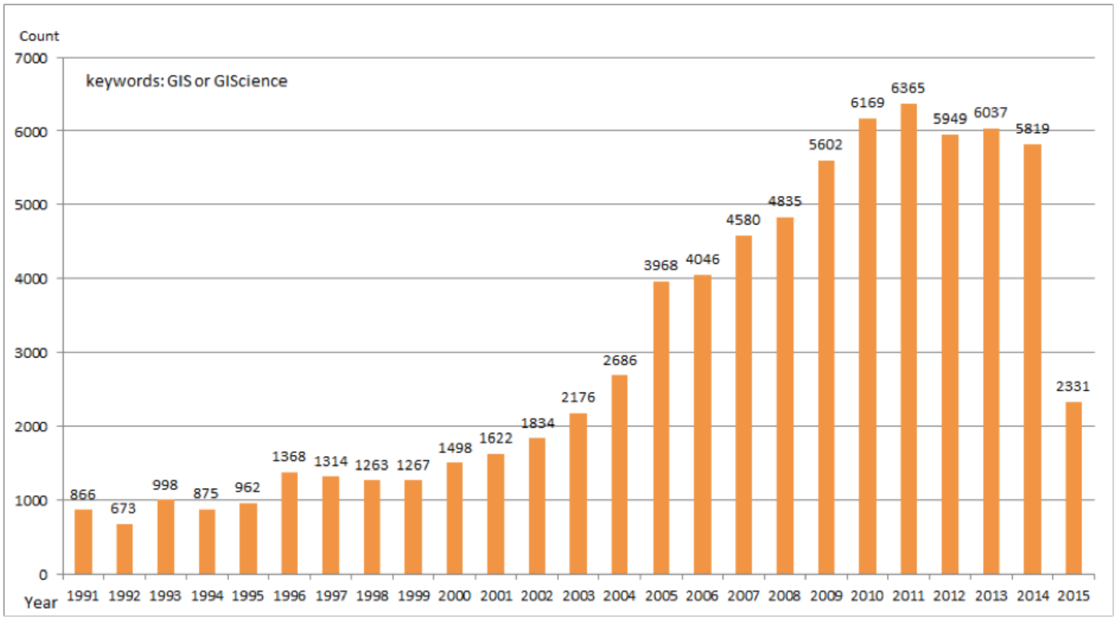

Figure 1: Total number of publications with the keywords GIS or GIScience, based on a Scopus query for the years 1991 through 2015, executed in July 2015.

5 The Outlets of Geographic Information Science over the last Twenty Years

The landscape of the outlets that cater to advances in geographic information science and geographic information systems has changed quite dramatically over the last twenty years. In 1995, the IJGIS was the only journal that targeted GIS research as its primary goal. A year later, Transactions in GIS published its first issue. At the First International Conference on Geographic Information Science (GIScience 2000), a panel on journals that were interested in recruiting papers on research in geographic information science was crowded with editors of sixteen journals (Table 1).

Table 1: Journals represented at the editors' panel at GIScience 2000.

- *Annals of the AAG*
- *Cartographica*
- *Cartography and Geographic Information Science*
- *Computers and Geosciences*
- *Computers, Environment and Urban Systems*
- *Environment and Planning B*
- *Geographic Information Sciences*
- *Geographical Analysis*
- *Geographical Systems*
- *GeoInformatica*
- *Geomatica*
- *International Journal of Geographical Information Science*
- *Networks and Spatial Economics*
- *Spatial Cognition and Computation*
- *Transactions in GIS*
- *URISA Journal*

A study of GIScience journals, published in 2008 [8], started with 121 journals, reduced them to 84 that were deemed more core to GIScience, ultimately focusing on a subset of 54 in an attempt to rank them. This means the core outlets for GIS and GIScience research more than tripled over eight years. More recently, further reputable outlets have appeared, such as the *Journal on Spatial Information Science*, *ACM Transactions on Algorithms and Systems*, *Earth Science Informatics*, and *Open Geospatial Data, Software and Standard*.

The landscape of regularly scheduled conferences that cater to geographic information science research has seen less volatility. Launching a new journal may be less involved than sustaining a conference series on a regular basis. The global distribution of the events over the last 20 years highlights over the years a focus on Europe and North America.

In the mid 1990s, the Spatial Data Handling Symposia (SDH) dominated the field of theoretical contributions to GIS (Section 5.5). Autocarto went into a hiatus in the late 1990s and the AAG meetings included selected sessions related to GIS research.

