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Editors

Cognitive and Linguistic Aspects of Geographic Space

New Perspectives on Geographic Information Research

Springer

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Preface

Twenty years is a long time for a follow-up meeting but this is exactly what happened when the 20th Anniversary Meeting on Cognitive and Linguistic Aspects of Geographic Space was held in Las Navas del Marques in July 2010. Twenty years prior, from July 8 to 20, 1990, 60 researchers gathered for 2 weeks at Castillo-Palacio Magalia in Las Navas del Marques (Avila Province, Spain) to discuss Cognitive and Linguistic Aspects of Geographic Space. This meeting was the start of successful research on cognitive issues in geographic information science, produced an edited book, and led to a biannual conference (COSIT), a refereed journal (Spatial Cognition and Computation), and a substantial and still growing research community.

The 2010 meeting brought together many of the original participants, but was also open to others, and invited contributions from all who are researching these topics. Early career scientists, engineers, and humanists working at the intersection of cognitive science and geographic information science were invited to help assessing the achievements and to reconsider the research challenges in the field. The meeting was very successful and compared the research agenda from then with the achievements over the past 20 years, and then turned to the future: What are the challenges today? What are worthwhile goals for basic research? What can be achieved in the next twenty years? What are the lessons learned?

This edited book assesses the current state of the field through chapters by participants in the 1990 and 2010 meetings and also documents an interdisciplinary research agenda for the future. All chapters underwent a rigorous review process, which we believe resulted in an interesting and high-quality book. As editors, we thank Michael Gould and Werner Kuhn, who were involved both in the organization of the Las Navas 2010 meeting as well as in the early planning of this book. Our sincere thanks go also to all authors for their contributions and last but not least to the reviewers who provided their time and expertise (listed in alphabetical order): Maureen Donnelly, Geoffrey Edwards, Christian Freksa, Scott Freundschuh, Antony Galton, Tilbe Göksun, Stephen Hirtle, Toru Ishikawa, Krzysztof Janowicz, Bernhard Jenny, Marinos Kavouras, Carsten Kessler, Alexander Klippel, Werner Kuhn, Stephan Mäs, Daniel Montello, Bernhard Nebel, Jochen Renz, Kai-Florian Richter, Maria Andrea Rodríguez-Tastets, Tarek Sboui, Christoph Schlieder, Angela Schwering, Monika Sester, Tim Shipley, Dalia Varanka, and Stephan Winter.

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Researching Cognitive and Linguistic Aspects of Geographic Space: Las Navas Then and Now

Andrew U. Frank, David Mark and Martin Raubal

Abstract This chapter provides an introduction to this book on Cognitive and Linguistic Aspects of Geographic Space—New Perspectives on Geographic Information Research. As background we provide historical information for the Las Navas 1990 meeting and citation statistics regarding the resulting book and its chapters. We also review the major intellectual influences on our field at that time from different perspectives and compare them to what we have learned over the two decades since then. This chapter finishes with a brief outlook on future research and summaries of the remaining chapters of the book.

Keywords Geographic Information Science · GIS · Geographic Information System · Spatial Cognition · SpatialLanguage · Spatial Reasoning

1 Introduction

In July 1990, a NATO Advanced Study Institute (ASI) on the topic of "Cognitive and Linguistic Aspects of Geographic Space" was held in the Castillo-Palacio 'Magalia' in Las Navas del Marques, Avila, Spain. Twenty years later to the day,

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nine participants from that Advanced Study Institute re-assembled at Magalia and were joined by 21 others, to reflect on the earlier meeting, to discuss current research on the same topic as it has evolved, and to think about future research on cognitive and linguistic aspects of geographic space. The breadth of the discussion 20 years later reconfirmed the vitality of the topic.

The 1990 NATO ASI was designated as the closing event for Research Initiative 2 "Languages of Spatial Relations" of the US National Center for Geographic Information and Analysis (NCGIA). Seen in retrospect, the "closing" designation is somewhat ironic, because the meeting at Las Navas was really the opening of an important research theme in the emerging fields of Spatial Information Theory and Geographic Information Science.

The U.S. National Science Foundation (NSF) request for proposals for a National Center for Geographic Information and Analysis listed "general theory of spatial relations and database structures" as one of the 5 major research areas to be worked on (Abler 1987). The quest for new theory for geographic information had taken a cognitive turn just a few years before, and this influenced some of us as we wrote what turned out to be the successful proposal to the US National Science Foundation to host the NCGIA (1989). The group from UC Santa Barbara, SUNY Buffalo, and the University of Maine proposed a series of Research Initiatives, each of which would last about 2 years, and which would open with a "Specialist Meeting", and have a closing event to summarize progress and future directions.

NCGIA's Research Initiative 2 was entitled "Languages of Spatial Relations", and was co-led by Andrew Frank and David Mark. The underlying theme was that new theories of spatial information were to be found in a fusion of cognitive science and mathematics. The Specialist Meeting for Initiative 2 was held in Santa Barbara, California, in January 1988 (Mark et al. 1989) and a preparatory meeting a few months before in Buffalo (Mark 1988).

Two years later, David Mark and Andrew Frank received a grant from the North Atlantic Treaty Organization (NATO) to conduct a two-week long Advanced Study Institute (ASI). Two weeks! Who would have time for that sort of thing today? But in 1990, we found 60 researchers from 13 countries and 16 disciplines who were more than willing to gather for two weeks in a lovely castle in a somewhat isolated town in Spain, to discuss cognitive and linguistic aspects of geographic space. We found much in common among our research interests and goals. Unfortunately, several of the most prominent and influential invited lectures at the ASI, including George Lakoff, Zenon Pylyshyn, and Leonard Talmy, chose not to submit chapters for the resultant book. However, their ideas permeated the conference, and many of the chapters in the book (Mark and Frank 1991) have been well cited and influential. A community of scholars was born at Las Navas, a community that subsequently has held 11 conferences with fully-refereed proceedings volumes published by Springer (the *COSIT* series), that founded a journal (*Spatial Cognition and Computation*), and that re-convened 20 years later in the same castle for a meeting that produced this volume.

2 What Did We Know? What Influenced Us?

2.1 Geography

The influence of the Quantitative Revolution in the social sciences is difficult to overestimate. Waldo Tobler, a prominent member of the "quantitative revolution" who completed his Ph.D. in Seattle as part of the group that started the Quantitative Revolution in geography (with William Bunge, Duane Marble, Brian Berry, Michael Dacey, Richard Morill, John Nystuen, and Arthur Getis, among others) and who contributed to the NCGIA as senior scientist, studied the transformation of real space to other conceptualizations of space. In his dissertation (Tobler 1961), for example, Tobler used transportation cost as a distance measure and then investigated geometric properties of the resulting space. The dream of transformations of physical (Euclidean) space to better represent the mental concepts of people (e.g., mental maps) was shown later in Gould and White (1986). The approach was inspired by Einstein's work, where space and geometry are defined such that they include the distribution of matter; the formulae describing physical processes, e.g., light rays, become simpler in this geometry. Tobler pioneered cartograms, which show, for example, the countries of the world with area corresponding to their population and communicate a very different message than the ordinary world map where country size corresponds to land area, often seriously deformed by map projections.

We knew that maps were not automatically "true" depictions of reality and that bias in maps and cartography is sometimes used to establish power relations (Harley 1989; Monmonier 1991). Some of us knew about "post structuralism" (Derrida 1978) and Harvey's "critical geography" (Harvey 1990), but we felt that a focus on the underlying aspects, firstly, the physical and geometric, and secondly, the neural cognitive aspects, would be warranted before moving towards economics and power.

Lynch (1960) gave a description of a city from a "user's perspective" and listed conceptually salient spatial elements, which structured space differently than Euclidean geometry and we felt a generalization of these ideas could advance geographic thinking in general and GIS software in particular.

2.2 Geometry

A GIS must include methods to represent geometric aspect of the physical world. Couclelis and Gale (1986) differentiated a single naive concept of 'space' into multiple conceptualizations, from physical to biological and finally to perceptual, and they connected the conceptualizations to algebraic structures. Two major approaches were used and are still used today: raster and vector representations; these were considered hardly integratable, and there was special software for either representation and conversion fraught with errors (Peuquet 1984). Early work by Peucker, Mark, and their colleagues focused on data structures for representation of terrain as discrete Triangulated Irregular Networks (TIN) (Peucker et al. 1978). Palmer and Frank (1988) identified the issues in discrete representations when they become finer and finer—comparable to the problem of the Greek philosophers wondering whether the fast running Achilles was ever capable of overtaking the slow turtle.

The practical issues of discrete finite representations being incapable of representing Euclidean geometry precisely was resolved by the practice of storing topology explicitly and never computing the same topological fact from coordinates twice, thus avoiding inconsistency (Frank and Kuhn 1986); a more fundamental justification was given by Knuth (1992). Despite the fact that some commercial systems used related approaches, the method did not become popular in practice, however.

Egenhofer (1989) in his Ph.D. thesis had given a succinct classification of topological relations but similar methods for other spatial relations were missing. At the Las Navas conference, Freksa (1991) and Hernández (1991) presented founding papers on what later became *qualitative spatial reasoning*. These two papers are the most frequently cited chapters from the Las Navas 1990 book.

2.3 Cartography

Cartography has the goal of communicating spatial (geographic) situations. As mentioned in Sect. 2.1, Tobler pioneered the use of cartograms, especially the value-by-area variety, to communicate spatial properties other than position and size in space (Tobler 1986). Bertin (1967) had earlier separated the cartographic language in several cartographic variables and Head and Schlichtmann showed how to apply concepts of transformational grammar to cartography (Head 1984; Schlichtmann 1985).

It was apparent in the 1980s that users could submit queries to a GIS and expect a map as an answer; this asked for languages to describe the desired appearance of the map and its content (Frank 1982). Conditions for objects to be selected and shown on a map should not only be formulated as conditions on object attributes (e.g., "all cities with more than 200,000 inhabitants") but also by geometric conditions (e.g., "all cities on rivers"); there also would need to be room on the map for the names of places or features. This required a language for describing spatial conditions for user-driven mapping connected to the questions of qualitative spatial reasoning and human spatial cognition. Spatial query languages, the definitions of geometric and topological conditions and, ultimately, their standardization, were hotly debated issues (Raper and Bundock 1991).

2.4 Language and Cognition

George Lakoff's (1987) book "Women, Fire and Dangerous Things" provided inspiration for us around the beginning of our efforts on formalizing spatial relations and language. Three points appeared to be especially important for GIScience:

- The semantics of human natural languages give us a window into understanding how humans conceptualize space. This point was made originally by Whorf (1956) and then by Jackendoff (1983). The title of Leonard Talmy's (1988) paper "How Language Structures Space" suggested a distinctly Whorfian implication, but Talmy denied this. Other readings appeared possible, and this led to intense discussion with Len in Las Navas.
- Image schemata as a simple, cognitively and even neuronally justified mechanism pointed to a foundation for the description of semantics for more complex situations.
- Experiential realism suggested an attractive method to give meaning to geographic terminology and to avoid circular definitions, as they occurred occasionally in standards for data exchange.

Experimental psychology informed us about another research method that could be used to understand human spatial cognition. The article by Stevens and Coupe (1978) became a landmark, as it showed systematic errors in human reasoning about space and spatial situations; it suggested a cognitive model different from Euclidean geometry. The influence of hierarchical containment (Hirtle and Jonides 1985) and alignment seemed formalizable—although, 20+ years later, such a formalization has not yet been published! The difference between the "correct" (Euclidean) reasoning and the results of human reasoning could systematically reveal something about human spatial cognition: the effects of alignment and containment. These ideas linked intuitively to Talmy's use of "topology" to describe linguistic phenomena: how to differentiate "along" from "across", which are the same relationships in mathematical topology. It appeared interesting to try to understand in what sense a linguistic-cognitive topology compares to the mathematical concept. This seemed to connect back to discussions earlier in the twentieth century, especially influenced by the Vienna Circle (Wiener Kreis) (Blumenthal 1986; Blumenthal and Menger 1970; Carnap 1922, 1960).

2.5 Data Structures, Semantics and Ontology

The database literature (Codd 1970, 1979, 1982; Lockemann and Mayr 1978) mentioned the connection between the data structure and the meaning of the data. Several articles had discussed the logic to be used for interpreting a collection of data and queries (Gallaire et al. 1984; Reiter 1984). In his Ph.D. thesis, Frank (1983) had indicated that the data structures expressed as Entity-Relationship diagrams represented some (static) aspects of semantics. The database literature, especially Kent (1978), stressed that a database schema was a conceptualization of a part of the world connected to the philosophical notion of Ontology. François Bouillé presented similar ideas in his dissertation and derived publications (Bouillé 1976), and Mark (1979) advocated "phenomenon-based data structuring" for elevation data. Ontology strives to give a true description of the world, which appeared at odds with the observed differences between conceptualizations and database schemas for different purposes. Wittgenstein's (1960) theories on semantics did not increase our optimism that a universal description could be achieved.

2.6 Formalization: Mathematics

A hallmark of the Quantitative Revolution in geography was to push for clarity and mathematical precision; quantitative descriptions were expected. The use of computers for storage and manipulation of geographic information was evident and the need for programs to select data from collections and display them in an intelligible fashion was high. Computer programs are instructions in a formal language and thus are akin to mathematical formulae. We assumed that quantitative approaches were possible and observed others stressing spatial analysis and spatial statistics, but were also warned that "numbers would not be sufficient" to capture the variation found in the world. How can one capture the meaning of words, or the structure of the real world, in mathematical formulae? Approaches using logic (Clocksin and Mellish 1981; Kowalski 1979; Sernadas 1980) had been tried and found insufficient for the Open World Interpretation (Reiter 1984) necessary for GIS and some of us had turned to abstract data types (Ehrich 1981; Goguen et al. 1975; Guttag and Horning 1978; Liskov and Zilles 1974) and algebraic specifications, advanced by some mathematically minded computer scientists. Herring et al. (1990) had earlier pointed to the use of category theory, but the step from a static logic description to algebraic specifications with operations was already difficult, and it was also difficult to convince others of the usefulness, even though the concept of "universal algebra" had been introduced by Whitehead (1898).

3 Organization of the 1990 Workshop

The workshop of two weeks lengths was very different from the 2 to 3 days workshops common then and today; perhaps it is more comparable with today's summer schools, which may last for a week or two. Unlike most summer schools, however, the difference between "instructors" and "participants" at the 1990 ASI was in the organizers' minds mostly as a formal differentiation to satisfy the NATO organizational requirements.

At the meeting, the single lectures were substantial, with enough time for discussion and debate; in general, discussions were allowed to run as long as it was of general interest, and smaller group discussions were moved to the long and productive breaks. The nice weather, the generous spaces in the building, and the excellent coffee prepared by Jesús contributed to fruitful discussions. Between the morning and the afternoon session we introduced a long break for a leisurely lunch with long debates, and later a siesta or a walk or both. Work resumed only in the late afternoon, when the midday heat had dissipated.

The balance between the disciplines present was reasonable, despite the fact that one-third of the participants were nominally geographers, and computer scientists, with 12 participants, were the second largest group; such nominal statistics are according to the names of the departments the participants were affiliated with and did not account for the diverse and broad disciplinary interests of the participants. Fortunately, no disciplinary group was strong enough to impose its terminology on the meeting, and all struggled to understand each other, because of serious differences in the terminology. A problem emerged in 1990, when we observed that the use of English as the language of communication reduced contributions by some participants; a special effort was made to organize a "Romance Language Table" to hear the perspective from the southern European countries in their own voices and languages. At the time, some of us wondered if the problem of English-language dominance pervaded GIS software itself, since most of the widespread GISs had been developed in countries where English or German were the dominant languages. Campari's (1991) book chapter was an outcome of this discussion, and a research effort to understand the dependency of GIS on cultural and linguistic specifics emerged, although it largely remained dormant until the most recent decade.

4 Citations and Other Impacts of the 1991 Book

On March 6, 2012, we checked citation counts for the chapters in the 1990 Las Navas book on Google Scholar. Thomson Reuters "Web of Science" has higher quality control, but Google Scholar has more extensive coverage of publications in computer and information science outlets. The results are reported in Table 1. As of March 2012, the book and its chapters had at total of 906 citations, and had an H-index of 13. In this section, we will comment on the most-cited chapters and on the pattern across major fields or subdisciplines represented in that book.

4.1 Citation Frequency by Section

The 1991 book was divided into six sections, and each section had some introductory pages written by the editors. To some extent, the section topics and titles reflect the important subtopics of the time, as filtered through the participant

Table 1 Chapters in the 1991 Las Navas book, ranked by citation counts from Google scholar on March 6, 2012

Chapter section and number	Author(s)	Chapter title	Google scholar citations
5.3	Freksa	Qualitative spatial reasoning	203
–	Mark and Frank	Cognitive and linguistic aspects of geographic space [the whole book]	118
5.4	Hernández	Relative representation of spatial knowledge: The 2-D case	91
6.1	Kuhn and Frank	A formalization of metaphors and image-schemas in user interfaces	89
5.1	Herring	The mathematical modeling of spatial and non-spatial information in geographic information systems	79
3.2	Gluck	Making sense of human wayfinding: Review of cognitive and linguistic knowledge for personal navigation with a new research direction	56
3.3	Blades	Wayfinding theory and research: The need for a new approach	45
1.1	Nunes	Geographic space as a set of concrete geographical entities	45
3.4	Freundschuh	The effect of the pattern of the environment on spatial knowledge acquisition	25
3.1	Blades	The development of the abilities required to understand spatial representations	24
6.3	Raper and Bundock	UGIX: A layer based model for a GIS user interface	19
4.1	Head	Mapping as language or semiotic system: Review and comment	18
1.2	Campari	Some notes on geographic information systems: The relationship between their practical application and their theoretical evolution.	13
6.4	Egenhofer	Deficiencies of SQL as a GIS query language	12
6.6	Jacobson	Virtual worlds, inside and out	12
2.1	Catedra	“Through The Door”: A view of space from an anthropological perspective	8
5.5	McGranaghan	Matching representations of geographic locations	8
5.6	Worboys	The role of modal logics in the description of knowledge in a geographic information system	6
4.4	Edwards	Spatial knowledge for image understanding	5
6.2	Gould	Elicitation of spatial language to support cross-cultural Geographic Information Systems	5
3.6	Pratt	Path finding in free space using sinusoidal transforms: III	5
3.5	Gentry and Wakefield	Methods for measuring spatial cognition	4

(continued)

Table 1 (continued)

Chapter section and number	Author(s)	Chapter title	Google scholar citations
4.2	Schlichtmann	Plan information and its retrieval in map interpretation: The view from semiotics	4
2.2	Bjorklund	Culture as input and output of the cognitive-linguistic processes	3
5.2	Chan and Tomlin	Map algebra as a spatial language	3
6.5	Joao	The role of the user in generalization within geographic information systems	3
2.3	Kas	Dialogic and argumentative structures of bumper stickers	1
1.3	Philbrick	A hand-in-glove paradigm for geography.	1
4.3	Varanka	An approach to map/text interrelationships	1
	Total		906

list of the ASI and the particular mix of papers that needed to be placed in sections. The section titles were:

1. Geographic Space
2. Cultural Influences on the Conceptualization of Geographic Space
3. Wayfinding and Spatial Cognition
4. Cartographic Perspectives
5. Formal Treatment of Space in Mathematics
6. User Interfaces and Human–Computer Interaction.

The section on "Formal Treatment of Space in Mathematics" had by far the highest mean citation rate per chapter in the March 2012 Google Scholar data, with an average of 65 citations per chapter. It seems that the fields of Geographic Information Science and Spatial Information Theory were ready for theory and formalization of this topic at that time, and that some of these chapters were foundational for their topics. The section with the second-highest mean citation rate per chapter was the "Wayfinding" topic with 26.5 citations per article, and the HCI section, which averaged 23.3 citations. The opening section ("Geographic Space") emphasized Ontology before that term began to be used in information science, and its chapters were cited on average 19.7 times. The chapters in the 1990 book on "Cultural Influences" and "Cartographic Perspectives" have received little subsequent interest in the literature, with averages of only 4 citations and 7 citations per chapter, respectively. Some of these differences might even relate to the relative emphasis on refereed journals versus book chapters and conference proceedings in the associated disciplines.

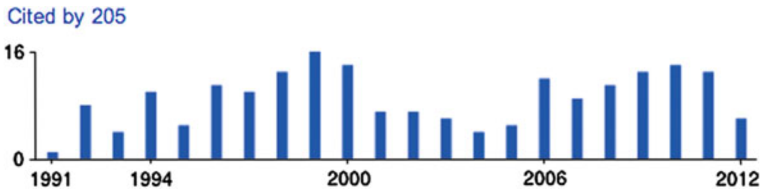

Fig. 1 Year by year citation frequency for Freksa's chapter in the 1990 book

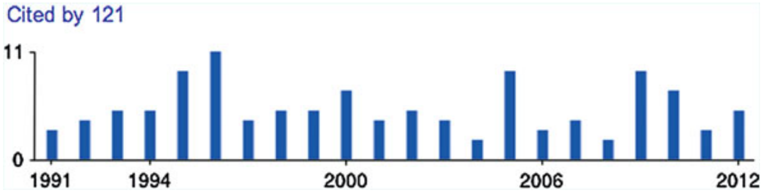

Fig. 2 Year by year citation frequency for the entire 1990 book

4.2 Citations of Selected Individual Chapters

As mentioned above, the most frequently-cited chapter in the book is the one written by Christian Freksa (1991), which had been cited 205 times up to the date of the citation counts. Figure 1 shows the temporal sequence of citations to Freksa's chapter.

The time sequence histogram clearly shows two peaks, one around 1999 and the other peaking in 2010. It may be a complete coincidence, but Christian Freksa hosted the COSIT meeting held in Stade, Germany, in 1999, and the 20th anniversary Las Navas meeting was held in 2010. According to Google Scholar, only two of Christian Freksa's other publications have been cited more often than his Las Navas chapter.

The second most cited publication is the total book itself (Fig. 2). What makes an author cite a whole edited book rather than its individual chapters? Perhaps a wish to acknowledge the role of the meeting itself in the field? The citation pattern for the whole book is rather different than that for Freksa's chapter, with the over-all peak relatively early, in 1996, and with more irregular ups and downs since then.

The second-most frequently-cited chapter was another qualitative reasoning chapter, by Hernández (91 citations), a student of Freksa's. This was followed in frequency by two other formalization papers, by Kuhn and Frank (89 citations) and by Herring (79 citations). Clearly, the dominant contribution of the Las Navas 1990 book was in the area of formalization of geographic and spatial principles and concepts.

Following the pattern noted for sections are two chapters on wayfinding and navigation (Gluck 56 citations; Blades 45) and then Nunes' chapter on what we would now call ontology (45 citations). There is somewhat of a break in the relative frequency, with the next highest citation number for a chapter being 25.

5 What We Have Learned Since 1990

Almost as soon as the 1990 Las Navas ASI ended, the term "Spatial Information Science" was introduced by Michael Goodchild in a keynote address at an international meeting that began just a few days later at the SDH conference in Zurich. Goodchild changed the name to Geographical Information Science when the lecture was published two years later in the *International Journal of Geographical Information Systems* (Goodchild 1992).

Research in Geographic Information Science during the last two decades has been very active. The technological development increased not only the processing power and the storage capacity of the computers we use for GIS, but in addition, three technological breakthroughs made the widespread use of geographic information possible. Today, it is difficult to imagine, or to remember, the state of affairs 20 years ago: email and ftp were available, but there was no World Wide Web, and few if any laptops or mobile wireless devices, which we now use on a daily basis including various location-based applications (Raubal 2011). Use of computers to access information was the domain of engineers, scientists, and a few professions. Crude maps and instructions for wayfinding were available, but not in widespread use. The 3G (HSPA) standard for data transfer on mobile phone networks appeared only in 2001!

In 1990, we expected mostly public agencies and possibly some major companies to use digital geographic information and most of us did not even imagine the use made today, when everybody has access and uses occasionally GIS capabilities in their car to navigate, at home to plan business trips and vacations, etc. The commercially distributed applications based on geographic information put in evidence the needs for the research outlined 20 years ago: query languages for spatial data, intelligent mapping software, descriptions of the meaning of data, etc., are all crucial elements of today's information products.