In the early 1990s, two new conferences series adopted the computer scientists' rigor of fully refereed full papers for conferences with the biennial Symposia on *Large Spatial Databases (SSD*) and the *Conference on Spatial Information Theory (COSIT)* (Section 5.2), with proceedings published in Springer's Lectures Notes in Computer Science series and a single-track conference program. Both established themselves as venues for focused work in specific subfields of geographic information science. The annual *ACM Workshops on Geographic Information Systems*, which also had a rigorous reviewing system, attracted only small audiences, however.

In order to provide a forum for a more encompassing perspective of geographic information science research, the biennial conference series on Geographic Information Science, dubbed *GIScience*, started in 2000 (Section 5.1). With the formation of *ACM SIGPATIAL* (Section 5.4)—a Special Interest Group with a focus on the acquisition, management, and processing of spatially-related information—in the early 2000s, ACM GIS became the SIG's annual meeting of that SIG, drawing large crowds to the presentations of fully refereed papers on systems issues in GIS.

Specialized meetings with a focus on a subfield of GIScience continue on *Spatial Accuracy*, *Spatial Cognition*, *GeoComputation* (Section 5.6), *Web and Wireless GIS*, and *Digital Earth*. Regional GIS meetings (e.g., *GISRUK* in the UK, *AGIT* in Austria, *GeoInfo* in Brazil) complement the conference landscape.

The GIScience Conferences portal giscienceconferences.org is a comprehensive archive of these events.

5.1 GIScience

The first international conference on Geographic Information Science was held in Savannah (Georgia, USA) in October 2000. It was hosted by NCGIA, UCGIS, and the AAG. This conference aims to bring together GIScience researchers from a wide variety of disciplines, including cognitive science, computer science, engineering, geography, information science, mathematics, philosophy, psychology, social sciences, and statistics. In order to focus on fundamental GIScience advances papers that deal with applications of Geographic Information Systems are systematically discouraged. This multi-track conference brings around 300 researchers every two years. Since of 2002, GIScience has been offering both fully refereed papers as well as extended abstracts that were screened by program committee members. This mixture catered to the different disciplinary preferences in the computational and the geographic fields of GIScience. Paper sessions are usually preceded by workshops and tutorials and followed by a poster session.

5.2 COSIT

The initiation of the series of Conferences on Spatial Information Theory (COSIT) was preceded by the international conference "From Space to Territory: Theories and Methods of Spatio-Temporal Reasoning," which was held in Pisa (Italy) in 1992. It is at times referred as COSIT 0. The first COSIT meeting was held in 1993 as an interdisciplinary biennial European conference on the representation and processing of information about geographic space. COSIT changes its venue every two years, and so far has been held in Australia, Austria, France, Germany, Italy, Switzerland, the UK, and the US. The COSIT conferences cover multiple fields of interests, such as the cognitive aspects of geographic information, the ontology of space, the cartography, and the behavioral geography. COSIT is a single-track conference. It includes a doctoral colloquium, workshops, tutorials, and poster presentations. Full papers have been published in the LNCS series. Between 100 and 130 researchers participate in COSIT every two years.

5.3 AGILE

The mission of the Association of Geographic Information Laboratories for Europe (AGILE) is to "promote academic teaching and research on GIS at the European level and to stimulate and support networking activities between member laboratories." This mission is notably achieved through an annual research conference that systematically takes place in Europe. AGILE's conference series on Geographic Information Science started in 1998 in Enschede (Netherlands) and clearly became a European reference in the area of GIScience. This conference focuses on research areas related to GIScience, from spatial cognition to geodesign, through health and medical Informatics. Full articles are published in Springer's Lecture Notes in Geoinformation and Cartography, whereas short papers are included in different electronic proceedings.

5.4 ACM SIGSPATIAL

The ACM SIGSPATIAL International Conferences on Advances in Geographic Information Systems is nowadays a series of symposia and workshops. It brings together researchers and developers specialized in GIS and other systems based on geospatial data. ACM SIGSPATIAL clearly emphasizes the technical aspects of geographic information systems (e.g., algorithms, database systems, and geometric computations). This annual conference is typically sponsored by such companies as ESRI, Google, Oracle, and Microsoft. ACM SIGSPATIAL is organized around paper and demo sessions as well as Ph.D. showcases. Topics addressed during ACM SIGSPATIAL cover numerous research areas (e.g., currently Big Spatial Data, GPU and Novel Hardware Solutions, Spatial Data Analytics, and Web and Real-Time Applications). Proceedings are published by ACM.