5.1 Geography

The influence of the observer on the observation, the classification and the encoding of what is in reality, is now clearly recognized, and the illusion of an "objective" depiction of reality "as it is" has been shown to be somewhat naive; some types of observations are more likely to be "objective"—in the sense of inter-subjectively comparable—the height of the peak of a mountain is easier to determine than the distribution of poverty in a country! Only naive users of GIS believe that what a GIS depicts is THE TRUTH; one must assess the source of information on the web as critically as any other information obtained, e.g., from a newspaper. The question of data quality becomes important and attention is linked to standards such as the Dublin Core to document the "classic" metadata elements, describing the data, but not including data quality descriptions. ISO 19115 "international metadata standard for geographic information" addresses these issues, but practice is lacking (Boin 2008; Boin and Hunter 2007a, b).

The issue of scale (Montello 2001), clearly very important, was addressed in another NCGIA research initiative from the viewpoint of remote sensing, producing a book (Quattrochi and Goodchild 1997), which in its introduction connected scale to processes.

5.2 Geometry

One of the authors of this chapter believes that one of the most serious errors in the research approach used at the NCGIA was that we assumed that space and spatial concepts could be dealt with independent of time, and before addressing time—which was scheduled as a separate NCGIA research initiative to start several years later (Egenhofer and Golledge 1994, 1998). It appears today that for many applications and processes, movement is crucial, not only at the perceptual level, where stereo-vision is difficult without movement, but at every level of cognitive processing of spatial information. Discussing movement means dealing with space and time simultaneously (Hägerstrand 1975; Hornsby and Egenhofer 2000; Mau et al. 2007; Medak 1999). The relative success with abstract data types, i.e., an algebraic kind of specification for semantics and the disenchantment with temporal and model logics (Worboys 1991) led us to concentrate on algebras and lately on category theory as a unifying concept for different parts of mathematics (e.g., topology, metric) in GIScience.

A big success for this research community since 1990 was the development of qualitative spatial reasoning, with many publications on the topic. As mentioned earlier, the article by Freksa (1991) is the most cited chapter from the Las Navas book and with the publication by Egenhofer and Franzosa (1991) started an extensive trail of research and eventually led to the inclusion of these formalizations into the SQL query language standard [ISO/IEC 13249-3:1999, Information technology—Database languages—SQL Multimedia and Application Packages—Part 3: Spatial]. The concept had been reformulated in logic by Randell et al. (1992) and became in this form an enormously popular starting point for further research in spatial reasoning.

5.3 Cartography

In 20 years since the first Las Navas meeting, cartography underwent a complete change, from manual scribing of originals and photographic darkroom work to computer-produced maps on demand. In 1990 there were university courses called "Computer Cartography". Now, people might ask how else maps could be produced! The technical opportunities for computer driven graphic production and the distribution of map graphics on the web transformed cartographic business and research. A second wave of challenges has originated from the possibilities of rapid interaction with web generated content (the so called Web 2.0). Continuous discussion occurred in a number of specialized conferences (primarily in the new series Springer Lecture Notes in Geoinformation and Geography, edited by Cartwright, Gartner, Meng and Peterson). Fundamental questions of communication and representation of spatial situations were addressed separately.

5.4 Language and Cognition

The ground-breaking volume on Language and Space by Jackendoff (1996) collected many of the ideas influencing work in GIScience. The work by Berger and Luckmann (1996) and Searle (1995) on construction of concepts in the social realm was most helpful for understanding the context-dependence of concepts, an idea that Fleck (1981) published already in 1935, which are the result of social processes and thus also may change over time (Raubal 2008). Starting with Campari's article (Campari 1991), a discussion on effects of cultural differences or the universality of other concepts raised the awareness for multi-language and multi-cultural situation of the world in general and the context dependence of descriptions (Montello 1995; Montello and Xiao 2011). The application of quantum mechanics as a theory to deal with prototype effects and context in general was recently proposed (Gabora et al. 2008) and a special issue on quantum mechanics applied to cognitive science was recently published (Bruza et al. 2009).

5.5 Data Structures, Semantics and Ontology

The definition of ontologies as formalizations of "conceptualizations" has become commonplace in information engineering (Guarino 1995) and specific proposals for GIS have been discussed (Couclelis 2010; Frank 2001). Kuhn and his co-workers have pointed out that grounding of terms, along the lines of experiential realism, can be achieved (Scheider et al. 2009). The use of Resource Descriptor Framework (RDF) triples has become popular as a way to describe relations and capture semantics in a simple formalism, which can be effectively processed; surprisingly large collections of descriptions of semantics are available on the web. The connection between natural language expressions and formalizations of spatial relations was shown by Tenbrink and Kuhn (2011).

Research on data quality is reported in a series of proceedings of several conferences (Shi et al. 2002) and later by (Devillers et al. 2006) among others. A connection between ontology and data quality was established by Frank (2007).

The past 20 years were dominated by relational databases and the technical solutions of major commercial or open-source software, which over time included spatial access methods and geometric data types. A conference series "Advances in Spatial Databases" started in 1989 (Günther 1999) and was later renamed to "Advances in Spatial and Temporal Databases".

5.6 Formalization: Mathematics

The use of object-oriented design has become mainstream in software engineering, despite the fact that serious restrictions and practical difficulties have been discovered theoretically (Abadi and Cardelli 1996) and the most commonly used approaches are quite informal and lack automatic checking. The next step of abstraction, progressing from algebra to categories (Asperti and Longo 1991) is slowly gaining acceptance in the GIScience community (Frank 1999).

The formalization of taxonomies with logic based methods is well established and powerful tools, e.g., Protégé, are used, producing research ontologies in the standardized OWL format. Logic based approaches limit, however, the formalization of processes.

6 Future Research

Some of the major research questions which were identified at Las Navas 1990 are still major challenges in GIScience: Hierarchies, movement and temporal data, communicating meaning, and defining semantics across cultural and language boundaries are some of the most prominent of these challenges—as also demonstrated by several of the chapters in this book.

Las Navas 1990 did not concentrate on topics related to social effects of Geographic Information, as we did not envisage the widespread use encountered today. Societal issues were reviewed around that time at another NATO meeting (Masser and Onsrud 1993), but societal impacts have changed drastically as wireless networked information devices become almost ubiquitous in developed countries. When Geographic Information was being used mostly in public agencies, issues such as privacy, quality of data, copyright etc. did not play the dominant role which they do today. The immensely popular and commercially successful social networks gradually have embraced spatial information, and the new phenomena of "crowd sourcing"—specifically Volunteered Geographic Information (Elwood et al. 2012)—create new problems and opportunities for research.

7 Outline of the Remainder of this Book

The remainder of this book consists of 14 chapters written or co-authored by participants at the Las Navas 2010 meeting. Each of these chapters was thoroughly reviewed by 2 international experts and the editors of the book. Based on the reviews we had to reject 2 chapters out of the initial 16 chapter submissions. The chapters provide both a snapshot in time regarding research on cognitive and linguistic aspects of geographic space, and also provide new perspectives on geographic information research in the twenty-first century. Below we provide summaries of the chapters in the order they appear in the book.

Chapter "How Spatial Structures Replace Computational Effort" by Freksa investigates whether all spatial problems are necessarily dealt with in a geometric form, i.e., if we always have to transform a spatial question into a problem formulated in terms of coordinates. The expectation in 1990 was that we would find methods for representation and processing of spatial situations other than the well-known coordinate based geometry, which has substantial drawbacks. The chapter reviews the different qualitative spatial reasoning methods, most of which were published after 1990, and shows a system that integrates these calculi in a qualitative spatial reasoning toolbox (SparQ). It ends with the discussion of 'spatial computing' where the spatial configuration is used to find a solution quickly.

Chapter "The Cognitive Development of the Spatial Concepts NEXT, NEAR, AWAY and FAR" by Freundschuh and Blades concentrates on few specific spatial concepts with respect to distance, namely NEXT, NEAR, AWAY and FAR; unlike previous studies, the authors report about results obtained with children between 3 and 9 years of age (and an adult control group) in both, a tabletop space and a large model space. The results corroborate that children, at least from the age of 7, differentiate between these four distance locatives, confirming the theories of Piaget and Inhelder as well as those by Huttenlocher and Newcombe. The difference between the tabletop and the large model space were observable, but not statistically significant; more research is required. The interesting question, whether younger children do not differentiate between NEXT and NEAR or AWAY and FAR remains also open for future studies along the same lines.

Chapter "From Compasses and Maps to Mountains and Territories: Experimental Results on Geographic Cognitive Categorization" by Giannakopoulou and co-authors reports on the repetition of an experiment, originally done to explore geographic categorization. It tried to identify whether there are significant differences between Greek speakers and Americans on the one side, and experts and non-experts on the other side. The identification of cultural differences between Greeks and Americans were not easily detectable, as some details of the experimental setup were slightly different and made the results hard to interpret (but the differences seem to be small). Interesting to note is the difference in the responses between experts and non-experts, where non-experts listed for 'geographic phenomenon' mostly concepts from physical geography whereas experts listed concepts from human geography. Likewise for 'geographic relations' the non-experts listed cardinal directions and similar items, whereas experts often listed topological relations.

Chapter "Prospects and Challenges of Landmarks in Navigation Services" by Richter focuses on the importance of landmarks for structuring and understanding space, with a particular emphasis on their use in navigation services. Although research over the past decades has produced methodologies and computational approaches for automatically identifying landmarks to be integrated in navigation services, its impact on commercial services has been low. Based on a categorization of approaches that distinguishes between landmark identification and landmark integration, Richter analyses why this is the case and thereby identifies several challenges that need to be addressed. User-generated landmark content is identified as a promising way to move landmark-based navigation systems forward in the future.

In chapter "Landmarks and a Hiking Ontology to Support Wayfinding in a National Park During Different Seasons", Sarjakoski and co-authors discuss the use of landmarks in wayfinding; multiple studies have demonstrated the importance of landmarks in wayfinding and route descriptions, but most studies were done in cities. The authors investigate the use of landmarks in outdoor wayfinding, specifically hiking in Finland. Their experiments consider the different appearances of the natural environment in summer and winter, when snow covered. They find that people report different types of landmarks in summer and winter: participants mentioned more often 'passages' (roads, path, path crossings, etc.) in summer than in winter; in winter, however, more references to landforms were used. Their findings correspond to the general observation that salience of a landmark is a relative property. In the last part of the chapter, the authors attempt an ontology for landmarks when hiking; this is an important step forward in organizing data to automatically produce wayfinding instructions including references to landmarks.

In chapter "Talking about Place Where it Matters", Winter and Truelove discuss the requirements for fully-natural interaction between users and devices regarding spatial information. After describing the problem as having comprehension and production aspects, the chapter focuses on the interpretation of spatial queries, with examples from Google for places in the Melbourne, Australia, area. They find that Google's query parser sometimes misinterprets queries that contain cardinal direction modifiers. The chapter concludes with a proposed research agenda for dealing with place in information systems.

Chapter "Many to Many Mobile Maps" by Hirtle and Raubal reviews the rapid expansion of geo-located mobile devices capable of providing or replacing maps. Technology has made drastic changes to how people can access geographic information in real time. Such information is generated not only by traditional sources but also by social networks or geowikis. Despite the benefits, which the paradigm of 'many to many mobile maps' has created for its users, there are also new challenges and problems to be solved, such as human–computer-environment interaction, personalization and context, and the impact on people's spatial learning. The chapter closes with a discussion of the future of maps.

In chapter "Cognitive and Linguistic Ideas in Geographic Information Semantics", Kuhn reviews cognitive and linguistic ideas that have been applied in research on the semantics of geographic information. Las Navas 1990 seemed to be a starting point for many researchers in GIScience and related disciplines for taking such ideas and applying them to the formalization of semantics in information systems. The chapter begins with defining the problem of semantics and then describes each of the ideas—covering experiential realism, geographic information atoms, reference systems, semantic datum, similarity measurement, conceptual spaces, meaning as process, and constraining the process of meaning—and the insights gained during the last two decades. Based on this understanding the author speculates on where this research will be leading to in the future.

Chapter "Spatial Relation Predicates in Topographic Feature Semantics" by Varanka and Caro investigates the semantics of spatial relation predicates with respect to topographic features. Spatial relations are a major component of geographic analysis but many of them lack a formalization of their semantics. The authors address this problem by typifying spatial relation characteristics of topographic features via a linguistic analysis of definitions. Topographic feature definitions were analyzed with respect to their spatial aspects in order to identify relation concepts for developing a vocabulary of semantic web triples. The specific motivation for this research concerned the future development of reasoning algorithms for The National Map of the U.S. Geological Survey, but the study was designed so that its results would be applicable to any topographic map.

In chapter "The Egenhofer-Cohn Hypothesis: or, Topological Relativity?" entitled 'The Egenhofer-Cohn Hypothesis—or, Topological Relativity?', Alexander Klippel and his co-authors review various cognitive and behavioral evidence regarding the validity and adequacy of two qualitative reasoning models of spatial relations. They describe an Egenhofer-Cohn Hypothesis that topology is most important and geometry refines, and find that data do not support a strong version of that hypothesis. They also discuss implications of the model for dynamic spatial situations.

Chapter "Twenty Years of Topological Logic" by Pratt-Hartmann continues with qualitative spatial reasoning and starts with the expressiveness of languages to describe topological relations. It then discusses reasonable restrictions on spatial regions. Most innocent looking mathematical definitions include regions with infinitely many components and other strange behavior. A fundamental problem for logical treatment of spatial relations between regions is to restrict regions to what is geographically meaningful. The chapter also addresses the expressiveness of different sets of topological relations, considered as logic first without quantifiers (i.e., constraint languages) and second with the usual existential and all quantifier. One of the interesting insights gained is that RCC8 or the equivalent 9-intersection model is insensitive to the number of dimensions and the same relations hold in spaces of any dimension.

In chapter "Reasoning on Class Relations: an Overview", Mäs presents an account of reasoning over classes (rather than over instances), using spatial reasoning as a domain. Explicit knowledge about logical properties and interrelations between relations is fundamental for automated reasoning based on semantic data descriptions. The author argues that the formal definition of class relations and their logical properties has not been sufficiently addressed yet. Reasoning over class relations is different to reasoning over instances because cardinality restrictions must also be considered. The chapter summarizes current research with regard to class relation reasoning based on properties such as symmetry, composition, and conceptual neighborhood. The author also discusses potential application areas and identifies directions for future work such as dependencies of class relations in class hierarchies.

Chapter "Creating Perceptually Salient Animated Displays of Spatiotemporal Coordination in Events" by Shipley and his co-authors points to an important problem in visualization, namely that approaches which focus on individual spatiotemporal phenomena in isolation are cognitively inadequate because they omit the relational structure that humans use in order to process and reason about events. Humans mostly care about the complete picture and only rarely look at spatio-temporal entities in isolation. Starting with their thoughts on animations, perception of movement, and visualizations, the authors then highlight implications for animation design. There is a strong need for perceptually salient and cognitively inspired animated displays that help humans more effectively and efficiently in detecting relationships in complex events.

In chapter "Exploring and Reasoning about Perceptual Spaces for Theatre, New Media Installations and the Performing Arts", Edwards and his co-authors present an exciting and innovative approach for bringing together GIScience and the performing arts. Perceptual models to support qualitative spatial reasoning are extended to model soundscapes. The authors present a new model that draws on the Huygen's Principle of Wave Propagation to supplement the earlier models with a component that handles sound. The resulting space segmentation was actually worked out and tested with the narrative structure of Homer's Odyssey, which was demonstrated through a real-time performance at Las Navas 2010 involving various virtual sound sources that move around in space.

8 Conclusions

Las Navas 2010 clearly demonstrated that Cognitive and Linguistic Aspects of Geographic Space is still a vibrant research area within Geographic Information Science. This chapter reflected on what was known at the time of Las Navas 1990, what happened between Las Navas 1990 and 2010, and also provided some thoughts on what the future might bring.

The research situation today is changed compared with what it was in 1990. The chapter discussed these changes, some originating from the outside of GIScience, some in GIScience proper, and some even originating from the discussions in Las Navas. Interesting is the question, which direction research should take. Interdisciplinary approaches are still necessary, bridging between the disciplines and areas of geography, geometry, cartography, language and cognition, data structures, semantics and ontology, and computer science and mathematics. Special challenges are likely posed by topics such as hierarchies, movement and temporal data, communicating meaning, and defining semantics across cultural and language boundaries, as demonstrated by a number of chapters in this book. Several chapters of the 1991 book had a strong impact over the years on these topics and we hope this will also be the case for the chapters in the present book.

References

Abadi M, Cardelli L (1996) A theory of objects. Springer, New York

Abler R (1987) The National Science Foundation—National Center for Geographic Information and Analysis. IJGIS 1(4):303–326

Asperti A, Longo G (1991) Categories, types and structures: an introduction to category theory for the working computer scientist. The MIT Press, Cambridge
Berger P, Luckmann T (1996) The social construction of reality. Doubleday, Garden City
Bertin J (1967) Sémiologie graphique. Mouton/Gauthier-Villars, Paris
Blumenthal L (1986) A modern view of geometry. Dover Publications Inc, New York
Blumenthal L, Menger K (1970) Studies in geometry. W.H. Freeman and company, San Francisco
Boin A (2008) Exposing uncertainty communicating spatial data quality via the internet. PhD Thesis, The University of Melbourne
Boin A, Hunter G (2007a) Facts or fiction: consumer beliefs about spatial data quality. Paper presented at the spatial science institute biennial international conference (SSC 2007), Hobart
Boin A, Hunter G (2007b) What communicates quality to the spatial data consumer? Paper presented at the international symposium on spatial data quality 2007 (ISSDQ 2007), Enschede, The Netherlands
Bouillé F (1976) A model of scientific data bank and its applications to geological data. Comput Geosci 2:279–291
Bruza P, Busemeyer J, Gabora L (2009) Introduction to the special issue on quantum cognition. J Math Psychol 53(5):303–305
Campari I (1991) Some notes on geographic information systems: the relationship between their practical application and their theoretical evolution. In: Mark D, Frank A (eds) Cognitive and linguistic aspects of geographic space. Kluwer Academic Press, Dordrecht, pp 35–44
Carnap R (1922) Der Raum - Ein Beitrag zur Wissenschaftslehre. Reuther & Reichard, Berlin
Carnap R (1960) Einführung in die symbolische Logik mit besonderer Berücksichtigung ihrer Anwendungen. Springer, Wien
Clocksin W, Mellish C (1981) Programming in PROLOG. Springer, Berlin
Codd E (1970) A relational model of data for large shared data banks. Commun ACM 13(6): 377–387
Codd E (1979) Extending the database relational model to capture more meaning. ACM TODS 4(4):379–434
Codd E (1982) Relational data base: a practical foundation for productivity. Commun ACM 25(2):109–117
Couclelis H (2010) Ontologies of geographic information. Int J Geogr Inf Sci 24(12):1785–1809
Couclelis H, Gale N (1986) Space and spaces. Geografiska Annaler B, 68B(1):1–12
Derrida J (1978) Writing and difference. University of Chicago Press, Chicago
Devillers R, Jeansoulin R, Goodchild M (2006) Fundamentals of spatial data quality. Wiley Online Library, Hoboken
Egenhofer M (1989) Spatial query languages. Ph.D. Thesis, University of Maine
Egenhofer M, Franzosa R (1991) Point-set topological spatial relations. Int J Geogr Inf Syst 5(2):161–174
Egenhofer M, Golledge R (1994) Time in geographic space: report on the specialist meeting of research initiative 10. National Center for Geographic Information and Analysis (Vol. Report 94-9)
Egenhofer M, Golledge R (eds) (1998) Spatial and temporal reasoning in geographic information systems. Oxford University Press, New York
Ehrich H (1981) Specifying algebraic data types by domain equations. Paper presented at the FCT '81—1981 international fct-conference on fundamentals of computation theory
Elwood S, Goodchild M, Sui D (2012) Researching volunteered geographic information: spatial data, geographic research, and new social practice. Ann Assoc Am Geogr 103(3):571–590
Fleck L (1981) Genesis and development of a scientific fact. University of Chicago Press, Chicago
Frank A (1982) Mapquery: database query language for retrieval of geometric data and its graphical representation. ACM SIGGRAPH 16(3):199–207

Frank A (1983) Data structures for land information systems - semantical, topological and spatial relations in data of geo-sciences—in German. Ph.D. Thesis, Swiss Federal Institute of Technology

Frank A (1999) One step up the abstraction ladder: combining algebras—from functional pieces to a whole. In: Freksa C, Mark D (eds) Spatial Information Theory. Cognitive and Computational Foundations of Geographic Information Science COSIT'99, LNCS 1661:95–109, Springer-Verlag, Berlin, Heidelberg

Frank A (2001) Tiers of ontology and consistency constraints in geographic information systems. Int J Geogr Inf Sci 75(5):667–678 (Special Issue on Ontology of Geographic Information)

Frank A (2007) Data quality ontology: an ontology for imperfect knowledge. In: Winter S, Duckham M, Kulik L, B Kuipers (eds) Spatial information theory. Proceedings of the 8th international conference on spatial information theory, COSIT 2007, Melbourne, Australia, LNCS vol 4736. Springer, Berlin, pp 406–420

Frank A, Kuhn W (1986) Cell graph: a provable correct method for the storage of geometry. Paper presented at the second international symposium on spatial data handling

Freksa C (1991) Qualitative spatial reasoning. In: Mark D, Frank A (eds) Cognitive and linguistic aspects of geographic space. Kluwer Academic Press, Dordrecht, pp 361–372

Gabora L, Rosch E, Aerts D (2008) Toward an ecological theory of concepts. Ecol Psychol 20:84–116

Gallaire H, Minker J, Nicolas J-M (1984) Logic and databases: a deductive approach. ACM Comput Surv 16(2):153–185

Goguen J, Thatcher J, Wagner E, Wright J (1975) Abstract data types as initial algebras and the correctness of data representations. Paper presented at the conference on computer graphics, pattern recognition and data structures

Goodchild M (1992) Geographical information science. Int J Geogr Inf Sci 6(1):31–45

Gould P, White R (1986) Mental Maps. Allen & Unwin, Boston

Guarino N (1995) Formal ontology, conceptual analysis and knowledge representation. Int J Hum Comput Stud 43(5):625–640

Günther O (1999) Looking both ways: SSD 1999 ± 10. Paper presented at the SSD '99—6th international symposium on advances in spatial databases

Guttag J, Horning J (1978) The algebraic specification of abstract data types. Acta Informatica 10(1):27–52

Hägerstrand T (1975) Space, time and human conditions. In: Karlqvist A et al (eds) Dynamic allocation of urban space. Saxon House Lexington Book, Lexington

Harley J (1989) Deconstructing the map. Cartographica Int J Geogr Inf Geovisual 26(2):1–20

Harvey L (1990) Critical social research, vol 21. Unwin Hyman, London

Head C (1984) The map as natural language: a paradigm for understanding. Cartographica 21: 1–32

Hernández D (1991) Relative representation of spatial knowledge: the 2-D case. In: Mark D, Frank A (eds) Cognitive and linguistic aspects of geographic space. Kluwer Academic Press, Dordrecht, pp 373–386

Herring J, Egenhofer M, Frank A (1990) Using category theory to model GIS applications. Paper presented at the 4th international symposium on spatial data handling, Zurich

Hirtle S, Jonides J (1985) Evidence of hierarchies in cognitive maps. Mem Cogn 13(3):208–217

Hornsby K, Egenhofer M (2000) Identity-based change: a foundation for spatio-temporal knowledge representation. Int J Geogr Inf Sci 14(3):207–224

Jackendoff R (1983) Semantics and cognition. MIT Press, Cambridge

Jackendoff R (1996) The architecture of the linguistic-spatial interface. In: Bloom P, Peterson M, Nadel L, Garrett M (eds) Language and space. MIT Press, Cambridge, pp 1–30

Kent W (1978) Data and reality—basic assumptions in data processing reconsidered. North-Holland, Amsterdam

Knuth D (1992) Axioms and hulls. LNCS vol 606. Springer, Heidelberg

Kowalski R (1979) Logic for Problem Solving. The Computer Science Library: Aritificial Intelligence, vol 7. North Holland, Amsterdam

Lakoff G (1987) Women, fire, and dangerous things: what categories reveal about the mind. University of Chicago Press, Chicago

Liskov B, Zilles S (1974) Programming with abstract data types. ACM SIGPLAN Not 9(4):50–59

Lockemann P, Mayr H (1978) Rechnergestützte Informationssysteme. Springer, Berlin

Lynch K (1960) The Image of the City. The MIT Press, Cambridge

Mark D (1979) Phenomenon-based data-structuring and digital terrain modelling. Geo-processing 1:27–36

Mark D (1988) Report on a miniconference: cognitive and linguistic aspects of geographic space, State University of New York at Buffalo

Mark D, Frank A (eds) (1991) Cognitive and linguistic aspects of geographic space, vol 63. Kluwer, Dordrecht

Mark D, Frank A, Egenhofer M, Freundschuh S, McGranaghan M, White R (1989) Languages of spatial relations: initiative two specialist meeting report. National Center for Geographic Information and Analysis

Masser I, Onsrud H (1993) Diffusion and use of geographic information technologies. Kluwer Academic, Dordrecht

Mau I, Hornsby K, Bishop I (2007) Modeling geospatial events and impacts through qualitative change. Proceedings of the international conference on spatial cognition, spatial cognition 2006, vol 4387. Springer, Berlin, pp 156–174

Medak D (1999) Lifestyles—a paradigm for the description of spatiotemporal databases. PhD Thesis, Department of Geoinformation

Monmonier M (1991) How to lie with maps. The University of Chicago Press, Chicago

Montello D (1995) How significant are cultural differences in spatial cognition? In: Frank A, Kuhn W (eds) Spatial information theory: a theoretical basis for gis, vol 988. Springer, Berlin, pp 485–500

Montello D (2001) Scale in geography. In: Smelser N, Baltes P (eds) International encyclopedia of the social and behavioral sciences. Pergamon Press, Oxford, pp 13501–13504

Montello D, Xiao D (2011) Linguistic and cultural universality of the concept of sense-of-direction. In: Egenhofer M, Giudice N, Moratz R, Worboys M (eds) Spatial information theory—proceedings of COSIT ‘11, LNCS vol 6899. Springer, Heidelberg, pp 264–282

NCGIA (1989) The research plan of the national center for geographic information and analysis. Int J Geogr Inf Syst 3(2):117–136

Palmer B, Frank A (1988) Spatial Languages. Paper presented at the third international symposium on spatial data handling, Sydney

Peucker T, Fowler R, Little J, Mark D (1978) The triangulated irregular network. Paper presented at the american society for photogrammetry, Proceedings digital terrain models symposium

Peuquet D (1984) A conceptual framework and comparison of spatial data models. Cartographica Int J Geogr Inf Geovis 21(4):66–113

Quattrochi D, Goodchild M (eds) (1997) Scale in remote sensing and gis. Lewis Publishers, Boca Raton

Randell D, Cui Z, Cohn A (1992) A spatial logic based on regions and connection. Paper presented at the 3rd Int. conference on knowledge representation and reasoning

Raper J, Bundock M (1991) UGIX: a layer based model for a GIS user interface. In: Mark D, Frank A (eds) Cognitive and linguistic aspects of geographic space. Kluwer Academic Press, Dordrecht, pp 449–476

Raubal M (2008) Representing concepts in time. In: Freksa C, Newcombe N, Gärdenfors P, Wölfl S (eds), Spatial cognition VI—learning, reasoning, and talking about space. Proceedings of the international conference spatial cognition 2008, Freiburg, Germany, vol 5248, Springer, Berlin, pp 328–343

Raubal M (2011) Cogito ergo mobilis sum: the impact of location-based services on our mobile lives. In: Nyerges T, Couclelis H, McMaster R (eds) The Sage handbook of gis and society. Sage Publications, Los Angeles, pp 159–173

Reiter R (1984) Towards a logical reconstruction of relational database theory. In: Brodie M, Mylopoulos J, Schmidt J (eds) On conceptual modelling: perspectives from artificial intelligence, databases, and programming languages. Springer, New York, pp 191–233

Scheider S, Janowicz K, Kuhn W (2009) Grounding geographic categories in the meaningful environment. In: Hornsby K, Claramunt C, Denis M, Ligozat G (eds), Spatial information theory, 9th international conference, COSIT 2009, Aber Wrac'h, vol 5756. Springer, France, pp 69–87, 21–25 Sept 2009

Schlichtmann H (1985) Characteristic traits of the semiotic system 'map symbolism'. Cartographic J 22(1):23–30

Searle J (1995) The construction of social reality, The Free Press, New York

Sernadas A (1980) Temporal aspects of logical procedure definition. Inf Syst 5:167–187

Shi W, Fisher P, Goodchild M (2002) Spatial data quality. CRC, Boca Raton

Stevens A, Coupe P (1978) Distortions in judged spatial relations. Cogn Psychol 10:422–437

Talmy L (1988) How language structures space. In: Pich H, Acreolo L (eds) Spatial orientation: theory, research and application. Plenum Press, New York

Tenbrink T, Kuhn W (2011) A model of spatial reference frames in language. In: Egenhofer M, Giudice N, Moratz R, Worboys M (eds) Spatial information theory, proceedings of COSIT 2011, vol 6899. Springer, Berlin, pp 371–390

Tobler W (1961) Map transformations of geographic space. PhD Thesis, University of Washington

Tobler W (1986) Pseudo-cartograms. Cartography Geogr Inf Sci 13(1):43–50

Whitehead A (1898) A treatise on universal algebra. Cambridge University Press, Cambridge

Whorf B (1956) Language thought and reality—selected writing of Benjamin Lee Whorf. The MIT Press, New York

Wittgenstein L (1960) Tractatus logico-philosophicus Tagebücher, Philosophische Untersuchungen. Suhrkamp Verlag, Frankfurt

Worboys M (1991) The role of modal logics in the description of a geographical information system. In: Mark D, Frank A (eds) Cognitive and linguistic aspects of geographic space. Kluwer Academic Press, Dordrecht, pp 403–414

Spatial Computing

How Spatial Structures Replace Computational Effort

Christian Freksa

Abstract At the Advanced Study Institute on Cognitive and Linguistic Aspects of Geographic Space in Las Navas del Marqués in July 1990, I presented a chapter on *Qualitative Spatial Reasoning*. In that chapter, I suggested that spatial inference engines might provide the basis for rather general cognitive capabilities inside and outside the spatial domain. In the present chapter, I will follow up on this perspective and I will illustrate the ways in which research in spatial cognition has progressed towards understanding spatial reasoning and spatial computing in a more literal sense: using a spatial substrate. The chapter presents a progression of approaches to spatial reasoning from purely descriptive to increasingly spatially structured. It demonstrates how spatial structures are capable of replacing computational processes. It discusses how these approaches could be developed and implemented in a way that may help us to better understand higher-level spatial abilities of cognitive systems that are frequently attributed to the right cerebral hemisphere in humans. The chapter concludes by discussing the special role of space and time for cognition and advocates a thorough overall analysis of the specific problem to be solved to identify the most suitable approach to computation.

Keywords Spatial cognition · Spatial computing · Symbolic computing · Structure of space · High-level spatial abilities

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Lecture Notes in Geoinformation and Cartography, DOI: 10.1007/978-3-642-34359-9_2,

1 Spatial Problems

Let us consider examples of common spatial problems we might encounter. The problems are to be taken literally; i.e., no additional information is provided; missing information must be added from knowledge or assumptions about the environment.

1. Given the triangle ABC with the coordinates $A = (1, 3)$, $B = (9, 2)$, $C = (6, 8)$; is $P = (8, 4)$ inside or outside the triangle ABC?
2. (How) can I get the piano into my living room?
3. How do I get from here to John's place?
4. Which is closer: from here to John, or to Mary?
5. Is the tree on my property or on your property?
6. 

Problem 1 is a classic high school geometry problem which can be solved abstractly with linear equations; the correct algebraic solution will locate P on the line BC; numeric solutions may place P inside or outside the triangle, depending on the number format and algorithm chosen.

Problem 2 is a form of the classic *Piano Movers' Problem* in mathematics (Schwartz and Sharir 1983); although this problem can be represented geometrically, in practice it is rarely approached mathematically in the abstract representation domain but by trial and error in the physical problem domain.

Problem 3 cannot very well be presented in geometric terms; a graph structure that depicts the location 'here', John's place, and a traversable connection between them is more appropriate and often times preferable to a solution in the physical domain, particularly if John's place is far away.

Problem 4 typically does not require the mathematically correct solution, which may take a long time to determine. A quickly provided estimate tends to be more helpful, in practice.

Problem 5 is an example where a formal approach alone may not suffice. Although the boundaries of the properties will be defined in a legal document in terms of precise geo-coordinates, the real-world correspondence of the legal boundary may be too expensive to determine; therefore the correct boundary often is not known. In addition, it may not be clear where the branches and roots of the tree start and where they end, in formal terms.

Problem 6 (related to the Piano Movers' Problem) is not posed in terms of words or numbers but in terms of spatial objects (resp. an image thereof). It is a truly spatial problem presented physically to small children who will try to fit the small colored objects into the openings of the wooden cube and thus learn about spatial features like size and shape through physical processes by trial and error.

These examples illustrate that spatial problems may come in different modalities: in terms of numbers, language, or spatial configurations; and in different domains: abstract mathematical or legal and concrete physical space. Likewise, the solutions to spatial problems may be required in terms of numbers, language, or spatial configurations. The solution may or may not be needed in the same modality or domain as the problem statement. A correct solution may not always be the best solution, as quickly or cheaply available sub-optimal solutions may be more useful in certain situations. In other words, we may need to transform problems and solutions between different modalities and domains, and the generation of a problem solution may take place in a variety of modalities and domains. Accordingly, it may be helpful to have approaches available that are tailored to the respective requirements (cf. Sloman 1985).

This observation raises the issue whether we always have to transform spatial problems into geometric formalisms to enable computational solutions by means of sequential interpretation of instructions, or whether we can find ways to directly process entire spatial configurations, as humans seem to be able to do (Shepard and Metzler 1971). I will dub the classic computer science approach of sequential interpretation as *left-brain computing,* as information processing in the left cerebral hemisphere is associated with bottom-up or language-like sequential processing; I will dub the approach of processing entire spatial configuration as *right-brain computing,* as the right cerebral hemisphere in humans is associated with top-down or holistic processing (cf. Kosslyn 1987).

In the present chapter, I will first review foundations of qualitative temporal and spatial reasoning. I will then discuss the notion of *conceptual neighborhood* and how we can exploit this notion for spatial computing. I will introduce tools for processing qualitative spatial relations, and then address the transition from spatial relations to spatial configurations. Finally I will demonstrate and analyze the notion of *spatial computing* as contrasted to *symbolic computing*.

2 Qualitative Temporal and Spatial Reasoning

The starting point for much of the research in qualitative temporal and spatial relations since the late 1980s was the chapter *Maintaining knowledge about temporal intervals* by Allen (1983), although the underlying insights had been published previously (Nicod 1924; Hamblin 1972).

The intriguing result of this research was that thirteen 'qualitative' relations could describe temporal relations between events uniquely and jointly exhaustively (Fig. 1). There was an expectation that the idea of qualitative relations could

Relation	Symbol		Pictorial Example
before – after	<	>	
equal	=		
meets – met by	m	mi	
overlaps – overlapped by	o	oi	
during – contains	d	di	
starts – started by	s	si	
finishes – finished by	f	fi	

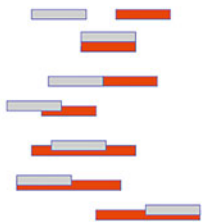


Fig. 1 The 13 jointly exhaustive and mutually exclusive qualitative relations between two temporal intervals

B r2 C / A r1 B	<	>	d	di	o	oi	m	mi	s	si	f	fi
"before" <	<	no info	< o m d s	<	<	< o m d s	<	< o m d s	<	<	< o m d s	<
"after" >	no info	>	> oi mi d f	>	> oi mi d f	>	> oi mi d f	>	> oi mi d f	>	>	>
"during" d	<	>	d	no info	< o m d s	> oi mi d f	<	>	d	> oi mi d f	d	< o m d s
"contains" di	< o m di fi	> oi di mi si	o oi dur con =	di	o di fi	oi di si	o di fi	oi di si	di fi o	di	di si oi	di
"overlaps" o	<	> oi di mi si	o d s	< o m di fi	< o m	o oi dur con =	<	oi di si	o	di fi o	d s o	< o m

Fig. 2 Upper part (facsimile) of the composition table for the qualitative temporal relations (without the 'equals' relation) from Allen (1983). The relation r1 is composed with the relation r2 to obtain the composite relation found in the table. In most cases, more than one relation may result from a composition. "no info" means that all 13 relations may result from a given composition

be extended to one- and higher-dimensional spatial objects that share the extendedness property of temporal intervals. Initially, researchers had in mind a single spatial calculus that would compute all-embracing spatial relations between objects based on information about spatial relations between other objects. However, it became apparent soon that it would be more effective to develop specialized calculi that deal with individual aspects of space rather than a comprehensive spatial calculus that would integrate multiple aspects of space in a single formalism. For example, Allen's interval calculus (see Fig. 2 for the rules of combining interval relations) can be easily adapted to 1-dimensional oriented space (Freksa 1991b; Skiadopoulos and Koubarakis 2004; Liu and Li 2011) or to three spatial dimensions individually (Guesgen 1989).

3 Conceptual Neighborhood

Interval relations can be described at a finer level of resolution in terms of point relations, i.e., in terms of relations between the starting points and the ending points of the intervals. An important feature of physical time and space is that gradual change in position or size results in small qualitative changes or no changes at all between the point relations involved. For example, in the transition from the *before* relation to the *meets* relation, only one of the four point relations between beginnings and endings of the intervals changes: the relation between the ending of the first interval and the beginning of the second interval changes from *smaller than* to *equals*. Accordingly, spatio-temporal configurations that result from small physical changes are perceptually and cognitively closely related.

Furthermore, events in close temporal vicinity are related more easily to one another than events in different epochs. Similarly, nearby spatial locations are more easily related to one another than locations far apart. This insight is captured in *Tobler's First Law of Geography:* "Everything is related to everything else, but near things are more related than distant things" (Tobler 1970).

The role of nearness extends from temporal and spatial neighborhood to the more abstract level of relations: certain relations are closer to one another than others; in fact, some relations are distinguished only by a single detail. These relations are called *conceptual neighbors* (Freksa 1991a). In Fig. 3 the thirteen interval relations from Fig. 1 are applied to one-dimensional oriented space. Conceptually neighboring relations are depicted next to each other.

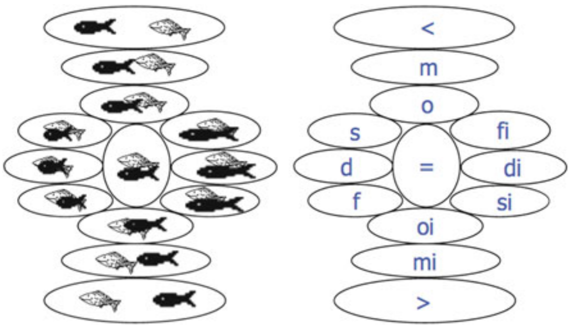


Fig. 3 *Left* Thirteen qualitative relations for objects (here fishes) in one-dimensional oriented space. The example classifies positions of objects in the horizontal dimension. The 13 relations are arranged by *conceptual neighborhood*. *Right* The corresponding labels of the qualitative temporal relations from Allen (1983) depicted in the same spatial arrangement (adapted from Freksa 1991b)

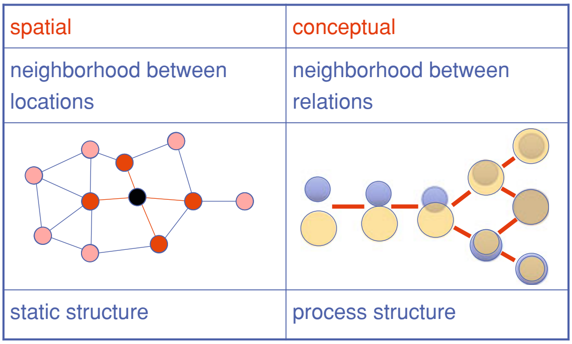


Fig. 4 Spatial and conceptual neighborhood: The *left* graph depicts relations between static spatial locations; directly connected nodes represent spatial neighbors. The *right* graph depicts direct transitions between spatial relations due to processes in the domain; edges correspond to conceptually neighboring relations caused by a minimal spatial change in the domain

The notions of conceptual and spatial neighborhood are closely related: Whereas two directly connected objects are called *spatial neighbors*, two by minimal differences directly connected relations are called *conceptual neighbors* (Fig. 4).

Arranging temporal and spatial relations by conceptual neighborhood enables numerous features for representing spatial knowledge and for spatial reasoning:

- Sets of neighboring relations can be lumped together to define *coarse relations* (Freksa 1992a, b);
- Conceptual neighborhoods define hierarchies for representing incomplete knowledge (Freksa and Barkowsky 1996);
- Qualitative reasoning based on conceptual neighborhoods allows for efficient non-disjunctive reasoning (Nebel and Bürckert 1995; Balbiani et al. 2000);
- Neighborhood-based incomplete knowledge can be easily augmented as additional knowledge is gained during successive reasoning (Freksa 1992b);
- Coarse relations based on conceptual neighborhoods frequently exhibit a natural correspondence to everyday human concepts (Freksa 1992a);
- Spatial and temporal inferences in qualitative reasoning typically result in conclusions that form conceptual neighborhoods (Freksa 1992a, b);
- Conceptual neighborhoods can be formed on various levels of granularity (cf. Fig. 5).

4 Neighborhood-Based Reasoning

One important feature of conceptual neighborhood-based abstraction is that *incomplete knowledge* can be conceptualized and represented as *coarse knowledge* (Fig. 5). By abstracting from missing or unnecessary details, reasoning can be carried

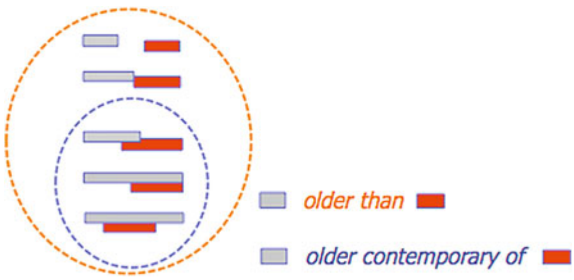


Fig. 5 Coarse temporal relations forming an abstraction hierarchy. The relation 'older contemporary of' corresponds to the conceptual neighborhood of the three finer relations 'overlaps', 'finished by', and 'contains'. The even coarser relation 'older than' corresponds to a larger conceptual neighborhood that additionally includes the two fine relations 'before' and 'meets'

out efficiently. In this way, computationally and conceptually problematic properties of disjunctive knowledge processing are avoided which are encountered when incomplete knowledge is represented as a set of completed potential alternatives.

Coarse reasoning does not necessarily yield coarser results than reasoning with fine relations. But reasoning with coarse relations calls for different inference procedures than reasoning with fine relations. Conjunctions of partially overlapping coarse inferences based on imprecise or incomplete knowledge fragments from different sources result in more precise or *fine* conclusions if the premises are appropriately chosen. With this property, the coarse reasoning approach is suited to model the synergy of multimodal coarse knowledge sources that result in precise knowledge (cf. distributed representations and *coarse coding* in biological or artificial perceptual systems, e.g. Edelman and Intrator 2000). Figure 6 presents a coarsened version of the Allen composition rules that exploits conceptual neighborhood relations between fine relations. For example, the relation *older contemporary* (oc) corresponds to the union of *overlaps* (o), *finished by* (fi), and *contains* (di).

5 A Multitude of Specialized Calculi and SparQ

A considerable variety of spatial calculi have been developed over the past 20 years (Cohn and Hazarika 2001); these can be classified as

- Measurement calculi, e.g. Δ-Calculus (Zimmermann 1995);
- Topological calculi, e.g. 4-intersection calculus, 9-intersection calculus, RCC-5, RCC-8 (Egenhofer and Franzosa 1991; Randell et al. 1992);
- Orientation calculi, e.g. point/line-based: DCC, FlipFlop, QTC, dipole or extended objects (Freksa 1992b; Ligozat 1993; Van de Weghe et al. 2005; Moratz et al. 2000);
- Position calculi, e.g. Ternary point configuration calculus (TPCC—Moratz et al. 2003).

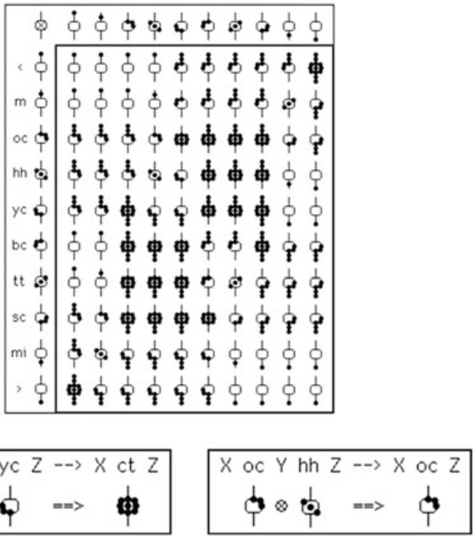


Fig. 6 Conceptual neighborhood-based composition table and inferences based on this table. Spatial pictograms symbolically depict 1D oriented spatial or temporal relations. Each black dot corresponds to a fine relation; conceptually neighboring relations form lumps of dots that correspond to coarse relations. *Top* Conceptually neighboring columns and conceptually neighboring rows from the original table have been merged. *Bottom* Two coarse inferences using this composition table (composition operator is denoted by ⊗). Above the pictograms, the relations are symbolized in classical logic notation. For an elaborate explanation see (Freksa 1992a)

To simplify and support the use of qualitative spatial calculi for specific reasoning tasks, various tools have been developed. Prime examples are SparQ (Wallgruen et al. 2007; Wolter and Wallgruen 2012); GQR (Westphal et al. 2009); QAT (Condotta et al. 2006); and CLP (QS) (Bhatt et al. 2011). While some approaches focus at specialized spatial reasoning methods, others aim to integrate specialized techniques with general knowledge representation methods for logic-based reasoning.

The toolbox SparQ[1] integrates numerous calculi for qualitative spatial reasoning and allows for adding arbitrary binary or ternary calculi through the specification of their base relations and their operations in list notation or through algebraic specification in metric space. SparQ has a modular architecture and can easily be extended by new modules (Fig. 7).

SparQ performs a number of operations that are helpful for dealing with spatial calculi:

- Qualify: quantitatively described configurations are translated into qualitative relations;

[1] www.sfbtr8.spatial-cognition.de/project/r3/sparq/ (accessed: 1 Jan 2012).