5.5 Spatial Data Handling

The international symposium on Spatial Data Handling (SDH) began in Zurich (Switzerland) in 1984. It is the key meeting of the International Geographical Union (IGU) Commissions on Geographical Information Science and on Modeling Geographical Systems. SDH is a well-know biennial research forum in the field of GIScience. It brings together geographers, cartographers, computer scientists, and other GIScientists every two years. The latest SDH (16th) was held in Toronto in October 2014 jointly with the ISPRS Technical Commission II Symposium.

5.6 GeoComputation

The GeoComputation meeting started in 1996 in Leeds (UK) as an annual conference centered on geographic analysis, statistics, and, modeling, computation algorithms on geospatial data. GeoComputation takes place every alternate year with the GIScience conference since 2002. This is a classic conference where workshops, paper sessions, and poster presentations are proposed.

6 Systematic Analyses of Publications

The development of a scientific community relies on many researchers and key players' contributions to this domain. A past analysis of social and spatial networks aimed at identifying patterns of collaborations among researchers, universities, and institutions in GIScience [2]. The results revealed to what degree individual trajectories (change of affiliations) of researchers impact the formation of a network of the GIScience communities. Citation counts remain a key currency when assessing the impact of research. André Skupin presented a citation analysis of the GIScience literature at the 2008 symposium, which identified Peter Burrough, Mike Goodchild, and Max Egenhofer as the three most-cited researchers in GIScience [36]. These results might be biased, however, because of the bibliographic datasets used in the analysis.

In a complementary analysis, Keßler *et al.* demonstrated how to semantically annotate and interlink bibliographic datasets using Linked Data technology and enable complex queries [49]. One such query showed that by 2012 only seventeen researchers had published full papers at ACM GIS, COSIT, and GIScience conferences, and another five have met this criterion in the meantime (Table 2). Most of them either have a background in computer science or collaborate with computer scientists.

Table 2: The seventeen researchers who published at least one full paper in each of the three conference series ACM GIS, COSIT, and GIScience by 2012 [52], plus the five who joined this club by 2015.

Benjamin Adams	Krzysztof Janowicz	Andrea Rodríguez
Christophe Claramunt	Christopher B. Jones	John Stell
Matthew P. Dube	Werner Kuhn	Egemen Tanin
Matt Duckham	Lars Kulik	Jan Oliver Wallgrün
Max J. Egenhofer	Ross S. Purves	Stephan Winter
Leila De Floriani	Martin Raubal	Michael Worboys
Andrew U. Frank	Kai-Florian Richter	
Mark Gahegan	Claus Rinner	

In order to complement the previous review and assessment, we employed two analyses based on 2015 data. The first analysis focuses on the most frequently cited articles in key outlet (Section 6.1). The citation searches focused on two journals and two refereed conferences. The second analysis looked at the development of the most prominent terms used in the publications of a conference series over seven consecutive events (Section 6.2).

6.1 Most Frequently Cited Papers in Selected GIScience Outlets

Occasionally, journal editors have published citation counts of their top-rated articles in editorials of their journal [26, 57]. These counts show that typically, publications must have been disseminated for some time before they collect significant numbers of citations. Also, more dated publications have a greater opportunity to collect more citations. While these side effects seem to favor mostly dated work, novel seminal work often rises quickly into the top of the charts.

Here we used Google Scholar to identify the ten most frequently cited articles in five different GIS and GIScience outlets: (1) *The International Journal of Geographical Information Science*, and its predecessor *The International Journal of Geographical Information Systems* (IJGIS), (2) *Transactions in GIS* (TG), (3) the series of conferences on spatial information theory (COSIT), and (4) the GIScience conference series.

Among these four samples, the IJGIS citation counts are the highest (Table 3). IJGIS has the longest history of the four (published since 1987) and the highest frequency. Three of its top-ten papers appeared in 1995, the year of the first Young Scholars Institute. Four of the top cited papers appeared in during the pioneering years of geographic information science. Only one of the top ranked papers—a survey article—appeared after 2000. The top-ten articles are mostly methodological, focusing on novel theories and models. IJGIS's most frequently cited article relates to advances in theory, in particular the modeling of spatial relations, one of the five bullets in the NCGIA solicitation [1].

The top citation counts for TG include an article from the TG's inaugural issue in 1996, and most of the remainder from the early 2000s (Table 4). A rapidly rising paper from 2010 relates to the emerging theme of volunteered geographic information, while the most frequently cited paper in TG addresses ontologies, one of the topics that are emerged in recent years (Section 10.1). Unlike in the other samples publications, topics related to the geographies of the information society [80] are more prominently represented in TG's top ten.