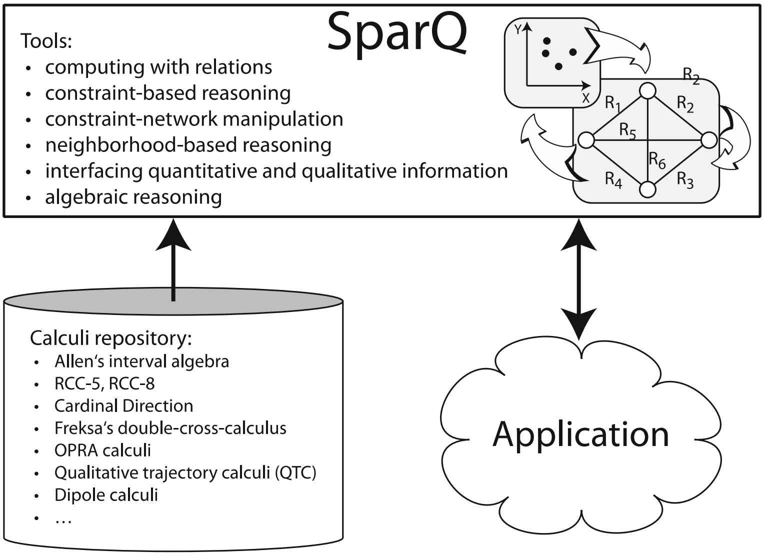


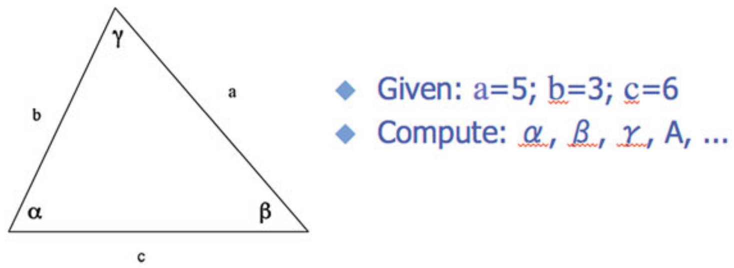
Fig. 7 Modular SparQ architecture. Operations in different qualitative reasoning calculi can be invoked through standardized commands (from Wolter and Wallgruen 2012)

- Compute-relation generates a qualitative inference for a given calculus based on the premise relations and the calculus specification;
- Constraint-reasoning allows for the specification of an inference strategy on a given spatial configuration and returns scenarios that are consistent with the configuration; if the description of the scenario is inconsistent, SparQ informs about the inconsistency;
- Neighborhood-reasoning enables conceptually compatible constraint relaxation and yields semantically meaningful neighboring inferences;
- Quantification generates prototypical 'general' pictorial instances of abstract qualitative descriptions (this is still in an experimental stage).

Although it is helpful to have a variety of calculi available in uniform specification and interface languages, there is still an issue about which calculus to select to solve a given problem. Thus, there is a challenge to understand and describe spatial calculi on the meta-level. The goal is to specify spatial configurations and the type of required problem solution in such a way that the available calculi can be automatically configured to solve the problem.

6 From Spatial Relations to Spatial Configurations

Quantitative computation of spatial configurations by means of Euclidean geometry is well understood. For example, in planar geometry, we can compute all angles, heights, and the area of arbitrary triangles, if the lengths of the edges of the triangles are given by means of the formulae depicted in Fig. 8.



$$\alpha = \arccos\left(\frac{b^2+c^2-a^2}{2bc}\right)$$
$$\beta = \arccos\left(\frac{a^2+c^2-b^2}{2ac}\right)$$
$$\gamma = \arccos\left(\frac{a^2+b^2-c^2}{2ab}\right)$$

$$A = \frac{1}{2}ah_a = \frac{1}{2}bh_b = \frac{1}{2}ch_c,$$

$$h_a = c \cdot \sin\beta = b \cdot \sin\gamma$$
$$h_b = a \cdot \sin\gamma = c \cdot \sin\alpha$$
$$h_c = b \cdot \sin\alpha = a \cdot \sin\beta$$

Fig. 8 Formal abstraction of geometric relations in the Euclidean plane

These formulae are valid for planar spatial configurations independently of position, orientation, scale, or other influences. Spatial relations in physical environments conform to topological and geometric laws that are not affected by contextual influences from other modalities. As a consequence, only few constraints need to be specified and many—or even all—spatial relations are determined.

The principle is well known from high school geometry. For example, on a flat sheet of paper, we can construct exactly two triangles from the specification of three line segments, provided the specified lengths conform to the triangle inequality. In this construction, a compass and ruler are capable of qualitative representation and they exhibit certain abstraction capabilities: the compass represents a distance equal to the length of a given line segment and can apply this distance abstracting from location and orientation. Similarly, the ruler represents a distance and can apply it to any pair of points, independently of orientation and location (within practical bounds).

7 Preserving Spatio-Temporal Structure

Although the formal abstraction shown in Fig. 8 is capable of generating arbitrary spatial relations through abstract computation, the abstraction mechanism does not preserve spatial structure in the way neighborhood-based representations preserve the structure of the represented spatial domain. Structure-preserving representations exploit structural correspondences between the representation medium and the represented domain. They have the advantage that essentially the same operations can be applied to the representation as to the represented domain. For example, on a geographic map we can navigate much like in the geographic environment with the advantage that we can maintain an overview more easily and that we do not need to cover large distances.

As a consequence, structure-preserving representations (Sloman 1971) are advantageous at least for those situations in which humans use the representations; this is the case for assistance systems, for example, where spatial and temporal representations are employed as human–machine interfaces. Humans can carry out zooming operations by moving towards or away from the representation medium; at the same time they can perform refinement and coarsening operations; they can perform perspective transformations by looking at the medium from different angles; they can aggregate and partition spatial regions by making use of natural neighborhood structures; they can move across the medium much like in the represented domain and they can experience spatial and conceptual transitions while doing so; structure-preserving media also may support shape transformation operations in similar ways as in the represented domain.

Are there additional reasons for exploring structure-preserving representations besides the convenience for human users? I believe so. The operations described in the previous paragraph are helpful not only for human users; they may be useful whenever

- problem statement and problem solution are in the spatial domain;
- there is a single spatial configuration about which we may want to answer many questions;
- there are agents with spatial perception and locomotion, e.g., mobile robots;
- several agents need to communicate about a given spatial configuration;
- they can save resources by avoiding unnecessary operations.

In other words: structure-preserving representations also may be advantageous for machine processing. We will come back to this consideration in the next section.

Geometric-diagrammatic constructions on a piece of paper can serve as structure-preserving representations of space, since flat paper provides the universal spatial structure that guarantees the correctness of trigonometric relations in a planar domain. Figure 9 depicts universal correspondences between geometric functions in planar spatial structures.

Computation by diagrammatic construction is a form of *analogical reasoning* (cf. Gentner 1983): the basis for establishing analogies is given through the universal spatial interdependencies that justify the comparison between the source domain and the target domain; the analogies usually concern the abstraction from specific values in the domain. Nevertheless, geometric constructions are sequential constructions that are most easily described by classical algorithms and procedures.

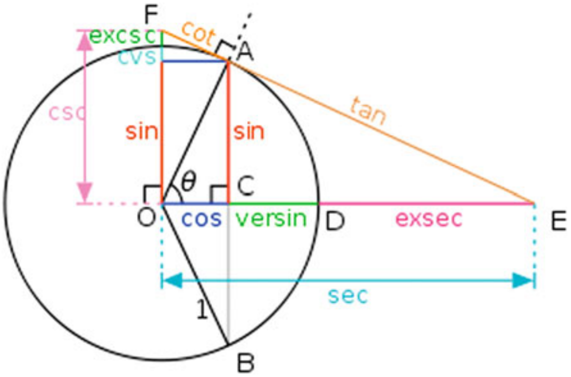


Fig. 9 Spatial construction of trigonometric functions. The graph depicts interdependencies of geometric relations. All trigonometric functions of an angle Θ can be constructed geometrically in terms of a unit circle centered at O

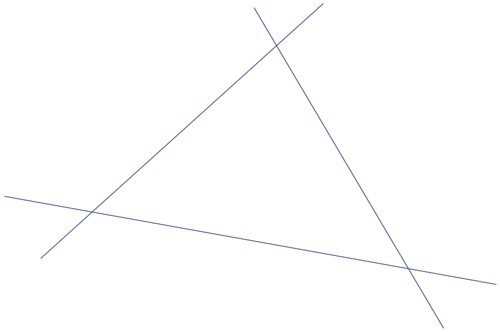


Fig. 10 Three line segments are applied to a spatially structured domain. Numerous new entities and relations are established through the interaction of these lines and the constraints of the domain: nine new line segments, 12 angles, a triangle, its area, and the spatial relations between all these entities

8 Space as Computer

In his book *Rechnender Raum* ('Computing Cosmos' or 'Calculating Space') (Zuse 1969), the computer pioneer Konrad Zuse discussed the issue of structure correspondence between computational representations and the physical domain. He addressed the issue on the micro-level of discrete versus continuous structures, maintaining that discrete representations only approximate continuous structures and mimic random deviations rather than replicating the physical laws of quantum mechanics.

In this section, I want to discuss the idea of structure correspondence on the macro-level of spatial configurations and carry the notion of diagrammatic construction one step further.

Suppose we apply three line segments to a flat surface as shown in Fig. 10. What do we see in this figure? We can easily identify nine additional line segments of specific lengths, three line intersections at specific locations, twelve specific pairwise identical angles, one triangle with a specific area, and numerous relations between those entities.

Where did all these entities and relations come from as we only placed three simple straight lines onto the surface? One way to answer this question is: The surface *computed* these entities and relations according to the laws of geometry. This would be the type of answer we would give if we gave a computer the line equations and the procedures to generate the mentioned entities and relations. What is the difference between the computer approach and the 'flat paper approach'?

The computer algorithm encodes knowledge about the spatial structure of the surface that enables its interpreter to reconstruct in a sequential procedure step-by-step certain abstractions of its spatial structure that are constrained by abstract representations of the lines and their relationships. On the other hand, the flat surface itself and its spatial structure relate *directly* and *instantly* to the lines and generate the entities and relations without computational procedure by means of the inherent structural properties. It represents space rather than knowledge about space. This is why I call this approach *spatial computing* rather than knowledge processing.

9 The Notion of Spatial Computing

Much of what we do in artificial intelligence and computer science takes place on the knowledge level (Newell 1982). The hype of general purpose computing in the 1960s was based on the insight that we can express everything we can think and talk about in terms of physical symbols and that we can manipulate these symbols in a computer similarly to the way we reason and talk *about* arbitrary domains. In this way we can use our knowledge and understanding of these domains to answer questions about them and to solve problems. In the generality of this insight we may have lost sight of the fact that the domains of space and time are omnipresent not only in the worlds we talk about but also within our physical symbol manipulation systems. Considering this fact, couldn't we make use of the spatial and temporal properties of these physical systems on the object level rather than reason about them on the meta-level? For certain tasks in the spatial and temporal domains we would simply act in space and time and *see* what happens rather than process knowledge about space and time and *know* what happens.

Figure 11 schematically depicts the relation between the meta-level of formal and computational reasoning and the object level of spatial configurations. The formal reasoning approach to computing spatial relations is shown in the upper part of the figure; the approach that applies spatial structures directly is shown in the lower part of the figure. In the classical formal reasoning approach, the task either must be given in formal terms or it must be formalized from object-level configurations before formal reasoning processes can be invoked. The formal result can be presented on a formal level or be transformed to an object-level configuration by instantiation.

The spatial computing paradigm takes place on the object level of spatial configurations. The task is directly presented as spatial configuration (e.g., the configuration of Fig. 10), or a spatial configuration is generated through instantiation from a formal specification. If the task is to answer questions about spatial properties and relations of the configuration, the result is available instantly due to

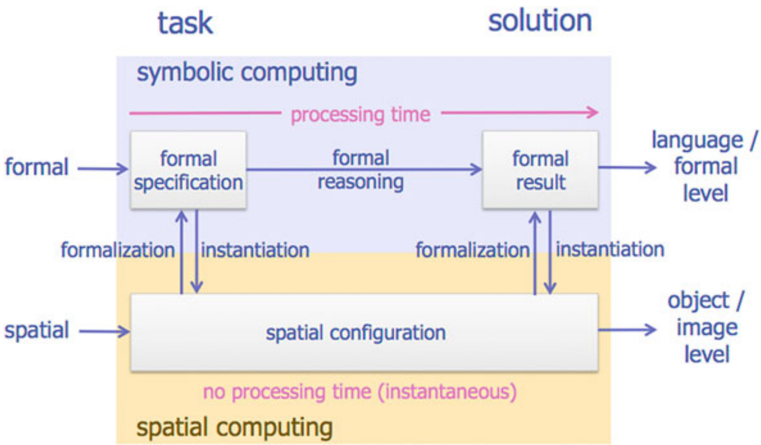


Fig. 11 Two approaches to generating spatial entities and relations: in the *upper* part of the figure, a classical sequential symbolic computing approach transforms a formal specification of a spatial configuration by means of formal reasoning into a formal result on the meta-level. In the *lower* part a spatially structured substrate on the object level guarantees compliance with spatial constraints and instantly makes available all spatial implications of the configuration in spatial form. Specific relations can be read-off directly from the configuration. Transformations between the object level and the meta-level can be carried out at the task stage or the solution stage

the intrinsic constraints of the spatial substrate on the object level. If the task involves physical operations on spatial configurations, these operations will be subject to spatial constraints of changing physical configurations and require processing time; but all spatial implications of the operations will be available instantly as the operations are performed. Depending on the form in which the result of the 'computation' is needed, we need processes that extract the desired result from the configuration (e.g., a line segment or an angle) as input for the next spatial computing task; if the result is needed on the formal level, the object-level entity needs to be formalized, e.g., for use in a classical computation process.

The spatial computing approach involves a paradigm shift that makes it difficult to compare with symbolic approaches by purely computational measures. The reason is that in the symbolic realm, we assume that problems are given in formalized form and that the results will be needed in formalized form, as well. Perceptual operations necessary to formalize spatial knowledge are not taken into account in symbolic approaches. Thus, computational cost is restricted to symbol manipulation processes. However, real-world spatial situations may be different as the example problems in the introduction suggest: for some of them the formalization task may be too time-consuming or expensive; a direct object-level mapping to a spatial substrate may become more feasible, particularly, as sensor technology continues to develop. Perception processes that had to be performed by humans in the process of formalizing spatial knowledge become a part of the spatial computing paradigm; however, they will not be discussed in this chapter.

The term ‘spatial computing’ is used by various researchers in interesting ways that are related to the topic of this chapter: In a Dagstuhl Seminar on *computing media and languages for space-oriented computation* the organizers state that ‘… it is important to make **space** not an issue to abstract away, but a first-order effect that we optimize. The distinguishing feature of *spatial computing* then is that computation is performed distributed in space and topology define the computation’ (DeHon et al. 2007). Similar goals are stated in a proposal for *spatial cloud computing* for use in the Geospatial Sciences (Yang et al. 2011). A student of the MIT School of Architecture and Planning posted the manuscript for a master thesis (Greenwold 2003) in which he defines ‘Spatial computing is human interaction with a machine in which the machine retains and manipulates referents to real objects and spaces.’ The artist Albert Hwang presents a video film series (Hwang 2012) in which he demonstrates simulations of augmented reality technology for interaction with spatial environments to illustrate the power of spatial computing technology that is yet to be developed.

Whereas the former two projects share technical goals—using spatial substrates for computation—with the approach presented here, the latter two projects share some of the motivation for our approach: interaction with spatial environments through perception and action. The main motivation for our approach, however, is to understand cognitive functionality by conceiving and implementing suitable representations, processes, and technical realizations.

10 Basic Entities of Cognitive Processing

In geometry, the spatial world can be described in terms of infinitesimally small points; lines are defined in terms of points; areas in terms of lines; etc. In contrast, in cognition, basic entities usually are not infinitesimally small points; they may be

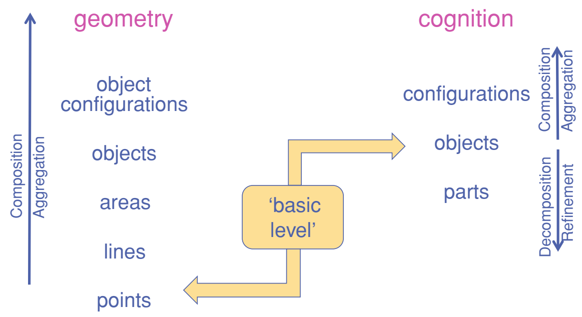


Fig. 12 Two ways to conceptualize physical objects. *Left* In geometry, we aggregate arbitrarily complex structures from atomic point entities. *Right* In cognition, basic entities may be geometrically complex, meaningful entities. Through cognitive effort, basic entities can be decomposed into more elementary entities or aggregated into more complex configurations; cognition on the level of basic cognitive entities is possible without invoking elementary constituents

entire physical objects like books or chairs (Fig. 12). Basic cognitive entities carry meaning related to their use and function and we perceive and conceptualize them in their entirety even if certain details are not accessible to our perception. We may not even know about the composition of basic cognitive entities; still, we are able to talk about them and to use them for daily activities. The cognitive apparatus appears to be flexible as to which level in a huge lattice of part-whole relations to select as 'basic level' (cf. Rosch 1978); it also appears to be able to focus either on the relation between an object and a configuration of objects, or alternatively, on the relation between an object and its parts. Both transitions involve cognitive effort, while the mere consideration of the basic level appears almost effortless.

It is known that we can apply simple mental operations, e.g., mental rotation, to entire spatial objects at once (Shepard and Metzler 1971). In spatial computing, we would like to implement processes that have comparable capabilities: manipulating entire objects without manipulating all their constituent parts. We would expect to obtain only a coarse result of cognitive operations on basic cognitive entities with little effort; to resolve details, we would have to invest cognitive power. This processing approach would be in contrast to geometric spatial processing where we would expect to know the details before we know the complex structure.

11 Conclusions and Outlook

Let me return to the spatial problems that I used in the beginning of the chapter to introduce various perspectives on spatial challenges. The main message of this exercise is that spatial problem solving consists of more than solving equations. First of all, a spatial problem needs to be perceived as one. Second, it needs to be represented as one. Third, the representation needs to be processed. Fourth, the result needs to be interpreted in spatial terms.

With regards to the representation of spatial knowledge for problem solving we have lots of options, as there are many ways to conceive of space. For example, space may be conceived of as empty space—"what is there when nothing is there"—or as the space spanned by physical objects. Space can be described in terms of a multitude of reference systems as becomes evident if we look at the many spatial representation systems and calculi we can develop. All the different representations have advantages and disadvantages, depending on the problems we want to tackle or the situations we want to describe. Some problems can be solved directly on the object level; others are facilitated by suitable abstractions.

Nevertheless, spatial structures—and to a similar extent temporal structures—play special roles in everyday actions and problem solving. Many other dimensions seem to dominate our lives: monetary values, quality assessments, efficiency criteria, emotions, social structures, etc.—but do they play comparable roles with respect to cognitive representation and processing? I do not think so. I propose that the special role of space and time has to do with the fact, that internal representations may be a-modal, but they cannot be "a-structural". In other words: cognitive representations and processes depend on a spatio-temporal substrate; without such a substrate, they cannot exist. But they may not depend on a specific spatio-temporal substrate: a multitude of structures may do the job. Different abstractions from physical space may be advantageous in different situations.

Space and time provide fundamental structures for many tasks that cognitive agents must perform and for many aspects of the world that they can reason about. Maintaining these structures as a foundation simplifies cognitive tasks tremendously, including perceiving, memorizing, retrieving, reasoning, and acting. This is well known from everyday experiences, such as using geographic maps for wayfinding. For other domains it is helpful to create spatially structured foundations to support and simplify orientation; for example, spatial structure is the basis for diagrams that help us reason about many spatial and non-spatial domains.

A conceptually simple implementation of a truly spatial computer could be a robot system that manipulates physical objects in a spatial domain and perceives and represents these objects, the configurations constructed from these objects, and the parts of the objects as well as their relations from various orientations and perspectives. A more sophisticated approach would involve the construction of a spatial working memory, perhaps visually accessed, whose basic entities are entire objects rather than their constituents. Spatial operations like translation, rotation, and distortion would globally modify configurations. Perception operators extract qualitative spatial relations from these representations. The development of this implementation can be guided by our knowledge about working memory capabilities and limitations as well as by our knowledge about spatial representations in the human mind (Schultheis and Barkowsky 2011).

As technological materials become more sophisticated, the connection between spatial substrates and digital computer technology will become successively stronger. Sensor technology will be integrated into spatially structured materials in the years to come. A vision of such materials of the future that would support the concept of spatial computing on the substrate level can be found in a recent special issue in sensors and actuators (Lang et al. 2011).

12 A Final Note

Although we talk about spatial cognition, spatial reasoning, and spatial computing, we frequently fail to characterize the type of solution to spatial problems that we want to achieve. Our repertoire of approaches yields results on different levels of sophistication: some approaches only yield solutions to spatial problems; others yield some sort of explanations along with the solutions or instead of a solution. Accompanying explanations may be: ‘this is the only solution’; ‘this is one of possibly several solutions’; ‘these are all solutions’; or ‘there is no solution’.

Why is sophistication an issue? For highly abstract, formal approaches the quality of a solution is not obvious. Formal proofs or explanations (or both) are required to characterize the type of solution. In the more concrete, spatially structured solutions, the results are more easily perceptible, more obvious in that proofs may not be required—cognition and commonsense reasoning seem to operate without formal proofs, for the most part. On the other hand, can we be *sure* that we found the best solutions, the only solution, or all solutions? This is an old debate that calls into mind the discussion on the validity of constructive geometry to find solutions or to prove correctness.

There are different domains in which we can ground our knowledge: perceptual experience about spatial and temporal environments that does not require proofs and formal logics that does not require empirical justification. Both domains are important for human intellect and human reasoning. It does not make much sense to say one is superior over the other; they are two rather different realms. They may become particularly powerful when they are engaged jointly, one to carry out spatio-temporal perception and action and the other to reason about them on the meta-level and to explain what is going on in an overarching theory.

It is interesting to note that artificial intelligence research on commonsense reasoning so far has been restricted to characterizing commonsense reasoning on a descriptive level. Almost no AI work exists that emulates spatial cognitive abilities in a similar way as constructive geometry reflects spatial laws in the physical world or as artificial neural networks reflect topological structures akin to those of biological systems.