The COSIT conference series (Table 5), including the 1992 meeting in Pisa, reveals very high citation counts in its early years (1992–1995), and another peak in 1999. Cognitive, computational, and conceptual work is fairly balanced among the top COSIT papers. Like with the IJGIS, COSIT's most frequently cited paper focuses on the modeling of spatial relations.

The GIScience conference series (Table 6) has the shortest history among the sampled outlets as it started with full papers only in 2002. Nine of its top-ten papers are from the first two LNCS volumes covering Geographic Information Science. Its top ranked article deals with landmarks, a topic that also fared well among the COSIT papers.

Table 3: The ten most frequently cited articles published in the *International Journal of Geographical Information Science/Systems*, based on Google Scholar.

Title	Authors	Year published	Cited by as of August 2015
Point-set topological spatial relations	Egenhofer and Franzosa	1991	1,808
The GARP modelling system: problems and solutions to automated spatial prediction	Stockwell	1999	1,185
Integrating multi-criteria evaluation with geographical information systems	Carver	1991	891
Loose-coupling a cellular automaton model and GIS: long-term urban growth prediction for San Francisco and Washington/Baltimore	Clarke and Gaydos	1998	858
Geographical information science	Goodchild	1992	858
Kriging: a method of interpolation for geographical information systems	Oliver and Webster	1990	784
Integrating geographical information systems and multiple criteria decision-making methods	Jankowski	1995	667
GIS-based multicriteria decision analysis: a survey of the literature	Malczewski	2006	637
An event-based spatiotemporal data model (ESTDM) for temporal analysis of geographical data	Peuquet and Duan	1995	605
Interpolating mean rainfall using thin plate smoothing splines	Hutchinson	1995	551

Table 4: The ten most frequently cited articles published in *Transactions in GIS*, based on Google Scholar.

Title	Authors	Year published	Cited by as of August 2015
Using ontologies for integrated geographic information systems	Fonseca, Egenhofer, Agouris, and Câmara	2002	507
Integrating dynamic environmental models in GIS: the development of a dynamic modelling language	Wesselung, Karssenberg, Burrough , and van Deursen	1996	286
GI science, disasters, and emergency management	Cuttler	2003	226
Critical issues in participatory GIS: deconstructions, reconstructions, and new research directions	Elwood	2003	212
A new GIS-based solar radiation model and its application to photovoltaic assessments	Šúri and Hofierka	2004	202
Quality assessment of the French OpenStreetMap dataset	Girres and Touya	2010	196
On the use of weighted linear combination method in GIS: common and best practice approaches	Malczewski	2000	180
Use of information technology for community empowerment: transforming geographic information systems into community information systems	Ghose	2001	175
Integration of space syntax into GIS: new perspectives for urban morphology	Jiang and Claramunt	2002	176
Technical Note: A GIS-coupled hydrological model system for the watershed assessment of agricultural nonpoint and point sources of pollution	Di Luzio and Srinivasan	2004	165

Table 5: The ten most frequently cited papers published in the proceedings of the *Conference on Spatial Information Theory* (including COSIT 0), based on Google Scholar.

Title	Authors	Year published	Cited by as of August 2015
Using orientation information for qualitative spatial reasoning	Freksa	1992	648
Naive geography	Egenhofer and Mark	1995	600
Cognitive maps, cognitive collages, and spatial mental models	Tversky	1993	526
Scale and multiple psychologies of space	Montello	1993	416
Reasoning about gradual changes of topological relationships	Egenhofer and Al-Taha	1992	399
People manipulate objects (but cultivate fields): beyond the raster-vector debate in GIS	Couclelis	1992	389
The nature of landmarks for real and electronic spaces	Sorrows and Hirtle	1999	358
Network and psychological effects in urban movement	Hillier and Iida	2005	287
Elements of good route directions in familiar and unfamiliar environments	Lovelace, Hegarty, and Montello	1999	285
Pictorial and verbal tools for conveying routes	Tversky and Lee	1999	280

Table 6: The ten most frequently cited papers published in the fully-refereed proceedings of the *GIScience*, conference series based on Google Scholar.