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References

Allen JF (1983) Maintaining knowledge about temporal intervals. CACM 26(11):832–843

Balbiani P, Condotta J-F, Ligozat G (2000) Reasoning about generalized intervals; preconvex relations and tractability. In: Proceedings of TIME-2000 conference, pp 23–30

Bhatt M, Lee JH, Schultz C (2011) CLP(QS): a declarative spatial reasoning framework. In: Egenhofer MJ, Giudice NA, Moratz R, Worboys MF (eds) COSIT'11, LNCS 6899. Springer, Heidelberg, pp 210–230

Cohn AG, Hazarika SM (2001) Qualitative spatial representation and reasoning: an overview. Fundamenta Informaticae 43:2–32

Condotta JF, Saade M, Ligozat G (2006) A generic toolkit for n-ary qualitative temporal and spatial calculi. In: TIME'06. IEEE Computer Society, Washington, pp 78–86 ISBN 0-7695-2617-9

DeHon A, Giavitto J-L, Gruau F (2007) 06361 Executive report — computing media languages for space-oriented computation. In: DeHon A, Giavitto J-L, Gruau F (eds) 06361 Abstracts collection—computing media languages for space-oriented computation, Schloss Dagstuhl. http://drops.dagstuhl.de/opus/volltexte/2007/1026

Edelman S, Intrator N (2000) Coarse coding of shape fragments + retinotopy ~ representation of structure. Spat Vis 13:255–264

Egenhofer MJ, Franzosa RD (1991) Point set topological relations. Int J Geogr Inf Syst 5: 161–174

Freksa C (1991a) Conceptual neighborhood and its role in temporal and spatial reasoning. In: Singh M, Travé-Massuyès L (eds) Decision support systems and qualitative reasoning. North-Holland, Amsterdam, pp 181–187

Freksa C (1991b) Qualitative spatial reasoning. In: Mark DM, Frank AU (eds) Cognitive and linguistic aspects of geographic space. Kluwer, Dordrecht, pp 361–372

Freksa C (1992a) Temporal reasoning based on semi-intervals. Artif Intell 54:199–227

Freksa C (1992b) Using orientation information for qualitative spatial reasoning. In: Frank AU, Campari I, Formentini U (eds) Theories and methods of spatio-temporal reasoning in geographic space, LNCS 639. Springer, Berlin, pp 162–178

Freksa C, Barkowsky T (1996) On the relation between spatial concepts and geographic objects. In: Burrough P, Frank A (eds) Geographic objects with indeterminate boundaries. Taylor and Francis, London, pp 109–121

Gentner D (1983) Structure-mapping: a theoretical framework for analogy. Cogn Sci 7:155–170

Greenwold S (2003) Spatial computing. Manuscript submitted to school of architecture and planning, Massachusetts Institute of Technology, Cambridge. http://acg.media.mit.edu/people/simong/. Accessed 1 Jan 2012

Guesgen HW (1989) Spatial reasoning based on Allen's temporal logic. ICSI TR-89-049. International Computer Science Institute, Berkeley

Hamblin CL (1972) Instants and intervals. In: Fraser JT, Haber FC, Müller GH (eds) The study of time. Springer, Berlin, pp 324–331

Hwang A (2012) http://albert-hwang.com/projects/spatial-computing/. Accessed 1 Jan 2012)

Kosslyn SM (1987) Seeing and imagining in the cerebral hemispheres: a computational approach. Psychol Rev 94:148–175

Lang W, Lehmhus D, van der Zwaag S, Dorey R (2011) Sensorial materials—a vision about where progress in sensor integration may lead to. Sens Actuators, A 171(1):1–2

Ligozat G (1993) Qualitative triangulation for spatial reasoning. In: Campari I, Frank AU (eds) COSIT 1993 LNCS 716. Springer, Heidelberg, pp 54–68

Liu W, Li S (2011) Reasoning about cardinal directions between extended objects: the NP-hardness result. Artif Intell 175:2155–2169

Moratz R, Renz J, Wolter D (2000) Qualitative spatial reasoning about line segments. In: Proceedings of ECAI 2000, pp 234–238

Moratz R, Tenbrink T, Fischer F, Bateman J (2003) Spatial knowledge representation for human-robot interaction. In: Freksa C, Brauer W, Habel C, Wender KF (eds) Spatial cognition III – Routes and navigation, human memory and learning, spatial representation and spatial reasoning, LNAI 2685. Springer, Heidelberg, pp 263–286

Nebel B, Bürckert HJ (1995) Reasoning about temporal relations: a maximal tractable subclass of Allen's interval algebra. JACM 42(1):43–66

Newell A (1982) The knowledge level. Artif Intell 18(1):87–127

Nicod J (1924) Geometry in the sensible world. Doctoral thesis, Sorbonne, English translation in Geometry and Induction, Routledge and Kegan Paul, 1969

Randell DA, Cui Z, Cohn AG (1992) A spatial logic based on regions and connection. In: Proceedings of 3rd international conference on knowledge representation and reasoning. Morgan Kaufman, Los Altos, pp 55–66

Rosch E (1978) Principles of categorization. In: Rosch E, Lloyd BB (eds) Cognition and categorization. Erlbaum, Hillsdale

Schultheis H, Barkowsky T (2011) Casimir: an architecture for mental spatial knowledge processing. Top Cogn Sci 3:778–795

Schwartz JT, Sharir M (1983) On the "piano movers" problem I: the case of a two-dimensional rigid polygonal body moving amidst polygonal barriers. Commun Pure Appl Math 36:345–398

Shepard RN, Metzler J (1971) Mental rotation of three-dimensional objects. Science 171:701–703

Skiadopoulos S, Koubarakis M (2004) Composing cardinal direction relations. Artif Intell 152:143–171

Sloman A (1971) Interactions between philosophy and artificial intelligence: the role of intuition and non-logical reasoning in intelligence. Artif Intell 2:209–225

Sloman A (1985) Why we need many knowledge representation formalisms. In: Bramer M (ed) Research and development in expert systems. Proceedings of BCS expert systems conference 1984. Cambridge University Press, Cambridge, pp 163–183

Tobler W (1970) A computer movie simulating urban growth in the Detroit region. Econ Geogr 46(2):234–240

Van de Weghe N, Kuijpers B, Bogaert P, De Maeyer P (2005) A qualitative trajectory calculus and the composition of its relations. In: Proceedings of geospatial semantics, vol 3799, pp 60–76

Wallgruen JO, Frommberger L, Wolter D, Dylla F, Freksa C (2007) Qualitative spatial representation and reasoning in the SparQ toolbox. In: Barkowsky T, Knauff M, Ligozat G, Montello D (eds.) Spatial cognition V: reasoning, action, interaction, LNAI 4387. Springer, Heidelberg, pp 39–58

Westphal M, Woelfl S, Gantner Z (2009) GQR: a fast solver for binary qualitative constraint networks. In: AAAI spring symposium on benchmarking of qualitative spatial and temporal reasoning systems, Stanford

Wolter D, Wallgruen JO (2012) Qualitative spatial reasoning for applications: New challenges and the SparQ toolbox, In: Hazarika SM (ed) Qualitative spatio-temporal representation and reasoning: Trends and future directions. IGI Global, Hershey. doi: 10.4018/978-1-61692-868-1

Yang C, Goodchild M, Huang Q, Nebert D, Raskin R, Xu Y, Bambacus M, Fay D (2011) Spatial cloud computing: how can the geospatial sciences use and help shape cloud computing? Int J Digit Earth 4:4

Zimmermann K (1995). Measuring without measures. The Δ-Calculus. In: Frank AU, Kuhn W (eds) COSIT 1995, LNCS 988. Springer, Heidelberg, pp 59–67

Zuse K (1969) Rechnender Raum: Schriften zur Datenverarbeitung. Vieweg, Braunschweig

The Cognitive Development of the Spatial Concepts NEXT, NEAR, AWAY and FAR

Scott Freundschuh and Mark Blades

Abstract Previous research on the cognitive development of *locatives* by English speakers, spatial concepts such as in, on, between, over and across has focused primarily on young children's understanding of relatively few locatives and only in small-scale spaces. Subsequently, these studies provide limited insight into the comprehension of locatives in general, the results are relevant to spatial relationships in only one spatial context, the studies provide little data about the development of spatial concept understanding beyond the childhood, and they therefore do not adequately address the relationship between spatial developmental theory and spatial concept understanding. In response, we examined the use of locatives in two spatial contexts: a tabletop layout and a large model space. Child (3, 4, 5, 7 and 9 years-old) and adult (control) participants placed, according to various instructions, objects within one of the two model spaces. This chapter focuses on one aspect of this study: locatives that have implicit reference to distance. We specifically explore the locatives NEXT, NEAR, AWAY and FAR in two spatial contexts. Results indicate that spatial context influences people's conceptions of locatives.

Keywords Language-spatial · Spatial cognition · Locatives · Spatial concepts

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1 Preface

> Whether language influences thought, it seems obvious that thought influences language, and that studying both the structure and use of natural language describing spatial situations is a good way to study how people think about such situations. More specific…distinctions made by language, and distinctions in spatial situations that must be made in order to account for linguistic differences, may reveal fundamentals of spatial representation that may be useful in GIS as well (Mark 1999, p. 82).

The kernel for this work was planted in 1989 during the specialist meeting of the National Center for Geographic Information and Analysis research initiative *Languages of Spatial Relations*. One of the objectives of this initiative was to "identify formal cognitive/semantic models of spatial concepts and relations in natural languages" (Mark and Frank 1992, p. 1). Las Navas 1990 was the third and concluding meeting of this research initiative, and it is the meeting where Freundschuh and Blades met and began discussions on a collaboration that has resulted in the research reported in this paper. Freundschuh, coming from the perspective of a geographer was interested in the effect of scale on the understanding of spatial concepts. Blades, on the other hand was interested in spatial concepts from a developmental psychologist's perspective. These combined interests resulted in several studies, the most recent reported here.

2 Introduction

Locatives are phrases or words which denote place location, and in English include terms such as in, under, near, far, through, front and back (Landau and Jackendoff 1993). Geographers often times refer to these as spatial concepts. Locatives are essential for descriptions of space. For example, it is impossible to describe the relationship between places without using locatives. Understanding any spatial information such as directions, maps, and geographical descriptions depends upon an appreciation of the spatial terms used in the description. Despite their importance, the way that locatives are used and understood has hardly been investigated from a geographic perspective. Research by Freundschuh and Blades (1997, 1998) and Freundschuh (2000) investigated the cognitive development of 19 different locatives, singularly and in combination (see Table 1). The motivations for their study included a number of factors, namely a broader developmental perspective of locatives from age 3 to adulthood, an assessment of a more comprehensive set of locatives, the consideration of scale (or size of space) in locative comprehension/expression, and finally a developmental theoretical framing for research on spatial concepts. Though this chapter focuses primarily on scale and the comprehension of only four locatives *NEXT, NEAR, AWAY* and *FAR* to understand this work the reader must be provided the framework for the methods used in the broader study.

Table 1 Locative terms investigated by Freundschuh and Blades (1997, 1998)

In	Near	Through	Between	Near and Next to
Front	Far	Corner	On and in Front	Close and Next to
Behind	Away	Among	Next to and Far	In and Across from
On	Next	Middle	Far and Away from	

3 Previous Research

3.1 Focus on Young Children and the Age of Acquisition

Previous research into the acquisition of locatives has focused almost exclusively on young children's first conception of locatives (for an exception, see Hermer-Vazquez et al. 1999). Johnston (1984) and Johnston and Slobin (1979) (among others), investigated some locatives and generally found that they were acquired by children in the following order: in, on, under, next to, between, and back-front, and that most children demonstrated some appreciation for these terms by 4 years of age (see also Bailystock and Codd 1987; Bowerman and Choi 2001; Bremner an Idowu 1987; Casasola et al. (2003), Choi and Bowerman 1991; Conner and Chapman 1985; Cox and Isard 1990; Durkin 1981; Gentner and Bowerman 2009; Johnston 1988; Simms and Gentner 2008; Spencer and Blades 2005). Two limitations of these previous studies are that they considered children only, and that in most instances assessment was measured by scoring each child's response as correct or incorrect. Assessment of comprehension was based on the experimenter's own implicit assumption of the correct use of the term, rather than on the performance of a control group, and that scoring children as being only correct or incorrect ignores any developmental differences in the way that children use a term (Sowden and Blades 1996).

3.2 Locatives Studied

Though Landau and Jackendoff (1993) suggested that there are 80 locative terms in the English language, previous work on the development of locative comprehension has concentrated on only a small number. The following list is a sample of the locatives that have been investigated in 27 published studies, and the number of times that they have been included in an empirical study: back/front (14), in (8), on (8), under/above (8), next to (8), left/right (5), between (4), near (1), with (1). One exception to this is work by Freundschuh and Sharma (1996). In this study the authors explored the number and kinds of locatives used in young children's books (pre K to 4th grade) to communicate spatial information. In a sample of the 25 "most popular" children's books identified at the time of the study, 41 different locatives were used to illustrate or describe spatial information. In most instances, the use of a locative made reference to a spatial relationship in a small-scale, object space (Freundschuh and Egenhofer 1997).

3.3 A Connection to Spatial Developmental Theory

The most influential theory of spatial development has been Piaget's (Piaget and Inhelder 1967). Piaget and Inhelder proposed that children's comprehension of spatial concepts/relations mirror general stages of cognitive development. Their cognitive developmental theory includes four stages, the first being *sensorimotor*, in which thought derives from movement and sensation (birth to age 2). The point at which children begin to talk until about age 7 is the *preoperational* stage of development. During this stage children begin to understand **topological spatial properties**, and are able to use symbols to represent objects. The next stage, the *concrete operational* stage, children develop the ability to think abstractly about observable phenomena. The age range for this stage is from age 7 to early adolescence. Children in the concrete operational stage can understand **projective spatial properties**. Appreciation of space is limited to an understanding of spatial relationships between pairs of objects or groups of objects, and the understanding that different views of an object or space have unique viewing perspectives. During the final developmental stage, *formal operations*, an adolescent is capable of hypothetical and deductive reasoning. It is here that children begin to understand **metric spatial properties**, and can use a coordinate system to define the location of an object. According to Piaget and Inhelder, it's not until the *concrete* and *formal* operations stages that children develop an appreciation of distances in spatial relationships.

In contrast, Huttenlocher and Newcombe (1984) proposed an earlier development of spatial competence suggesting that children from 4 or 5 years of age can relate one object to a 'framework' of other objects, and that they can take 'rough estimates of distance' into account. Many spatial terms involve an appreciation of distance (e.g. close, near, next, far, away) and it could be argued, from Piaget's and Inhelder's theory that children will have difficulty distinguishing such terms until after about 7–8 years of age. Alternatively, Huttenlocher and Newcombe's theory, with its emphasis on children's understanding of distance suggests that children will have at least a partial understanding of terms like 'far' or 'away', at the same time as they begin to understand locatives which require a knowledge of spatial frameworks. In other words, the two theories not only imply different ages of acquisition for locatives involving distance judgments, more importantly they suggest a different progression of acquisition for these locatives relative to locatives that do not involve concepts of distance.

3.4 Spatial Context

Previous studies on locative understanding have considered one spatial context, that of a table-top space, therefore little is known about locative use and understanding in other spaces. Spatial cognition operates in a variety of spaces (Montello 1998). Freundschuh and Egenhofer (1997) synthesized from the literature six different kinds of space: manipulable object space, non-manipulable object space, environmental space, geographic space, panoramic space and map space. There are results from a number of studies that offer evidence that these space types result in different cognitive representations. For example, work by Franklin and Tversky (1990) and Bryant et al. (1992) demonstrated that manipulable object space is represented cognitively with a spatial framework model.

Research on environmental spaces demonstrated that landmarks, routes and spatial configurations are learned concomitantly and refined over time (Montello 1993), and that this spatial knowledge contains distortions in distance (Couclelis et al. 1987; Freundschuh et al. 1990) and direction (Tversky 1981). Research by Lynch (1960) and Freundschuh (1992) demonstrated that road structure influences cognitive representations of environmental spaces. Research on map spaces has demonstrated that configurational knowledge is acquired from maps, and that procedural knowledge is acquired from navigation experience in environmental spaces (Thorndyke and Hayes-Roth 1982), and that survey descriptions of space resulted in configurational knowledge and that procedural descriptions resulted in route knowledge (Taylor and Tversky 1992).

Finally, contextual factors are particularly important in the use of locatives because few locatives have a precise definition, and some such as next, near, away and far are predominantly context dependent. Context dependency is often related to geographic scale. For example, the location of a bicycle can be described as ‘near a house’, but it would not usually make sense to describe the bike’s location as ‘near Los Angeles’.

4 This Study

We conducted a study that investigated 19 different locatives, singularly and in combinations (see Table 1). Locatives selected for this study included those examined in previous studies (BEHIND, IN FRONT, IN, ON, NEXT TO, BETWEEN, NEAR), locatives not examined before (THROUGH, ACROSS, MIDDLE, FAR, AMONG, CLOSE, AWAY FROM) and locatives that can be suitably combined in instructions (IN and ACROSS FROM, NEXT TO and FAR, NEAR and NEXT TO, FAR and AWAY FROM, CLOSE and NEXT TO).

Locatives selected for this study were of five types that referenced either one or two landmarks in the model, and either did or did not make reference to distance (see Table 2). A fifth type of locative was related to the geometry of space, and included THROUGH, CORNER, AMONG AND MIDDLE. The selection of these locatives was encouraged by the work of Mark and Egenhofer (1994) on the cognitive efficacy of the 9-intersection model for spatial relations between lines and regions. If Piaget's theory of spatial development is appropriate, children's understanding of locatives will be in the order of types listed in Table 2, and that a full understanding of *Type 4* locatives will be achieved after the age of 7 years. However, if Huttenlocher's and Newcombe's theory is more appropriate, one would expect children to understand *Type 1* locatives before those in *Type 2*, but would not expect major developmental differences in the comprehension of locatives from *Types 2*, *3* or *4*. Furthermore, on the basis of Huttenlocher's and Newcombe's theory we expect a fairly complete appreciation of most locative terms before 7 years of age.

We included participants of ages 3, 4, 5, 7 and 9 years, and a control group of adults. These ages were selected because previous research either demonstrated or suggested that differences in spatial abilities and comprehension appear at these ages (Blaut 1997; Blaut and Stea 1973; Blades et al. 2003; Cohen 1985; Downs and Liben 1997; Huttenlocher and Newcombe 1984; Piaget and Inhelder 1967; Plester 2004; Plester et al. 2003, 2005). Adults were included as a control group by which performance of other age groups was assessed.

We tested participants in a large landscape model space as well as in a tabletop layout. We created a large model landscape (4 feet × 6 feet) of the town of Frederick, Wisconsin, USA, carved out of a large piece of Styrofoam. This model possessed different terrain features such as a lake, fields, a park, forested areas and rolling hills, as well as a number of cultural features such as roads, houses, a school and fire hall, shops and theater, and a bakery and gas station (see Fig. 1). These features presented to participants many of the spatial divisions of a large-scale space such as boundaries, edges, regions, enclosures, and nodes (see Lynch 1960). We also tested participants in a tabletop layout (22 inch × 17 inch) having various objects, which we refer to as landmarks spread on a flat surface. Landmarks used in the tabletop layout included a small bed, bus, rocking chair, refrigerator, block, rocking chair and table (see Fig. 2). Participants were asked to use the same locatives (where sensible) in both the tabletop layout and in the landscape model space so that effects of the two different contexts could be compared (Fig. 3).

Table 2 Four locative types explored in this study

	One reference landmark		Two reference landmarks	
No reference to distance	Type 1	IN FRONT BEHIND ON	Type 2	BETWEEN IN and ACROSS FROM ON and IN FRONT
Reference to distance	Type 3	NEAR FAR AWAY FROM NEXT TO	Type 4	NEXT TO and FAR NEAR and NEXT TO FAR and AWAY FROM CLOSE and NEXT TO

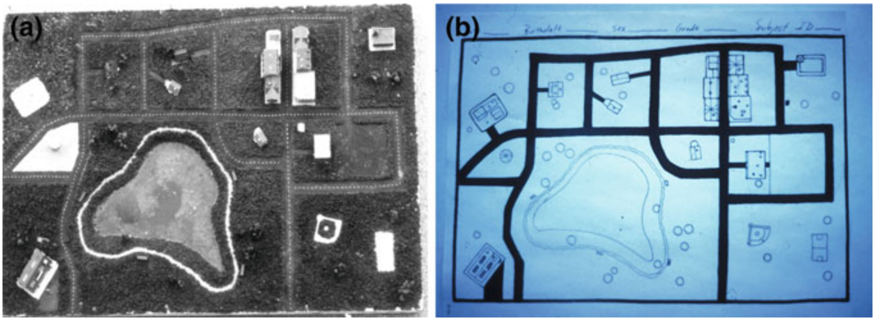

Fig. 1 Bird's eye view of landscape model (*left*) and map (*right*) of model: Frederick, Wisconsin, USA

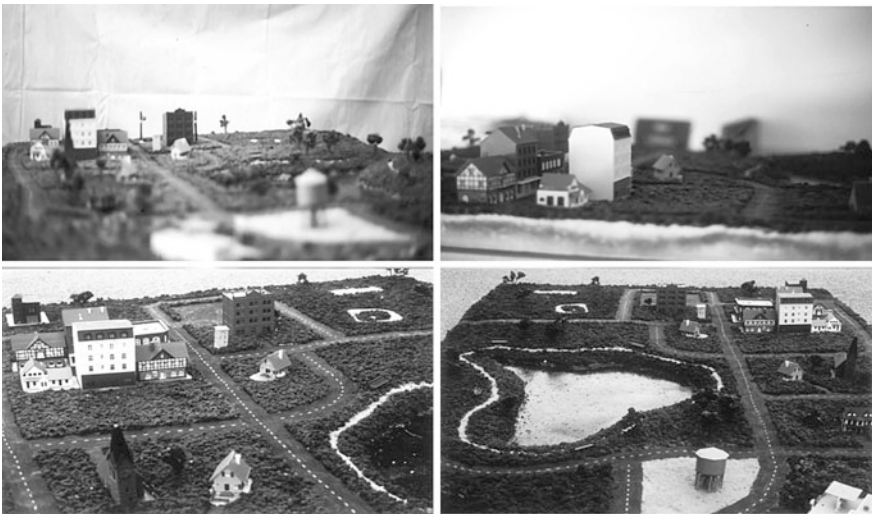

Fig. 2 Various oblique views of the model landscape

5 Experiment #1

5.1 Procedure

5.1.1 Participants

Two-hundred and forty volunteers participated in this study. There were 40 subjects, balanced for sex, in each age group of 3, 4, 5, 7, and 9-years, as well as a control group of adults. There were two reasons for including these age groups in this experiment. First, previous research has shown that there is rapid development in the understanding of some locatives between 3 and 4 years of age, but also

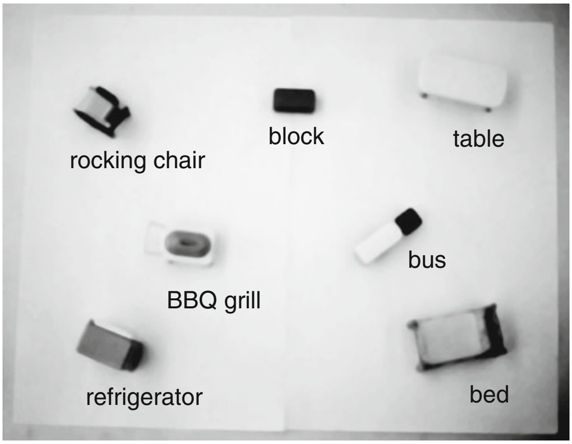

Fig. 3 Bird's-eye view of tabletop model

significant differences in the understanding of children at these two ages (Johnston and Slobin 1979; Johnston 1984). Second, the older age groups (5, 7 and 9 years) will permit the examination of predictions based on Piaget's and Inhelder's, and Huttenlocher's and Newcombe's theories. Subjects were recruited from area daycares, preschools, and an elementary school and a middle school. Subjects were required to be native English speakers.

5.1.2 Procedure and Scoring

Participants were tested individually. One half of the participants were tested first in the landscape model, then in the tabletop model, and vice versa. In addition, one half of the participants performed the tasks in a "forward" sequence, the other half in a "backward" sequence. Participants were tested individually. Participants responded to instructions in the form:

5.1.3 Put the [Object] [Locative Term] the [Referent]; e.g., Put the [Car] [Near] the [School]

For each task, the experimenter pointed to the referent(s) in the model, told the participant the task and then repeated it to ensure understanding, handed the object to the participant who then placed it in the model. A second experimenter observed this interaction, and recorded the placement of the object on a map of the model. From this object location the distance between object(s) and referent(s) were measured. Finally, a photograph was taken to document object placements by each participant.

5.2 Results and Analysis: NEXT, NEAR, AWAY and FAR

For locatives that made reference to distances, mean distance estimates were computed for each age and sex for each task. Distance estimates greater that 3 standard deviations around the mean were considered outliers and excluded from analysis (0.6 % of responses). Outliers occurred with the youngest participants (3 and 4 years of age), caused by these young participants being nervous at the start of testing, and therefore simply placing an object on the model closest to them. ANOVA was used for analysis (see Table 3).

Comparing participant responses to tasks with locatives that referenced one landmark and also made reference to distance (e.g., NEAR, FAR, AWAY and NEXT TO), we see a developmental progression. In general, the responses from 9-yr-old and adult participants were different than those for younger participants. Consider the locative NEAR in the task "put this person near the lake". Older participants put the person closer to the lake than did younger participants. With the exception of 4-yr-olds, 9-yr-olds and adults put the person closer to the lake than did all other age groups ($F \geq 3.88$, $p \leq 0.05$). For the task "put the car far from the lake", all age groups put the car farther from the lake than did the preceding age group ($F \geq 4.66$, $p \leq 0.03$). For the task "put the car away from the lake", older participants put the car farther away than did younger participants. This was significant for adults compared to all other groups ($F \leq 8.34$, $p \leq 0.005$) and for 9-yr-olds compared to 3- and 4-yr-olds ($F \geq 4.93$, $p \leq 0.03$). For the task "put this person next to the lake", like the locative NEAR, older participants put the person closer to the lake than did younger subjects. This was significant for 7-yr-olds, 9-yr-olds and adults compared to 3-, 4-, and 5-yr-olds ($F \geq 5.21$, $p \leq 0.03$).