Title	Authors	Year published	Cited by as of August 2015
Enriching wayfinding instructions with local landmarks	Raubal and Winter	2002	381
The SPIRIT spatial search engine: architecture, ontologies and spatial indexing	Jones, Abdelmoty, Finch, and Fu	2004	165
From objects to events: GEM, the geospatial event model	Worboys and Hornsby	2004	164
Project Lachesis: parsing and modeling location histories	Hariharan and Toyama	2004	168
Analyzing relative motion within groups oftrackable moving point objects	Laube and Imfeld	2002	125
Transmitting vector geospatial data across the Internet	Buttenfield	2002	123
Modeling the semantics of geographic categories through conceptual integration	Kuhn	2002	91
GeoVSM: An integrated retrieval model for geographic information	Cai	2002	59
Semi-automatic ontology alignment for geospatial data integration	Cruz, Sunna, and Chaudhry	2004	57
What is the region occupied by a set of points?	Galton and Duckham	2006	57

6.2 The Evolution of Terms in the GIScience Conference Series

The seven LNCS volumes of full papers published biennially in the GIScience meetings since 2002 provide a relatively concise opportunity to examine how specific terms were a focus in these articles of a period of twelve years. The word clouds for the titles and keywords of all full papers in these seven conferences (Figure 2) present some spatialization of the text strings. Authors used consistently the terms *spatial* and *data* in high frequency (although not necessarily in combination). Also *information* and *science* appear prominently throughout the years. Spatial is used consistently more frequently than geographic or geospatial. In recent years, the terms *ontology*, *indoor*, and *dynamic* emerged.

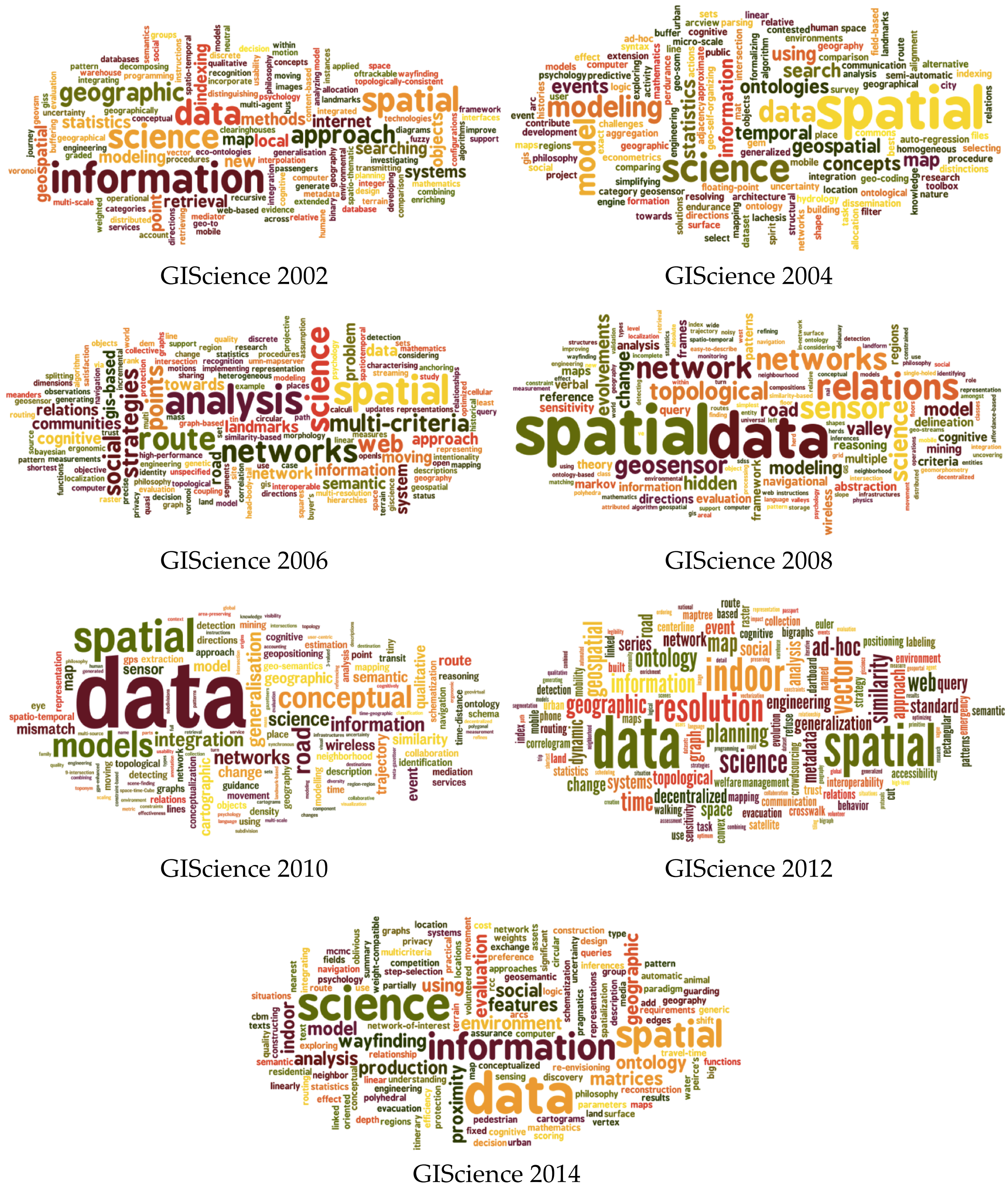

Figure 2: Word clouds of full papers of the GIScience conference 2002–2014.

7 Selected Research Highlights

7.1 Advances in Theory

As the core concept of GIScience is to study the *science behind the systems*, great efforts have been made towards advances in geographic information theories, such as models for spatial relations [19, 21, 29, 42, 74] and uncertainty in geographic data and GIS analysis, which exists in the whole process of data acquisition, geographical abstraction, representation, processing and visualization [94]. The studies of uncertainty help researchers and decision makers make better use of complex, multi-dimensional spatial data with regard to quality control that needs special handling, cleaning, and processing. Fisher discussed the critical causes and conceptual models of uncertainty in spatial data with a number of real-world examples [25]. Methods to visualize uncertainty information on maps were proposed and summarized [60, 62]. Longley *et al*. suggested five general dimensions of uncertainty in GIS data [59], namely, attribute accuracy, positional accuracy, logical consistency, completeness and lineage. Achievements in this field advance scientific analysis for geographic data.

7.2 The Cognitive World

UCGIS's research challenge on "Cognition of Geographic Information" investigates the understanding of human perception, memory, reasoning and communication toward spatial phenomena. Four of the former NCGIA research initiatives were dedicated to this theme (I2: Languages of Spatial Relations, I10: Spatiotemporal Reasoning in GIS, I13: User Interfaces for GIS, and I21: Formal Models of the Common Sense Geographic Worlds). In the same vein, the NCGIA's Varenius Project included a specific topic on "Cognitive Models of Geographic Space" [67]. The book *The Cognition of Geographic Space* [53] and the UCGIS research agenda on *Cognition of Geographic Information* [71] provide a clear overview of the main contributions done before the establishment of GIScience in 1992. These reviews notably include the concept of cognitive maps [14], theories of human spatial knowledge [78] and its acquisition from direct experience, languages, and maps [84, 85]. Recent advancements in the area of cognitive GIScience fall into the categories of (1) human factors of GIS, (2) geovisualization, (3) navigation systems, (4) cognitive geo-ontologies, (5) geographic and environmental spatial thinking and memory, and (6) cognitive aspects of geographic education [70].

7.3 The Computational World

Spatial is special [16]. The storage of geographic data needs handle not only the attributes but also the geometry information. In addition, the rates of geographic data generation were becoming far greater than that of the capabilities for the effective processing, storage, manipulation and analysis of such datasets. Thus new approaches to GIS data models, structures, management, queries and algorithms have been developed in the computational world to advance GIS-based computing and applications [76, 78].

7.4 The Social World

The NSF-funded National Center for Geographic Information and Analysis (NCGIA) helped establish a global standard core curriculum in GIS [39]. This NCGIA Core Curriculum was expanded from a set of hard copy lesson plans to various versions of an on-line shared curriculum, which fuelled the teaching of GIS, both within the discipline as well as the dissemination to many fields that use GIS in their domain analyses. At the same time, the expansion of textbooks at all levels in the field has been extraordinary. An important recent development has been the creation and subsequent improvement of the Geographic Information Science and Technology Body of Knowledge (www.aag.org/bok) [13]. This detailed specification of the core concepts and skill sets necessary for study and proficiency in GIS has influenced the Department of Labor's job specifications and descriptions, and is now supported by substantial online tools and an online ontology (http://gistbok.org/). In recent years the availability of online social networks and VGI outlets has led to a sub-field of GIS that studies social interactions via the Internet and the World Wide Web, using such tools as the geotags in Flickr, place names in tweets, and geocodes in Foursquare, Google+, and others. These activities often involve "big data" applications over millions or billions of records, challenging the limits of traditional desktop GIS [47].