For the tasks completed in both models some generalizations can be made:

- for the locative NEXT, the distance between object placement and landmark is increasingly closer with increasing age;

Table 3 Type 3 locatives, tasks that reference one landmark, reference to distance

	3 years	4 years	5 years	7 years	9 years	Adults
Tabletop model						
Trash can *NEXT* to the block	11.17	14	11.84	10.49	8.85	5.83
Sheep *NEAR* the block	9.16	13.7	20.08	16.63	11.63	12.85
Trash can *AWAY* from the block	119.2	135.8	143.9	151.1	168.5	194.9
Trash can *FAR* from the block	97.8	149	157.8	171	186.1	219.2
Landscape model						
Person *NEXT* to the lake	7.8	5.6	6.6	4.5	4.0	4.2
Person *NEAR* the lake	8.2	6.0	7.3	8.1	4.9	5.4
Car *AWAY* from the lake	37.6	42.7	49.2	46.9	53.4	66.8
Car *FAR* from the lake	36.3	48.2	53.7	59.6	66.4	78.3

Values are distances (mm). Note that distances for the landscape model were measured from the map of the model

- for the locative NEAR, again the distance between object placement and landmark is increasingly closer with increasing age, but not as close as object placement for NEXT;
- for the locative AWAY, the distance between object placement and landmark increases with increasing age; and
- for the locative FAR, again the distance between object placement and landmark increases with increasing age, and further than distances for AWAY.

In other words, the distance between object placement and landmark increases from NEXT, to NEAR, to AWAY and to FAR. Tables 4, 5, 6 and 7 illustrate between age group analysis for both the tabletop and landscape models. For all four locatives there appear to be differences in responses between all age groups. For NEXT in the table-top model there is not a significant difference between participants up to 9 years, but there were significant differences between the adults and all other age groups. On the other hand, by 7 years of age participant responses were not significantly different than responses for adults. For NEAR, for the most part by 9 years of age participant responses were not significantly different than responses for adults for both the table-top and landscape models. On the other hand, for AWAY there were significant differences between participants 7 years-old and younger for both the table-top and landscape model. Finally, there were significant differences for the most part between all age groups for FAR. It appears then, as the distance implied by a locative becomes larger, there is greater difference in participant responses.

5.3 Influence of Scale on Participant Performance

One question that motivated part of this study was the influence of the scale or size of space on the comprehension of locatives. Instead of simply comparing the actual distances between the landmarks and object placement, we calculated this distance as a proportion of the model size (see Fig. 4). In all 4 plots in Fig. 4, the distance between a landmark and object placement, for all age groups is greater for the Model Town than for the Tabletop model. It was not certain from these results if this difference was an artifact of the different absolute model sizes, or if in fact scale of space influences how people conceptualize locatives. To explore this result a second experiment was conducted.

6 Experiment #2

For this second experiment, the tabletop space was reproduced at the size of the model town. In other words, we increased the tabletop from 17 inch × 28 inch to 4 feet by 6 feet so as to negate the possible influence of the absolute model size on

Table 4 Analysis of between group differences for *NEXT*

Tabletop model	Trash can *NEXT* to the block	4 years	5 years	7 years	9 years	Adults
	3 years	$F(1,70) = 0.92$ $P = 0.34$	$F(1,76) = 1.48$ $P = 0.23$	$F(1,77) = 0.19$ $P = 0.66$	$F(1,78) = 0.37$ $P = 0.55$	$F(1,78) = 7.37$ $P = 0.008$
	4 years		$F(1,73) = 0.64$ $P = 0.43$	$F(1,74) = 1.78$ $P = 0.19$	$F(1,75) = 4.09$ $P = 0.05$	$F(1,75) = 10.68$ $P = 0.002$
	5 years			$F(1,75) = 1.05$ $P = 0.31$	$F(1,76) = 6.20$ $P = 0.02$	$F(1,76) = 29.61$ $P < 0.001$
	7 years				$F(1,77) = 2.17$ $P = 0.15$	$F(1,77) = 21.3$ $P < 0.001$
	9 years					$F(1,78) = 12.23$ $P = 0.001$
Landscape Model	Person *NEXT* to the lake	4 years	5 years	7 years	9 years	Adults
	3 years	$F(1,60) = 4.25$ $P = 0.04$	$F(1,64) = 1.41$ $P = 0.24$	$F(1,65) = 11.2$ $P = 0.001$	$F(1,66) = 17.3$ $P < 0.001$	$F(1,66) = 14.3$ $P < 0.001$
	4 years		$F(1,68) = 1.94$ $P = 0.17$	$F(1,69) = 2.80$ $P = 0.10$*	$F(1,70) = 8.26$ $P = 0.005$	$F(1,70) = 5.21$ $P = 0.03$
	5 years			$F(1,73) = 10.5$ $P = 0.002$	$F(1,74) = 21.1$ $P < 0.001$	$F(1,74) = 15.5$ $P < 0.001$
	7 years				$F(1,75) = 1.32$ $P = 0.26$	$F(1,75) = 0.35$ $P = 0.56$
	9 years					$F(1,76) = 0.31$ $P = 0.58$

Grey shaded cells indicate a significant difference between age groups; * indicates marginally significant differences. For example, there was no significant difference between 3, 4, 5, 7 and 9 year-olds, but there was a significant different between 3 year-olds and adults

Table 5 Analysis of between group differences for *NEAR*

Tabletop Model	sheep *NEAR* the block	4 years	5 years	7 years	9 years	Adults
	3 years	F(1,66) = 3.79 P = 0.06*	F(1,67) = 6.42 P = 0.01	F(1,69) = 10.91 P = 0.002	F(1,69) = 1.43 P = 0.24	F(1,69) = 3.51 P = 0.07*
	4 years		F(1,73) = 2.40 P = 0.13	F(1,75) = 1.52 P = 0.22	F(1,75) = 0.88 P = 0.35	F(1,75) = 0.16 P = 0.69
	5 years			F(1,76) = 0.76 P = 0.39	F(1,76) = 4.76 P = 0.03	F(1,76) = 3.55 P = 0.06
	7 years				F(1,78) = 5.45 P = 0.02	F(1,78) = 3.31 P = 0.07
	9 years					F(1,78) = 0.41 P = 0.52
Landscape Model	Person *NEAR* the lake	4 years	5 years	7 years	9 years	Adults
	3 years	F(1,65) = 0.58 P = 0.45	F(1,67) = 0.45 P = 0.50	F(1,68) = 0.01 P = 0.92	F(1,69) = 9.87 P = 0.002	F(1,68) = 8.00 P = 0.006
	4 years		F(1,70) = 1.43 P = 0.24	F(1,71) = 2.63 P = 0.11	F(1,72) = 3.14 P = 0.08*	F(1,71) = 1.44 P = 0.24
	5 years			F(1,73) = 0.28 P = 0.60	F(1,74) = 5.54 P = 0.02	F(1,73) = 3.88 P = 0.05
	7 years				F(1,75) = 6.89 P = 0.01	F(1,74) = 5.24 P = 0.03
	9 years					F(1,75) = 0.89 P = 0.35

Grey shaded cells indicate a significant difference between age groups; * indicates marginally significant differences

Table 6 Analysis of between group differences for *AWAY*

Tabletop model	Trash can *AWAY* from the block	4 years	5 years	7 years	9 years	Adults
	3 years	F(1,77) = 1.66 P = 0.20	F(1,77) = 3.38 P = 0.07*	F(1,77) = 5.21 P = 0.03	F(1,77) = 13.8 P < 0.001	F(1,77) = 37.8 P < 0.001
	4 years		F(1,78) = 0.50 P = 0.48	F(1,78) = 1.59 P = 0.21	F(1,78) = 8.31 P = 0.005	F(1,78) = 33.3 P < 0.001
	5 years			F(1,78) = 0.32 P = 0.58	F(1,78) = 4.19 P = 0.04	F(1,78) = 21.6 P < 0.001
	7 years				F(1,78) = 1.91 P = 0.17	F(1,78) = 14.3 P < 0.001
	9 years					F(1,76) = 6.05 P = 0.02
Landscape Model	Car *AWAY* from the lake	4 years	5 years	7 years	9 years	Adults
	3 years	F(1,72) = 0.96 P = 0.33	F(1,72) = 4.61 P = 0.04	F(1,72) = 2.93 P = 0.09*	F(1,72) = 9.72 P = 0.03	F(1,72) = 34.1 P < 0.001
	4 years		F(1,76) = 1.61 P = 0.21	F(1,76) = 0.67 P = 0.42	F(1,76) = 4.93 P = 0.03	F(1,76) = 25.6 P < 0.001
	5 years			F(1,76) = 0.19 P = 0.67	F(1,76) = 0.69 P = 0.41	F(1,76) = 12.4 P = 0.001
	7 years				F(1,76) = 1.65 P = 0.20	F(1,76) = 15.9 P < 0.001
	9 years					F(1,76) = 8.34 P = 0.005

Grey shaded cells indicate a significant difference between age groups; * indicates marginally significant differences

Table 7 Analysis of between group differences for *FAR*

Tabletop model	Trash can *FAR* from the block	4 years	5 years	7 years	9 years	Adults
	3 years	$F(1,76) = 15.3$ $P < 0.001$	$F(1,77) = 18.4$ $P < 0.001$	$F(1,77) = 31.3$ $P < 0.001$	$F(1,77) = 47.6$ $P < 0.001$	$F(1,75) = 106.1$ $P < 0.001$
	4 years		$F(1,77) = 0.60$ $P = 0.44$	$F(1,77) = 4.55$ $P = 0.04$	$F(1,77) = 13.9$ $P < 0.001$	$F(1,75) = 69.7$ $P < 0.001$
	5 years			$F(1,78) = 1.32$ $P = 0.25$	$F(1,78) = 6.42$ $P = 0.01$	$F(1,76) = 38.4$ $P < 0.001$
	7 years				$F(1,78) = 2.27$ $P = 0.14$	$F(1,76) = 31.9$ $P < 0.001$
	9 years					$F(1,76) = 16.7$ $P < 0.001$
Landscape model	Car *FAR* from the lake	4 years	5 years	7 years	9 years	Adults
	3 years	$F(1,70) = 2.55$ $P = 0.03$	$F(1,70) = 11.8$ $P = 0.001$	$F(1,70) = 18.4$ $P < 0.001$	$F(1,70) = 32.4$ $P < 0.001$	$F(1,70) = 86.2$ $P < 0.001$
	4 years		$F(1,76) = 1.22$ $P = 0.27$	$F(1,76) = 4.66$ $P = 0.03$	$F(1,76) = 12.5$ $P = 0.001$	$F(1,76) = 45.0$ $P < 0.001$
	5 years			$F(1,76) = 1.38$ $P = 0.25$	$F(1,76) = 6.74$ $P = 0.01$	$F(1,76) = 34.4$ $P < 0.001$
	7 years				$F(1,76) = 1.71$ $P = 0.20$	$F(1,76) = 16.8$ $P = 0.001$
	9 years					$F(1,76) = 7.23$ $P = 0.009$

Grey shaded cells indicate a significant difference between age groups; * indicates marginally significant differences

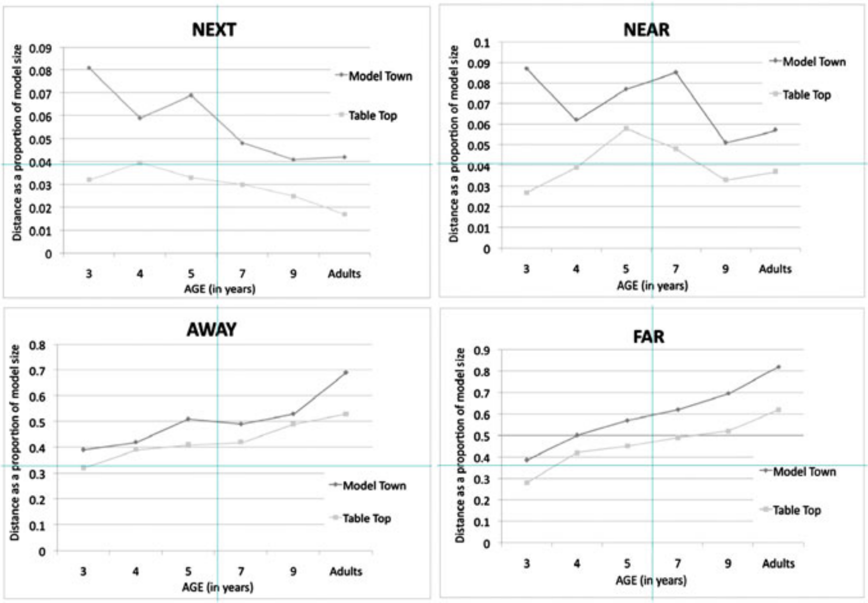

Fig. 4 Distance plotted as a proportion of model size

participant responses. The same objects used in the first experiment, the bed, block, barbeque grill, table, bus, rocking chair and refrigerator were used in this second experiment. The number of participants was limited to children of ages 5 and 9, and a group of adults. The reason for the selection of these age groups was because these were the ages, overall when differences between children and adults responses decreased significantly, or were the same in experiment #1. In addition, thirty participants, balanced for sex were included.

There were eight instructions, testing only the locatives that made reference to distance: NEAR, NEXT, FAR, AWAY, NEAR and NEXT, FAR and AWAY FROM, CLOSE and NEXT TO, and BETWEEN. Again, participants were tested individually, and the order of instructions was reversed for half of the participants. As in the first experiment, participants were asked to:

6.1 Put the [Object] [Locative Term] the [Referent]; e.g., Put the [Girl] [Near] the [Block]

Responses were marked on the large tabletop map, and distances between the object and referent were measured. Mean distance estimates were computed for each age. There were no distance estimates greater than 3 standard deviations around the mean (i.e., no outliers), therefore all responses were included in the

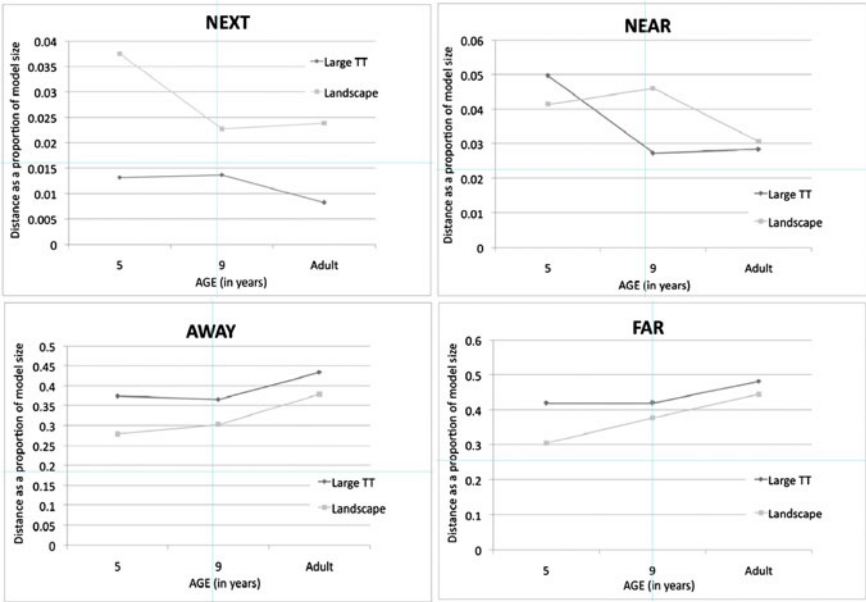

Fig. 5 Distance plotted as a proportion of model size, comparing the large tabletop model to the model town

analysis. Mean distances in the large, tabletop model, as a proportion of the model size were compared to the mean distances in the model town. ANOVA was used to analyze the results. Figure 5 illustrates the comparisons.

The plots in Fig. 5 show that for the locatives NEXT and NEAR, overall distances appear to be shorter on the large tabletop model than on the model town, and for the locatives AWAY and FAR, the distances on the large tabletop model appear larger than those for the model town. However, a statistical analysis indicates that only for the locative NEXT are these distances significantly different, $F(1,209) = 10.5$, $p = 0.03$.

7 Conclusion and Discussion

7.1 Developmental Differences in Type 3 Locatives

Results of the first experiment clearly demonstrated a developmental progression in the understanding of the locative terms NEXT, NEAR, AWAY and FAR. Based on the results in these two experiments, there appears to be support for both Piaget's and Inhelder's, and Huttenlocher's and Newcombe's theories. First off, all participants in both studies responded to each spatial instruction reasonably. In other words, none of the participants appeared unable to complete each task, nor did participants seem unsure how to respond. This result would support Huttenlocher and Newcombe in that children would have an appreciation of these terms by age 7. On the other hand, there were differences in how participants responded with regard to the distance between [referent] and [object]. For NEXT, participants 7 years of age and younger responded the same, and different from 9 year-olds and adults. Results for NEAR and AWAY were similar. However, for FAR there were differences in object placement between all age groups. These differences between age groups support Piaget and Inhelder.

An interesting result that illustrated the differences locatives NEXT, NEAR, AWAY and FAR showed that distances for NEXT are closer than for NEAR, and that NEAR is closer than AWAY, and that AWAY is closer than FAR. In addition, the distance between object and referent gets closer with increasing age for NEXT and NEAR, and that this distance becomes larger with increasing age for AWAY and FAR.

7.2 Spatial Context

The second experiment suggests that spatial context may play a role in the understanding of locative terms but the results of this experiment are inconclusive. Although Fig. 5 illustrates apparent differences between object placements for the two models, there was only one significant difference between the two models in experiment #2, and that was for the locative NEXT. There are several possible explanations for these results. First off, it is possible that scale is not a factor in spatial concept understanding. While this is possible, these authors believe that other explanations need further investigation before arriving at that conclusion. Another possible explanation is that both the table-top and landscape models are just that—models. Neither model was an immersive space. Participants were external to, or outside both spaces, a significant factor in resultant cognitive representations (Tversky et al. 1999). Additional experiments that compare locative understanding in table-top spaces to larger, real-world spaces, spaces like a large classroom, a play ground, or a park, might isolate the scale factor in spatial concept understanding.

Further studies that would enable a finer-grained analysis are needed to explore the possible effect that spatial context, i.e., scale or size of space have on the comprehension of locatives. Such studies might employ methods of measurement in the testing environment rather than from maps. In addition, further studies might consider testing in immersive environments, for example a park or play ground, in addition to model environments where participants are external to the stimulus.

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References

Bailystock H, Codd Z (1987) Children's interpretation of ambiguous spatial descriptions. Br J Dev Psychol 5:205–211

Blades M, Spencer C, Plester B, Desmond K (2003) Young children's recognition and representation of urban landscapes from aerial photographs and in toy play. In: Evans G (ed) Remembering where: advances in understanding spatial memory. Erlbaum, Hilldsale, pp 287–308

Blaut JM (1997) Children can. Ann Assoc Am Geogr 87:152–158

Blaut J, Stea D (1973) Some preliminary observations on learning in school children. In: Downs R, Stea D (eds) Image and environment. Aldine, Chicago, pp 226–234

Bowerman M, Choi S (2001) Learning to express motion events in English and Korean: the influence of language-specific lexicalization patterns. Cognition 41(1–3):83–121

Bremner G, Idowu T (1987) Constructing favorable conditions for measuring the young child's understanding of the terms in, on and under. Int J Behav Dev 10:89–98

Bryant DJ, Tversky B, Franklin N (1992) Internal and external spatial frameworks for representing described scenes. J Mem Lang 31:74–98

Casasola M, Cohen LB, Chiarello E (2003) Six-month-old infants' categorization of containment spatial relations. Child Dev 74:679–693

Choi S, Bowerman M (1991) Learning to express motion events in English and Korean: the influence of language-specific lexicalization patterns. Cognition 41:83–121

Cohen R (1985) The development of spatial cognition. Lawrence Erlbaum Associates, Inc., Hillsdale

Conner P, Chapman T (1985) The development of locative comprehension in Spanish. J Child Lang 12:109–123

Couclelis H, Golledge R, Gale R, Tobler W (1987) Exploring the anchor-point hypothesis of spatial cognition. J Environ Psychol 7:99–122

Cox MV, Isard S (1990) Children's deictic and non-deictic interpretations of the spatial locatives 'In Front Of' and 'Behind'. J Child Lang 17:481–488

Downs RM, Liben LS (1997) Piagetian pessimism and the mapping abilities of young children. Ann Assoc Am Geogr 87:168–177

Durkin K (1981) Aspects of late language acquisition: school children's use and comprehension of prepositions. First Lang 2:47–59

Franklin N, Tversky B (1990) Searching imagined environments. J Exp Psychol Gen 119:63–76

Freundschuh SM (2000) Micro- and macro-scale environments. In: Kitchin R, Freundschuh SM (eds) Cognitive mapping: Past, present and future. Routledge Inc, New York, pp 124–146

Freundschuh SM (1992) Is there a relationship between spatial cognition and environmental patterns? In: Frank AU, Campari I, Formentini U (eds) Theories and methods of spatial-temporal reasoning in geographic space. Springer, New York, pp 288–304

Freundschuh SM, Blades M (1998) Put the horse NEXT to the lake and FAR from the water tower: the development of locative understanding in large- and small-scale model spaces. In: Paper presented at the annual meeting of the Association of American Geographers, Boston, MA, pp 25–29

Freundschuh SM, Blades M (1997) Locative understanding in large-scale, geographic environments. In: Paper presented at the annual meeting of the Society for Research in Child Development, Washington, DC, pp 6–9

Freundschuh SM, Egenhofer MJ (1997) Human Conceptions of Spaces: implications for geographic information systems. Trans GIS 2(4):361–375

Freundschuh SM, Mark DM, Gopal S, Gould M, Couclelis H (1990) Verbal directions for wayfinding: implications for navigation and geographic information and analysis systems. In: Proceedings of the 4th international symposium on spatial data handing, Zurich, Switzerland, pp 478–487

Freundschuh SM, Sharma M (1996) Spatial image schemata, locative terms and geographic spaces in children's narrative: fostering spatial skills in children. Cartogr Monogr 46, Orienting Ourselves Space: Implic Sch Curric 32(2):38–49

Gentner D, Bowerman M (2009) Why some spatial semantic categories are harder to learn than others: the typological prevalence hypothesis. In: Guo J, Lieven E, Erivin-Tripp S, Budwig N, Ozcaliskan S, Nakamura K (eds) Crosslinguistic approaches to the psychology of language: Research in the tradition of Dan Isaac Slobin. Lawrence Erlbaum Associates, New York, pp 465–480

Hermer-Vazquez L, Spelke ES, Katsnelson AS (1999) Sources of flexibility in human cognition: dual-task studies of space and language. Cogn Psychol 39:3–36

Huttenlocher J, Newcombe N (1984) The child's representation of information about location. In: Sophian C (ed) Origins of cognitive skills. Lawrence Erlbaum Associates, Hillsdale, pp 81–111

Johnston JR (1988) Children's verbal representation of spatial location. In: Stiles-Davis J, Kritchevsky M, Bellugi U (eds) Spatial cognition: Brain bases and development. Erlbaum, Hillsdale, pp 195–205

Johnston JR (1984) Acquisition of locative meanings: behind and in front of. J Child Lang 11:407–422

Johnston J, Slobin D (1979) The development of locative expressions in English, Italian, Serbo-Croatian and Turkish. J Child Lang 6:529–545

Landau B, Jackendoff R (1993) 'What' and 'where' in spatial language and cognition. Behav Brain Sci 16:217–265

Lynch K (1960) Image of the city. MIT Press, Cambridge

Mark DM (1999) Spatial representation: a cognitive view. In: Maguire DJ, Goodchild MF, Rhind DW, Longley P (eds) Geographical information systems: principles and applications, 2nd edn. pp 1, 81–89

Mark DM, Egenhofer MJ (1994) Modeling spatial relations between lines and regions: Combining formal mathematical modes and human subjects testing. Cartogr Geogr Inf Syst 21(3):195–212

Mark DM, Frank AU (1992) NCGIA initiative 2 "Languages of Spatial Relations" closing report. National Center for Geographic Information and Analysis, University of California, Santa Barbara

Montello D (1998) Scale and detail in the cognition of geographic information. Report online: http://www.ncgia.ucsb.edu/varenius/scale/

Montello D (1993) Scale and multiple psychologies of space. In: Frank A, Campari I (eds) Spatial information theory: a theoretical basis for GIS. Lecture Notes in Computer Science pp 716(312–321), Springer, New York

Piaget J, Inhelder B (1967) A child's conception of space (trans: Langdon FJ, Lunzer JL). Norton, New York (Original work published 1948)

Plester B (2004) Small people thinking about big spaces: young children's navigational use of aerial photographs. In: Catling S, Martin F (eds) Researching primary geography. Register of Research in Primary Geography, London, pp 151–161

Plester B, Blades M, Spencer C (2005) Children's understanding of environmental representations: Aerial photographs and model towns. In: Blades M, Spencer C (eds) Children and their environments: learning, using and designing spaces. Cambridge University Press, Cambridge, pp 42–56

Plester B, Blades M, Spencer C (2003) Children's understanding of aerial photographs. Child Geogr 1(2):281–293

Simms N, Gentner D (2008) Spatial language and landmark use: can 3-, 4-, and 5-year-olds find the middle? In: Love BC, McRae K, Sloutsky VM (eds) Proceedings of the 30th annual conference of the cognitive science society, Cognitive Science Society, Austin, pp 191–196
Sowden S, Blades M (1996) Children's use of the spatial terms 'near to' and 'next to'. First Lang 16:247–259
Spencer C, Blades M (eds) (2005) Children and their environments: learning, using, and designing spaces. Cambridge University Press, Cambridge
Taylor H, Tversky B (1992) Spatial mental models derived from survey and route descriptions. J Mem Lang 31:261–292
Thorndyke PW, Hayes-Roth B (1982) Differences in spatial knowledge acquired from maps and navigation. Cogn Psychol 12:137–175
Tversky B (1981) Distortions in memory for maps. Cogn Psychol 13:407–433
Tversky B, Morrison J, Franklin N, Bryant D (1999) Three spaces of spatial cognition. Prof Geogr 51(4):516–524

From Compasses and Maps to Mountains and Territories: Experimental Results on Geographic Cognitive Categorization

Leda Giannakopoulou, Marinos Kavouras, Margarita Kokla and David Mark

Abstract The present study is part of the general effort to explore commonsense conceptualizations of the geospatial domain in order to deal with the massive access and use of geographic information by different groups of people. The chapter focuses on the perception and cognitive categorization of geographic entities. A basic working assumption is that although the surrounding geographic world has a real structure, there are differences in the way this structure is perceived and conceptualized by different individuals. The present study builds upon a series of experiments in order to provide a comparative investigation of the influence of two factors on geographic categorization: (a) language and (b) expertise.