8 Contributions of GIS to other Disciplines

GIS has made contributions to various domains in computer science, such as computational geometry. Geographers, such as at the Census, have been creating tools to process large databases since before the term *computational geometry* was even used in this context. One GIS contribution is to provide particularly hard problems with large datasets that need workable, fast solutions. An example is label placement on maps.

Another contribution within computer science is to the database domain. Spatial data types have been brought into mainstream databases with geospatial data model and query language support (e.g., Geodatabase, Oracle Spatial, PostgreSQL), as well as providing spatial indexing and spatial join methods [44]. However, more research is needed to improve support for network and field data, as well as spatial stream query processing [6, 77, 78].

In addition, the visualization of geographic information also draws a lot of attention from the computer scientists. Research of representation, visualization-computation integration, interfaces, cognitive/usability issues in geovisualization should be addressed in these crosscutting challenges [61]. Efforts have been made to foster a capable and integrated science and engineering community to conquer these challenges.

This influence of GIS is in the tradition of mathematics and physics where the big theoretical advances and conceptual unifications respond to applied problems. For example, in physics, Newton's theory of gravity described and unified both the orbit of the moon and the trajectories of small thrown objects. In GIS, the problem of overlaying two maps with almost coincident edges that cause slivers and rounding errors motivates the study of robust geometric algorithms in Computational Geometry. This crosscutting influence has great potential to continue into the future, when various 2D GIS algorithms may extend into 3D. For instance, overlaying maps in GIS in 2D provides techniques that can lead to overlaying 3D triangulations, a new approach that had benefits in the domains of Computer Aided Design and computational fluid dynamics.

Countless application domains have benefitted from GIS spatial analysis over the past twenty years. The two Big Books [58, 64] offer detailed accounts for many areas, but more recent advancements continue to ignite new cross-fertilizations, some of which we address here.

In regional planning and urban studies, GIS has been widely applied as an analysis and modeling tool to support decision-making [93], and as a simulator for urban growth [9].

Advancements in GIS also enabled GeoDesign as an emerging sub-field of landscape architecture that is supported by spatial decision analytical tools and illustrates using science in design as well as design in science [3]. Also, GIScience brings spatial analysis and statistics, as well as other location intelligence components, to facilitate traditional social science research, such as migration, demographics, crime analysis [49], and spatiotemporal access to urban opportunities [56].

In digital humanities, the development of geographic information retrieval spatial search, and digital gazetteer research has contributed to the new form of geolibrary [38]. The scientometrics community also addressed the importance of geospatial components in the scientific analysis of bibliographic data in order to identify institutional and international research collaboration and citation impact patterns [30].

GIS has led the spatial turn in health studies, in which spatial data, analysis, and global health research will be systematically incorporated for creating new discovery pathways in science [75]. This facilitates opportunities for new interdisciplinary research in which GIScientists to collaborate with medical scientists on research funded by the National Institutes of Health.

9 Changes of Topics in the Research Agenda of Geographic Information Science

Over the past twenty years, the research agenda in geographic information science has gone through a variety of iterations (Table 7), starting with Goodchild's initial list. The University Consortium for Geographic Information Science established in 1996 a list of ten research priorities [89]. The Varenius Project of the National Center for Geographic Information and Analysis [37] concisely formulated three research thrusts—cognitive [67], computational [20], and societal issues [80]. UCGIS updated its research priorities in 2004 and augmented them by another four challenges [63].

Table 7: Major priorities in GIScience research.

Goodchild [34]	Data collection and measurement Data capture Spatial statistics Data modeling and theories of spatial data Data structures, algorithms, and processes Display Analytical tools Institutional, managerial, and ethical issues
UCGIS [89]	*Research Priorities*: Spatial data acquisition and integration Distributed computing Extensions to geographic representations Cognition of geographic information Spatial analysis in a GIS environment Future of the spatial information infrastructure Uncertainty in spatial data Interoperability of geographic information Scale GIS and society
Varenius [37]	Strategic Areas for Geographic Information Science Research Cognitive models of geographic space Computational methods for representing geographic concepts Geographies of the information society
UCGIS [63]	*Research Challenges*: Spatial data acquisition and integration Cognition of geographic information Scale Extension to geographic representations Spatial analysis and modeling in a GIS environment Uncertainty in geographic data and GIS-based analysis The future of the spatial information infrastructure Distributed and mobile computing Interoperability GIS and society: interrelation, integration, and transformation
UCGIS [63]	*Emerging Themes*: Geographic visualization Ontological foundations for GIScience Remotely acquired data and information in GIScience Geospatial data mining and knowledge discovery

The major topics and priorities of GIScience research have changed over time. Some of them disappeared or were less developed than other topics, while new topics have also emerged. It is interesting to see how these research topics have been changed with regards to the twenty-one NCGIA research initiatives (http://www.ncgia.ucsb.edu/research/initiatives.html), which focused on the basic research on geographic analysis utilizing GIS and brought all parts of the GIS community to lay out appropriate research agenda. The topics of data modeling and theories of spatial data seem to be well studied with the achievements of vector, raster, and hybrid models in GIS. The geo-atom model, which represents the association between space-time point and property, can be taken as one of the generic forms for geographic information representations and combine discrete objects and continuous fields [40]. The research on geospatial data structures and modeling are related to the initiatives of "accuracy of spatial databases" and "multiple representations."

10 Topics that Recently Emerged in the GIScience Research Agenda

A series of new topics emerged recently in GIScience. Many of the are technology-driven or aimed at the development of new technologies, such as crowd-based solutions; spatial analysis of social media data; high-performance computing and the cloud; open-source solutions and software mashups; web-based mapping applications; location-based services and mobile computing; embedded solutions (e.g., within GPS routing systems), sensor-networks and their integration into real-time GIS; and integration of spatial and temporal processes into GIS functionality. We elaborate on four research threads (Sections 10.1-10.4) that are currently most prominent.

10.1 Ontologies in GIS

The study of ontologies in GIS bridges the gap between implementation and human conceptual modeling for representing geospatial phenomena and their analysis. Although it was not listed in the original research initiatives, it did play an increasing role in the series of core GIScience conference topics, as shown in the word cloud visualization of GIScience conference topics (Figure 2). Ontology plays an important role in knowledge organization and information integration. The use of ontologies in GIS development has been widely discussed in related research [27, 68], but relatively few works have addressed the design of the user interface based on semantic integration [55]. Semantic reference systems were suggested for solving semantic interoperability issues, especially to ground geospatial semantics in physical processes and measurements [54]. With the advent of Semantic Web and Linked Data, research on *geospatial semantics* is valuable for GIScientists interested in semantics research as well as knowledge engineers interested in spatiotemporal data exploration [50**].

10.2 Volunteered Geographic Information

The emergence of volunteered geographic information [35] and community mapping engaged the fast growth of the citizen science. The research on credibility, geoprivacy and other societal implication issues become more and more important as the growth of ubiquitous location awareness devices and crowdsourcing studies on geospatial Web [23, 83].

10.3 Spatial Big Data

Recently, as the context for geographic research evolves from a data-scarce to a data-rich or big-data environment, a *data-driven geography* [66] is emerging during the describes that large volumes of data with a geospatial component (including structured, semi-structured, and unstructured data) on various aspects of the environment and society are being created by millions of sensors constantly, in a variety of formats such as remotely sensed imagery, GPS logs, maps, blogs, videos, audios, and photos [31]. This trend sheds new light on spatial modeling and geographic knowledge discovery, and brings about innovative developments in

GIScience. The topic of *spatial big data* has emerged as one of the research challenges for advancing GIS in a new era.

10.4 CyberGIS

With the advancement of representative cloud computing systems, clusters and grids, high performance computing infrastructures have attracted increasing attention for GIScientists and geographers as a way of solving data-intensive, computing-intensive,and access-intensive geospatial problems [92]. The emerging concept of *CyberGIS,* which synthesizes cyberinfrastructure, spatial analysis, and high-performance computing, provides not only a promising solution to aforementioned geospatial problems as a cloud service but also facilitates a community-driven and participatory approach to achieve scientific breakthroughs across geospatial and other communities [90].

11 Conclusions

Twenty years after the first Young Scholars Summer Institute in Geographic Information, we reviewed the advances in the field. The field is still vibrant and continuous to reinvigorate itself with new challenges. Awareness of GIS and Geographic Information Science has increased significantly, and the academic field has matured with a much wider set of outlets for the dissemination of research results. Progress in Geographic Information Science has come through seminal work, but inside and outside of the field, which reflects the interdisciplinary character. Frequently, new technology has required novel approaches to dealing with spatial data and communicating spatial information. Over the last 20 years, the Web and mobile computing have provided unprecedented new opportunities, to which the GIScience research community responded with the development of a plethora of new methods. It is critical that the community is lead by the formulation of big intellectual challenges, like those presented in the NCGIA solicitation [1], and the visions of a geographic information science [34], a Naive Geography [22], a Digital Earth [41], a geospatial semantic web [17], or the volunteered geographic information [35].

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