Keywords Cognitive categorization · Geographic concepts · Expert/non-expert distinction · Language

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1 Introduction

Nowadays, GIScience has to deal with the massive access and use of geographic information by heterogeneous groups of people varying in culture, language, age, background knowledge, interests, etc. through the Spatial Data Infrastructures and the web. Geographic information and Geographic Information Systems cannot be strictly considered as scientific tools addressing exclusively the needs of skilled geo-scientists.

This popularization of geographic information has turned the attention of GIScience to commonsense conceptualizations of the geographic domain. The aim is to explore new ways for the semantic representation of geographic information in order to be properly understood and used even by non-experts. In this context, there are still many open research issues that need investigation:

- How are geographic concepts perceived?
- Are geographic concepts language-specific or is there a set of universally perceived geographic concepts?
- Do expert conceptualizations of geographic concepts differ from non-expert conceptualizations?
- Are there any geographic concepts that excel others in cognitive importance?
- How can geographic concepts be semantically represented in cross-cultural and cross-linguistic environments such as the Semantic Web and Spatial Data Infrastructures in order to be properly understood both by experts and non-experts?

The present Chapter attempts to raise some of these issues and explore them in the context of empirical research. The focus is on geographic concepts, i.e., on how geographic entities are perceived and categorized by people. Concepts are indissolubly related to the study of thought and language, as they constitute "the most fundamental constructs in theories of the mind" (Laurence and Margolis 1999, p. 3). They are indispensable for cognitive abilities such as categorization and understanding and they constitute the fundamental components of ontologies and linguistic systems. That is why they have attracted such attention by many scientific fields, such as philosophy, linguistics, cognitive science, conceptual analysis, etc.

Based on experiential realism (Lakoff 1986), we assume that although the geospatial world exhibits a real structure, there are differences in the way people perceive and understand this structure and thus in the formation of geographic concepts. These differences may be attributed to a number of factors, such as language, culture, prior knowledge, scientific background, etc.

Language is thought to be closely related to the cognitive organization of physical entities and phenomena. Therefore, the description of geographic entities and phenomena through natural language may be used as a starting point to study the way people perceive, conceptualize and understand geographic space. Thus, we may assume that linguistic distinctions reveal categorical distinctions of geographic entities and phenomena.

Prior knowledge, whether general or specific, also influences concept learning and categorization. People apply learning strategies which seem to use prior knowledge of formerly learned categories for the selection of certain features as more important than others and for the integration with new knowledge in a gradually revising process (Heit 1997).

Expert knowledge seems to play an important role in categorization as well. Experts draw finer distinctions among categories than novices do, since they form more specialized and distinct categories for their field of expertise (Tanaka and Taylor 1991). The difference between experts' and non-experts' cognitive categories is not only a quantitative issue relative to the number of categories but also involves the relations among the formed categories of a domain. Experts identify relations among categories that are not easily perceived by non-experts since experts have better developed theories of a domain (Murphy and Medin 1985).

Theory-based theories of concepts focus on the differences between concepts as perceived by experts and novices in order to explicate why experts' concepts are more specific and distinct than those of novices. Murphy and Medin (1985) draw a distinction between defining and characteristic properties of concepts in order to account for the fact that "experts have better developed theories about the domain than do novices" (p. 304). Defining properties are situated in the core of our knowledge, whereas characteristic properties are situated in the periphery of our knowledge (ibid). Although novices do not have such refined theories as experts do, they seem to have beliefs that there are defining properties for concepts, probably emanating from naive theories.

2 Experiment

The present study builds upon previous research and a series of cross-cultural and cross-linguistic experiments launched by David Mark and Barry Smith (Mark et al. 1999; Smith and Mark 1999, 2001) with a view towards developing Geographic Information Systems based on categories of geographic entities compatible with the conceptualizations of various groups of users.

These experiments were based on an experiment carried out by Battig and Montague (1969) in order to derive category norms for 56 categories such as: a precious stone, a bird, a crime, a unit of distance, a weather phenomenon, etc. Category norms are considered to reflect subjects' knowledge about category membership. For that reason, they are prominent in the study of categorization and in the representation of semantic knowledge. Van Overschelde et al. (2004) report that the Battig and Montague category norms were cited in over 1600 papers published in over 220 different journals according to a citation search performed in 2002. Due to their importance and wide use in many research fields, the study of category norms has been updated and expanded (Van Overschelde et al. 2004) in order to reflect the current conceptualizations of categories which have evolved since 1989. For example, subjects' conceptualizations of good category members for the categories "a type of dance", "a kind of money" and "a disease" have changed significantly during the past decades. The study of category norms has been extended to other languages such as Dutch (Ruts et al. 2004), French (Marshal and Nicolas 2003; Léger et al. 2008; Bueno and Megherbi 2009), and Spanish (Izura et al. 2005), as well as different age groups such as children (Price and Connolly 2006) and adults (Howard 1980). Besides the study of category norms for a specific language or age group, these studies also offer the possibility to perform comparisons between languages or age groups to identify significant similarities and differences (Yoon et al. 2004; Bueno and Megherbi 2009).

Smith and Mark (2001) aimed at investigating the most common members of geographic categories. In order to accentuate the effect of the target term "geographic" and minimize the effects of its accompanying term, Smith and Mark (2001) formulated five different wordings consisting of five different base nouns:

1. a kind of geographic feature
2. a kind of geographic object
3. a geographic concept
4. something geographic
5. something that could be portrayed on a map.

These wordings were presented to five different groups of subjects, expecting small differences in their responses. However, the experiment produced an unexpected result: the subjects' responses to the different phrasings were very different, thus leading to the evidence that the base nouns used (e.g., feature, object, concept, something) together with the term "geographic" recalled different superordinate categories in the minds of the subjects.

In light of these findings concerning subjects' responses and the role of the accompanying ontological terms to the term "geographic", the current experiment was designed in order to permit a comparison within subjects. Therefore, all subjects responded to every superordinate category. This method is more sensitive in "capturing" the different responses generated by different stimuli. However it has the disadvantage that the results are affected by the fatigue or familiarization of subjects with the experiment. In order to compensate the impact of the order of questions due to these factors, it was necessary to adopt a random or counter-balancing order for the superordinate categories.

The core of the present study is an experiment with human subjects carried out with two groups of subjects, one consisting of non-experts in the field of geography (so that a comparison with the results of Mark and Smith's experiment could be realized) and the other consisting of experts (which would permit a second set of comparisons between experts and non-experts). Therefore, the experiment was formulated in two phases as follows:

The first phase of the experiment involved 73 Greek non-expert subjects, (senior high school students and first-year college students). The results of this phase were compared to those of the American experiment (American non-experts) in order to perform a cross-cultural comparison.

The second phase of the experiment involved 37 Greek experts (postgraduate students of a Geographic Information Systems course) whose results were compared to those of Greek non-experts in order to study the effect of expertise.

The category "a kind of chemical element" appeared first in every questionnaire in order to provide the neutral stimulus.

The subjects were asked to give examples in response to the following eight superordinate categories:

1. « *ένα γεωγραφικό στοιχείο* » (a geographic feature),
2. « *ένα γεωγραφικό αντικείμενο* » (a geographic object),
3. « *μια γεωγραφικό έννοια* » (a geographic concept),
4. « *κάτι γεωγραφικό* » (something geographic),
5. « *κάτι που μπορεί να απεικονιστεί σε ένα χάρτη* » (something that could be portrayed on a map),
6. « *ένα γεωγραφικό φαινόμενο* » (a geographic phenomenon),
7. « *μια γεωγραφικό σχέση* » (a geographic relation), and
8. « *μια γεωγραφικό ιδιότητα* » (a geographic property)

The last two categories, i.e., "a geographic relation" and a "geographic property" were not included in the original experiment but were added due to their special interest.

The questionnaire consisted of nine pages, each one corresponding to a superordinate category, which was printed at the top of the page. The method of Latin square was used to create eight different combinations of the order of occurrence of categories; in that way each superordinate category appeared in a different order in each questionnaire.

The subjects were asked to write as many items included in the superordinate category in whatever order in 30 s. After the end of each 30 s interval, they were asked to stop writing and turn to the next page in order to start writing items for the next superordinate category.

Pires (2005) also replicated the experiment of Smith and Mark (2001) with Portuguese subjects in order to investigate cross-cultural patterns in geographic categorization. The study followed a similar experimental procedure to that of Smith and Mark (2001) in order to allow for a cross-cultural comparison. The experiment involved 160 non-expert students from different research fields and different cities of Portugal. The results were similar to these of the American experiment showing a tendency of subjects towards listing physical features such as rivers and mountains. However Pires (2005) points out that some methodological differences in the application of the two surveys, should be taken into consideration when comparing the results of the two countries. Firstly, in the Portuguese experiment subjects were asked to write items for all categories in the same questionnaire, whereas in the American experiment subjects responded to one of the five categories. Secondly, in the Portuguese experiment, subjects were asked to write six examples for each category, whereas in the American experiment subjects were prompted to write as many examples as they could.

3 Experimental Data Processing

3.1 General Processing

The analysis of the words and phrases given as examples of the aforementioned superordinate geographical categories and the double set of comparisons between experts and non-experts on one hand and between the American and Greek results on the other hand, reveal interesting elements about the way expertise and linguistic factors influence the categorization of geographic entities.

An initial processing of the experimental data involved mapping of terms, both at syntactic and semantic level. For example singular and plural terms were considered as equivalent. Terms with the same meaning were also considered equivalent, for example the terms « *όρος* » and « *βουνό* » that both mean mountain in Greek. This processing resulted in 405 terms for non-experts and 333 terms for experts.

Two main variables were used to process the experimental data:

- mean number of responses per subject
- term frequency

The *mean number of responses per subject* is an indication of the richness and familiarity of the categories. *Term frequency* on the other hand was the basic variable for the study of relations among categories. The *mean term frequency per category* is an indicator of the degree of convergence and homogeneity in subjects' responses concerning the terms that can be considered as good examples of a category.

Table 1 shows the mean number of responses per subject both for Greek experts and non-experts as well as for American non-experts. The category "something that could be portrayed on a map" has the largest mean number of responses per subject, even compared to the category "a chemical". Since the mean number of responses per subject is an indication of the richness and familiarity of the categories, it seems that the category "something that could be portrayed on a map" is the most familiar. However, the mean numbers of responses per subject are considerably larger for the American experiment, which may be attributed to the different conditions of carrying out the experiment (different groups of subjects responded to each superordinate category) or to the familiarity of American students with such experiments.

The categories "a geographic property" and "a geographic relation" have the least number of responses per subject for Greek non-experts and thus are considered as the least familiar. On the contrary, Greek experts seem to respond more easily to these categories, whereas for the category "a geographic phenomenon" they have a lower mean number of responses compared to non-experts.

For the analysis of the frequencies of terms, terms with frequency equal or greater than 3 for each superordinate category were selected. Thus after the mapping of terms and the application of the above criterion for term frequencies, a total of 65 terms remained for non-experts and 48 terms for experts.

Table 1 Comparison of mean numbers of responses per subject for Greek experts and non-experts and American non-experts

	Greek experts	Greek non-experts	American non-experts
A geographic object	2.65	2.14	5.48
A geographic feature	3.70	2.19	7.15
A geographic concept	3.41	2.25	5.15
Something geographic	3.14	3.27	6.17
Something that could be portrayed on a map	5.97	4.62	8.21
A geographic phenomenon	1.65	1.90	–
A geographic property	2.49	1.26	–
A geographic relation	3.32	1.29	–

Table 2 Term frequency and mean ordinal position for the category "something that could be portrayed on a map" for non-experts and experts

Non-experts			Experts		
	Term frequency	Mean ordinal position		Term frequency	Mean ordinal position
City	35	2.34	City	18	2.89
Country	31	2.39	Road	17	3.24
River	29	3.38	Mountain	15	4.13
Mountain	28	3.50	River	14	4.93
Lake	24	3.67	Country	12	2.17
Sea	22	4.41	Boundary	10	2.60
Road	16	2.38	Sea	9	4.44
Continent	10	4.20	House	6	5.00
Village	9	3.89	Island	5	4.20
Boundary	7	5.14	Settlement	5	3.00
Plain	7	4.71	Population	4	3.25
Island	6	3.17	Lake	4	6.75
Port	6	2.50	Building	4	6.75
Area	5	2.20	Contour lines	4	4.00

A frequency table was created in order to record for each superordinate category the total number of times each term was mentioned by all subjects, thus resulting in term frequencies.

Tables 2 and 3 show total frequencies and mean ordinal position of the most frequent terms listed under the superordinate categories "something that could be portrayed on a map" and "a geographic feature" for non-experts and experts.

Table 3 Term frequency and mean ordinal position for the category "a geographic feature" for non-experts and experts

Non-experts			Experts		
	Term frequency	Mean ordinal position		Term frequency	Mean ordinal position
Mountain	18	2.39	Mountain	12	3.33
Sea	11	2.36	River	11	2.18
Lake	10	2.60	City	9	2.89
Plain	9	3.22	Road	8	2.88
River	9	2.89	Sea	7	4.71
Population	5	1.20	Lake	6	4.17
Elevation	4	1.00	Elevation	4	2.00
Mountain range	3	4.67	Plain	3	5.67
City	3	1.33	Valley	3	3.33
Climate	3	1.33	Country	3	1.33
Ocean	2	4.00	Relief	2	5.00

3.2 Correspondence Analysis

After the general processing of experimental data, the method of Correspondence Analysis (Benzécri 1973; Greenacre 2007) was applied to the contingency table of term frequencies in order to detect possible relations among categories. Correspondence Analysis is an exploratory data analytic technique used to convert a data table (frequency or contingency table) to a graphical representation that accentuates the interrelations among the rows and columns of the original table. The aim is to detect the kind of structure immanent in data using a graphical representation, without presupposing a particular model of relationships or other precondition (such as a normal distribution of the initial variables or a linear relationship between two variables).

The main idea behind Correspondence Analysis is that each data row and column represents a point in a multidimensional space. Since the human mind is not able to perceive such multidimensional spaces, Correspondence Analysis aims at reducing a multidimensional space into a space of fewer dimensions in order to provide better understanding than that provided by the original space. The core of the method is a graphical representation which is derived from a double entry table. In this graphical representation, neighbor points indicate an interrelation among the corresponding rows/columns of the original data table: the closer two points are located, the stronger the association among the corresponding categories.

For the specific study, the cells of the original table represent term frequencies for the various superordinate categories. Four different applications of Correspondence Analysis were carried out; which means that four different basic contingency tables were formed:

1. Correspondence Analysis for exploring the table of term frequencies produced by Greek non-experts.
2. Correspondence Analysis for exploring the table of term frequencies produced by Greek experts.
3. Correspondence Analysis for exploring the table of term frequencies produced by Greek experts and non-experts.
4. Correspondence Analysis for exploring the table of term frequencies produced by American and Greek non-experts.

Since the graphical representation is the most informative part of Correspondence Analysis, containing the most valuable information, we will hereafter focus our discussion on the presentation of the most characteristic graphs (Column Plots), referring to three of the above application cases of Correspondence Analysis. We will mainly study the configuration of points (Column points which represent our geographic superordinate categories) in projection planes created mainly by axes 1 and 2 (Components 1 and 2), and sometimes by axes 1 and 3 (Components 1 and 3) in order to interpret the distances between them.

Figure 1 shows the result of Correspondence Analysis applied on the table of term frequencies produced by Greek non-experts: the category "geographic phenomenon" is far away from the center of the axes along the first axis (component 1) compared to the other superordinate categories. This implies that this category varies from the rest, since all other categories are arranged along the second axis (component 2). Moreover, the category "geographic relation" and to a lesser degree "geographic property" are drawn away from the other superordinate categories along the second axis, especially from the category "geographic object" (opposite signs).

Figure 2a presents the result of Correspondence Analysis applied on a unified table of term frequencies produced by Greek experts and non experts. This Figure is also important since it shows the stability of the overall framework of the eight superordinate categories between experts and non-experts. The categories as perceived by non-experts are shown in blue letters with the prefix "nx." whereas the categories of experts are shown in green letters with the prefix "x". From this figure it is evident that there is no variation between the answers of experts and non-experts along the axes 1 and 2 (components 1 and 2), since the corresponding superordinate categories are located close to each other.

The third axis (component 3) in Fig. 2b accentuates an important difference between experts and non-experts: the category "geographic phenomenon" as perceived by experts is located at the opposite side of the third axis compared to the equivalent category as perceived by non-experts.

Figure 3a, b demonstrates some aspects of the comparison between the American and Greek experiment based on a unified table of term frequencies produced by American and Greek non experts. More specifically, Fig. 3a shows stronger differences among the superordinate categories of American non-experts (shown in red letters) compared to those of Greek non-experts (shown in blue letters). The categories of the American experiment are located close to the centre

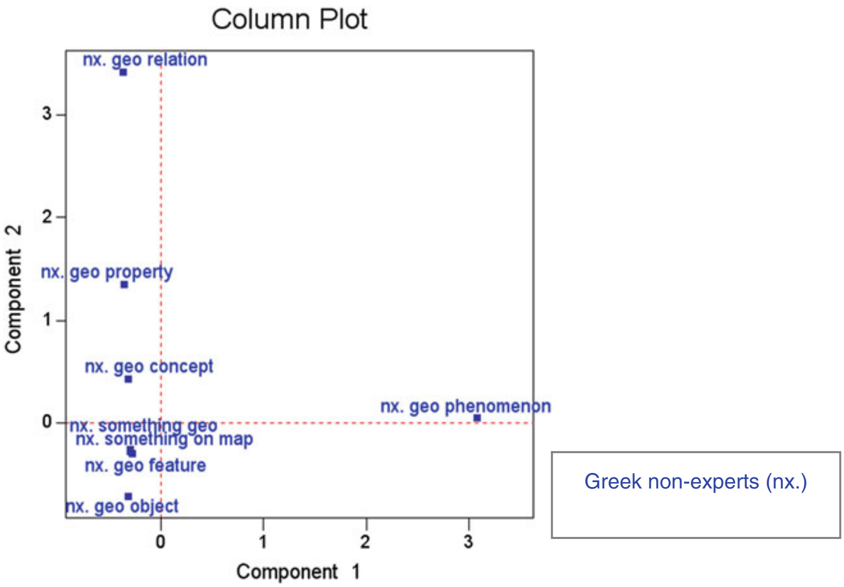

Fig. 1 Correspondence analysis of the 8 superordinate categories for Greek non-experts

of the axes, whereas the categories "geographic concept" and "geographic object" of the Greek experiment are scattered along the axes. The third axis (component 3) in Fig. 3b reflects the opposition between the category "geographic feature" as perceived by American subjects and the categories "something that can be portrayed on a map" as perceived by both American and Greek subjects. These three categories contribute to the 75 % of the variance along the third axis. This opposition refers to the prominence of physical entities (e.g., hill, valley, plateau) listed under the category "geographic feature" (American experiment) compared to the prominence of artificial entities (e.g., country, city, street) listed under the category "something that can be portrayed on a map" (both American and Greek experiments). Figure 3b also stresses the similarity of the category "something that can be portrayed on a map" for both American and Greek experiments.

Besides Correspondence Analysis, correlation coefficients were also calculated in order to highlight in a different way relations between corresponding categories. The correlation coefficient (Pearson) of the American and Greek versions of the category "something that can be portrayed on a map" was 0.82, which is the highest among the set of superordinate categories.

4 Results

The basic conclusion of Smith and Mark (2001) was that the basic term (such as "concept", "object", 'phenomenon", etc.) which accompanies the adjective "geographic" induces different responses regarding the representative members of the

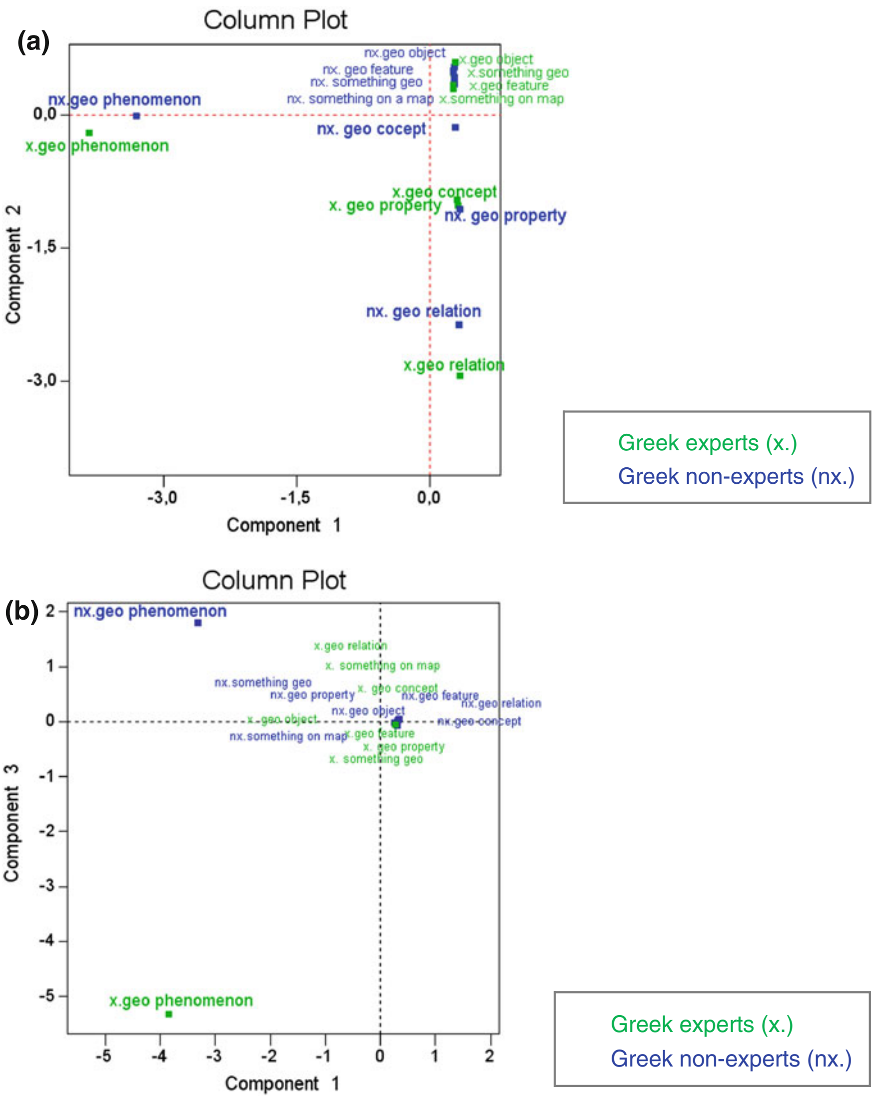

Fig. 2 **a** Correspondence analysis of the superordinate categories for the comparison between Greek experts and non-experts (*components* 1 and 2) **b** Correspondence analysis of the superordinate categories for the comparison between Greek experts and non-experts (*components* 1 and 3)

category. This conclusion was also confirmed for the Greek experiment (see Fig. 1). Furthermore, it was also discovered that different theoretical contexts, that is when moving from naïve theories to expert theories of a domain, as well as different linguistic contexts affect the meaning of certain categories by evoking different

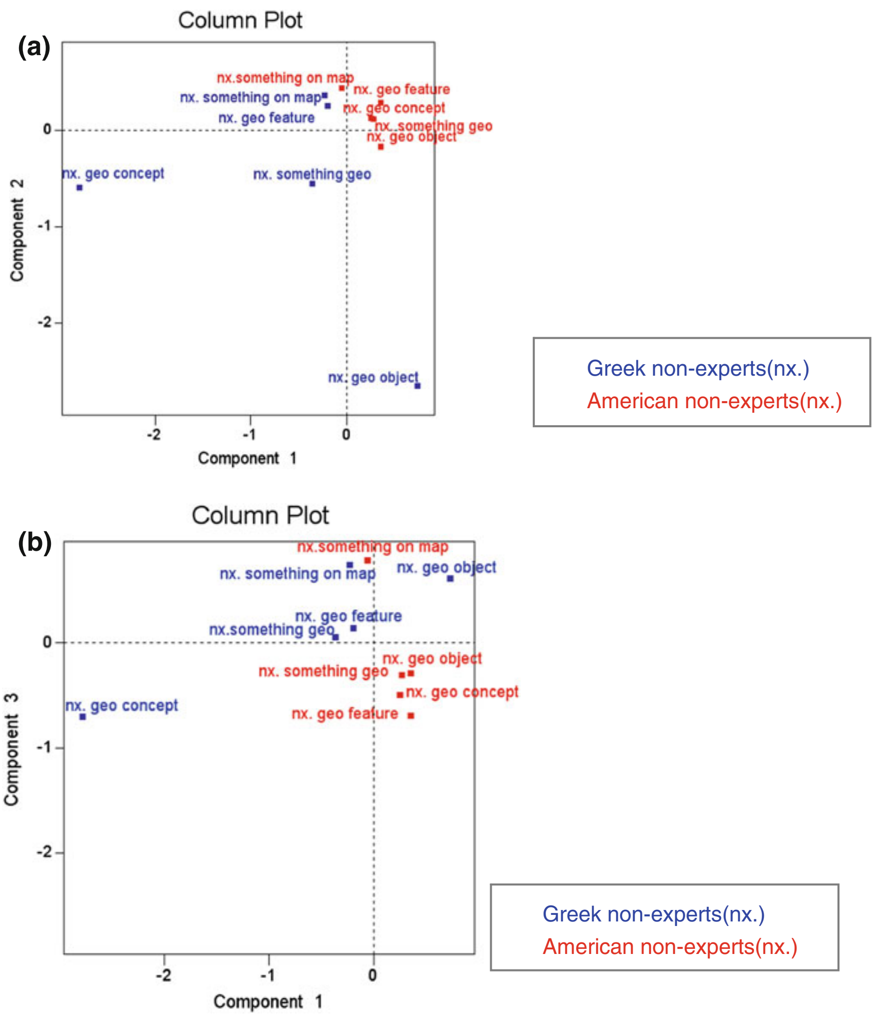

Fig. 3 **a** Correspondence analysis of the superordinate categories for the comparison between American and Greek non-experts (*components* 1 and 2) **b** Correspondence analysis of the superordinate categories for the comparison between American and Greek non-experts (*components* 1 and 3)

stimuli to the subjects. We will discuss the differences in the following after analyzing the elements that seem to have a broad and constant validity.

The main similarities regarding the content of the superordinate categories are:

- The category "geographic object" induced strong associations with small, portable objects (both to experts and non-experts) using terms such as "map", "compass", and "globe" as in the American experiment. Especially non-experts indicated many more small portable objects, such as "telescope" and "ruler", compared to experts as well as to American non-experts.

- For the category "geographic feature" subjects' responses were very similar to those of the American subjects, mainly focusing on entities of the physical environment such as mountain, sea, lake, plain, and river.
- The difference between the categories "geographic feature" and "something that could be portrayed on a map" is characteristic both for experts and non-experts. More specifically, just like for the American experiment, "geographic feature" is related to entities of the physical environment, in contrast to "something that could be portrayed on a map" which is related to features of the technical or manmade environment. This opposition constitutes a distinctive feature of three experiments, but is more evident in the American experiment.
- As in the American experiment, the category "something geographic" (both for experts and non-experts) is not differentiated compared to the other categories. It seems to be a commonplace, "flat" category which includes a mixture of terms, which were also listed under the other superordinate categories.
- In all cases, the most "familiar" and stable category seems to be the category "something that could be portrayed on a map" which presents the largest mean number of responses per subject in all three experiments.
- For the category "geographic concept", both experts and non-experts indicated (as expected) abstract concepts of Geography; however, the content of their responses was different. This focus on abstract terms was contradictory to the results of the American experiment as explained in the following.

The above mentioned similarities were identified using a combination of methodologies: Correspondence Analysis, calculation of correlation coefficients among corresponding categories, together with the study of the content of categories.

In retrospect the categories "something that could be portrayed on a map", "geographic object" and less the categories "geographic feature" and "something geographic" present similarities between Greek experts and non-experts. The categories "something that could be portrayed on a map", "geographic feature", "something geographic" and less the category "geographic object" present cross-cultural similarities.

Table 4 shows the most typical term for each superordinate category, based on term frequency. These terms present the highest frequencies and thus seem to be considered better examples of the corresponding superordinate categories. From this table, it seems that there is agreement on the most typical examples among experts and non-experts, as well as among American and Greek subjects for the categories "something that could be portrayed on a map", "a geographic feature", "something geographic" and "a geographic object".

Besides the similarities there were also important differences in the content of the categories. More specifically:

- The category "geographic phenomenon" generated different responses between Greek experts and non-experts. Experts mainly listed terms of Human Geography such as population movement, migration, and urbanization whereas non-experts listed terms of Physical Geography such as wind, cyclone, rain, sunlight, and volcano.

Table 4 The most typical term for each superordinate category, based on term frequency

Category	Greek experts	Greek non-experts	American non-experts
Something that could be portrayed on a map	City	City	City
A geographic phenomenon	Immigration flood	Earthquake	Earthquake
A geographic relation	Adjacency	East north	
A geographic property	Elevation	Mountainous	
A geographic feature	Mountain	Mountain	Mountain
Something geographic	Mountain	Mountain	Mountain
A geographic object	Map	Map	Map

- Regarding the category "geographic relation", experts listed terms which indicate topological relations, such as adjacency, boundaries, far, overlap, whereas non-experts listed terms representing cardinal directions (north, south, east, and west).
- Regarding the category "geographic property", experts' responses show a predominance of terms which denote geometric characteristics, such as depth, position, perimeter, elevation, and area, whereas non-experts' responses show a predominance of terms which denote more classic geographic characteristics, such as highland and lowland or the interpretation of the term "geographic property" as a profession, e.g., geologist.
- Regarding the category "geographic concept" although both Greek experts and non-experts responded with abstract geographic concepts, experts listed terms from the field of GIS such as: distance, adjacency, proximity, area, orientation, and topology. Greek non-experts on the other hand listed terms which are taught in the Geography course at school, such as: geographic longitude, geographic latitude, depth, meridian, equator, flora, and fauna. In contrast, although responses of American non-experts to this category present low coherence, the terms used mainly referred to natural features; the terms "sea" and "delta" had the highest frequency.
- It is also interesting to study the internal structure of the otherwise common and familiar category "something that could be portrayed on a map". Besides a common core, there are also certain differences. Experts mention terms such as boundaries, houses, contour lines, buildings, building plots, built-up areas, and hydrologic network. These terms refer to Surveying and Urban Planning. On the other hand, non-experts mention terms as lake, climate, seaport, airport, state, and trains. In addition, the term "capital" is especially popular among non-experts.

Regarding the comparison between Greek experts and non-experts, dissimilarities may be attributed to the different knowledge or theories possessed by the two groups of subjects. Besides common terms, experts also listed terms originating from Surveying, GIS and Human Geography, whereas non-experts listed terms from the field of Physical Geography, which is taught at school.

Table 5 The most frequent terms indicated by non-experts (for all superordinate categories)

Terms	Total frequencies
Mountain	76
River	61
Sea	53
Lake	53
City	53
Country	51
Map	45
Plain	36
Continent	23
Compass	23
Road	21
Latitude	19
Elevation	19
Longitude	17
Boundary	17
Earthquake	16
Capital	15
Island	14
Village	14
Globe	13
Population	12
Highland	10
Volcano	10
County	10
Mountain range	10

Table 6 The most frequent terms indicated by experts (for all superordinate categories)

Terms	Total frequencies
Mountain	42
City	42
River	33
Road	30
Map	27
Country	25
Sea	24
Adjacency	21
Boundaries	21
Elevation	19
Distance	18
Lake	17
Population	11
Coordinates	11
Village	10

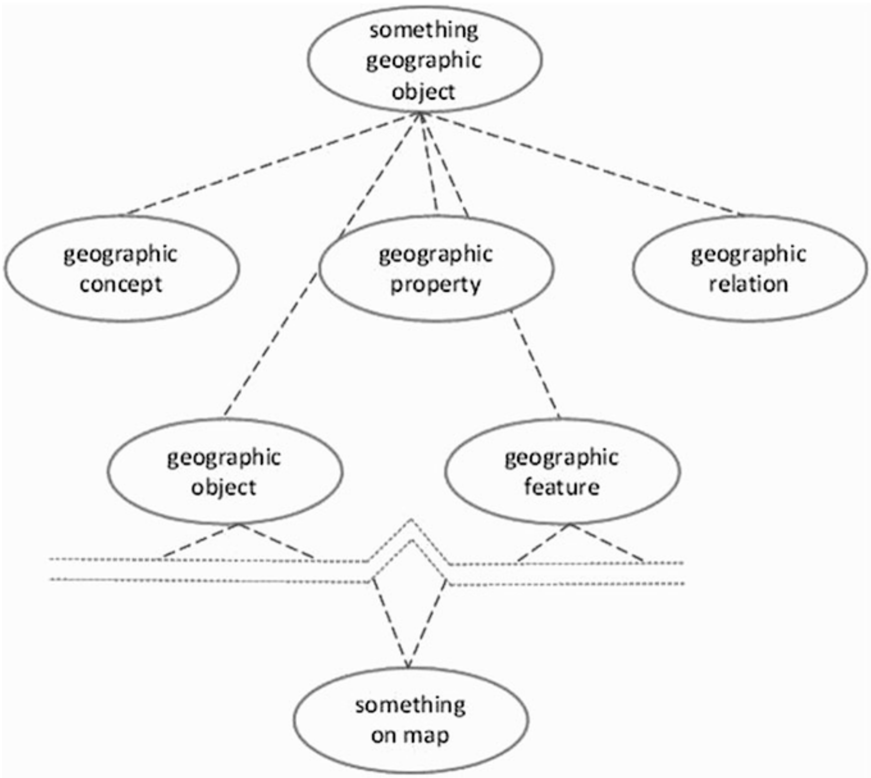

Fig. 4 Hierarchical organization among superordinate categories

Regarding the comparison between the American and Greek experiment, it is not easy to isolate cross-cultural differences due to different conditions of carrying out the experiment. The way the Greek experiment was conducted led to more intense polarities among categories. More specifically, it was not possible to verify the conclusion drawn by Smith and Mark (2001) that terms referring to the natural environment outweigh terms referring to abstract concepts and to the manmade environment (see Tables 5 and 6). Furthermore, the average of both experts' and non-experts' responses are notably lower than those of the American subjects. This however may be attributed to the different way of conducting the experiment since different groups of subjects were asked to respond to every category.

5 Conclusion

A general conclusion derived from the experiment is that subjects used a wealth of terms referring to both geographic reality and the representation of the reality, or terms referring to entities at geographic scale and entities at human scale (e.g., mountain and plain versus map and compass), to natural (e.g., river) and artificial entities (e.g., road), to real and abstract concepts (e.g., latitude and longitude) and to fiat and bona fide entities (mountain versus county, country and other territories).

A primary conclusion of Smith and Mark (2001) was that the basic term (such as "concept", "object", "phenomenon", etc.) which accompanies the adjective "geographic" had a strong influence on the meaning of the corresponding superordinate category and thus on the items indicated by the subjects. This conclusion was also confirmed for the Greek experiment: the ontological term used had a strong influence on the meaning of the corresponding superordinate category and thus on the items indicated by the subjects.

Moreover, the meaning of the ontological terms used imposed a somehow hierarchical organization among the superordinate categories. For example, the superordinate category "something geographic" is a general, flat category including a mixture of terms, also listed under other superordinate categories. This may be attributed to the fact that the term "something" or "thing" is the most general term in an ontological structure, used as the topmost concept in many top-level ontologies. Superordinate categories that can be considered to be situated lower in a hierarchical ontological structure such as "feature" and "object" and thus may be considered to be a part of a commonsense ontology appear to minimize differences due to language and expertise (Fig. 4).

Regarding the language parameter, it seems that subjects' responses coincide for those superordinate categories which are more familiar and commonsense, e.g., "something that could be portrayed on a map", "geographic feature", and "geographic object". Thus, despite the fact that people with different languages may develop different conceptualizations of geographic entities, some geographic concepts seem to be cognitively prominent. For example, although the conceptualization of a river, maybe different between American and Greek subjects, both groups consider it to be a characteristic example of a "geographic feature".

Regarding the expertise parameter, an important finding of the research is the discovery of a general stability of the overall framework of the eight-category system (regarding the relations among the categories) when comparing the results between experts and non-experts. This means that distances among the profiles of the different superordinate categories are stable in an almost "analog" way. For example, although the category "geographic phenomenon" is perceived differently by experts and non-experts, this category keeps a prominent stable distance from the other categories in both experiments (see Fig. 2a, b). The same holds for the superordinate categories "geographic relation" and "geographic property" as well as for "geographic object" and "geographic concept" with minor variations between the two experiments.

Theory-based theories of concepts may be employed to provide an explanation of the difference between experts' and non-experts' conceptual structures. Theory-based theories determine a concept's identity not relying on a set of distinguishing properties possessed by members of categories as Classical and Probabilistic theories (prototype and exemplar) do. More specifically, theory-based theories hold that human categorization is based not on a set of perceptible properties but on the knowledge that a concept incorporates an essence, "an appropriate internal structure or some other hidden property" (Laurence and Margolis 1999, p. 45) which results in the perceptible properties of the concept. The essence of concepts is determined by mental theories that limit the properties used for the cognitive representation of a concept. Since experts have more elaborate theories of a domain than non-experts, they seem to have more precise and unambiguous representations of concepts. However, non-experts also seem to believe that there are defining properties for concepts, probably based on naive theories. The view that people seem to be aware of an underlying essence of things is known as "psychological essentialism" (Medin and Ortony 1989; Medin and Rips 2005).

This may account for the fact that although non-experts may indicate different items under each superordinate category than experts, it seems that both groups agree on the meaning of the superordinate category. For example, it is characteristic that for the category "geographic concept", both Greek experts and non-experts listed abstract notions such as geographic latitude and longitude. This was more or less predictable for experts, but rather unexpected for non-experts, since the specific category was one of the vaguest of the questionnaire. Therefore, it seems that though non-experts may not fully possess a concept, they are aware of its meaning. This is a speculation worth further experimentation and study; specific evidence on this issue may reveal new ways for the semantic representation of geographic concepts, even vague and complex ones, in order to ensure their understanding and proper use by both experts and non-experts.

References

Battig WF, Montague WE (1969) Category norms for verbal items in 56 categories: a replication and extension of the Connecticut norms. J Exp Psychol 80(3):1–46

Benzécri JP (1973) L'Analyse des Données. Volume II. L'Analyse des correspondances. Dunod, Paris

Bueno S, Megherbi H (2009) French categorization norms for 70 semantic categories and comparison with Van Overschelde et al'.s English norms. Behav Res Methods 41(4):1018–1028

Greenacre M (2007) Correspondence Analysis in Practice, 2nd edn. Chapman & Hall/CRC, London

Heit E (1997) Knowledge and concept learning. In: Lamberts K and Shanks D (eds) Knowledge, concepts, and categories. Psychology Press, Taylor & Francis, London

Howard DV (1980) Category norms: a comparison of the Battig and Montague (1969) norms with the responses of adults between the ages of 20 and 80. J Gerontol 35(2):225–231

Izura C, Hernández-Muñoz N, Ellis AW (2005) Category norms for 500 Spanish words in five semantic categories. Behav Res Methods 37(3):385–397

Lakoff G (1986) Women, fire, and dangerous things: what categories reveal about the mind. University of Chicago Press, Chicago

Laurence S, Margolis E (1999) Concepts and cognitive science. In: Margolis E, Laurence S (eds) Concepts: Core Readings. MIT Press, Cambridge, pp 3–81

Léger L, Boumlak H, Tijus C (2008) BASETY: meaning extension and typicality of examples for 21 categories of objects. Can J Exp Psychol 62(4):223–232

Marchal A, Nicolas S (2003) Normes de production catégorielle pour 38 catégories sémantiques: Étude sur des sujets jeunes et âgés. /Category generation norms for 38 semantic categories in young and older subjects. L'Année Psychol 103(2):313–366

Mark DM, Smith B, Tversky B (1999) Ontology and geographic objects: an empirical study of cognitive categorization. In: Freksa C, Mark DM (eds) Spatial information theory: a theoretical basis for GIS. Lecture notes in computer sciences. Springer, Berlin, pp 283–298

Medin D, Ortony A (1989) Psychological essentialism. In: Vosniadou S, Ortony A (eds) Similarity and analogical reasoning. Cambridge University Press, Cambridge, pp 179–195

Medin D, Rips L (2005) Concepts and categories: memory, meaning, and metaphysics. In: Holyoak KJ, Morrison RG (eds) The Cambridge handbook of thinking and reasoning. Cambridge University Press, Cambridge

Murphy G, Medin D (1985) The role of theories in conceptual coherence. Psychol Rev 92:289–316

Pires P (2005) Geospatial conceptualisation: a cross-cultural analysis on Portuguese and American geographical categorisations. J Data Semant III, Lecture notes in computer science 3534:196–212

Price HL, Connolly DA (2006) BatMon II: children's category norms for 33 categories. Behav Res Methods 38(3):529–531

Ruts W, De Deyne S, Ameel E, Vanpaemel W, Verbeemen T, Storms G (2004) Dutch norm data for 13 semantic categories and 338 exemplars. Behav Res Methods Instrum Comput 36(3):506–515

Smith B, Mark DM (1999) Ontology with human subjects testing. Am J Econ Sociol 58(2):245–272

Smith B, Mark D (2001) Geographical categories: an ontological investigation. Int J Geogr Inf Sci 15(7):591–612

Tanaka J, Tayor M (1991) Object categories and expertise: is the basic level the eye of the beholder. Cogn Psychol 23:457–482

Van Oveschelde JP, Rawson KA, Dunlosky J (2004) Category norms: an updated and expanded version of the Battig and Montague (1969) norms. J Mem Lang 50:289–335

Yoon C, Feinberg F, Hu P, Gutchess AH, Hedden T, Chen HY, Jing Q, Cui Y, Park DC (2004) Category norms as a function of culture and age: comparisons of item responses to 105 categories by American and Chinese adults. Psychol Aging 19(3):379–393

Prospects and Challenges of Landmarks in Navigation Services

Kai-Florian Richter

Abstract In the past decades, empirical research has established the importance of landmarks in our understanding of and communication about space. These findings have led to the development of several computational approaches for the automatic identification and integration of landmarks in navigation instructions. However, so far this research has failed to make any impact on commercial services. This chapter will discuss reasons for this failure. It will develop a categorization of existing approaches and highlight their shortcomings. Finally, principles and methods of user-generated content will be identified as a promising, feasible way forward to future landmark-based navigation services.

Keywords Landmarks · User-generated content · Route directions · Location-based services

1 Introduction

In research on people's understanding of space, landmarks have been consistently shown to be of great importance, going back at least to Lynch's seminal work on 'the image of the city' (1960) which looked at how long-term residents conceptualize their cities' layout and social structure. Landmarks are important in learning environments (Siegel and White 1975) and in forming mental representations of environments (Couclelis et al. 1987; Hirtle and Jonides 1985). When communicating about an environment, for example, as when giving route

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directions, people use landmarks to anchor actions in space or to provide confirmation that the right track is still being followed (Denis 1997; Lovelace et al. 1999; Michon and Denis 2001).

Not surprisingly, landmarks are highly desired additions to automatic navigation services, such as car navigation systems. They are a top feature request of users (May et al. 2003). Using prototypical research systems, landmarks were found to improve users' performance and satisfaction with such systems in both car navigation (Burnett et al. 2001; Ross and Burnett 2001) and pedestrian wayfinding (May et al. 2003; Ross et al. 2004). However, they have hardly found their way into commercial systems and services—with a notable exception of the Australian routing service *WhereiS*.[1]

This chapter will explore some of the reasons why landmarks fail in end-user products. It will do so by analyzing and categorizing existing approaches for the identification and integration of landmarks in wayfinding instructions, and then pointing out shortcomings and challenges of these approaches. While there have been such analyses before (Sadeghian and Kantardzic 2008; Tezuka and Tanaka 2005), they restricted themselves to the extraction (identification) of landmarks; also, they miss some important recent developments in the field. The chapter will also propose novel ways of including landmarks that employ mechanisms of user-generated content and Web 2.0 technology. But first of all it will explain what is meant by the term 'landmark.'

1.1 What is a Landmark?

Lynch (1960) defined a landmark to be a readily identifiable object which serves as external reference point. This definition is frequently picked up in the literature, often resulting in landmarks being conceived as point-like features along a route. However, anything that sticks out from the background may serve as a landmark (Presson and Montello 1988). In light of this broad definition, the Urban Knowledge Data Structure (Hansen et al. 2006; Klippel et al. 2009) provides an elaborate formal specification of which types of geographic features may serve as landmarks in automatically generated route directions, from signage found along a street and individual buildings, such as churches, to linear features, such as rivers (Richter 2007), to salient street intersections, such as roundabouts (Klippel et al. 2005).

The "sticking out from the background" of a feature is often defined through its salience (Elias 2003; Raubal and Winter 2002). Sorrows and Hirtle (1999) identified three key characteristics of landmarks that influence this salience: (1) singularity, i.e., contrast with surroundings; (2) prominence of spatial location; (3) content, i.e., meaning or cultural significance. Several approaches aim at covering

[1] http://www.whereis.com.au

these characteristics in calculating salience values for landmark candidates. These will be discussed in the next section.

1.2 Landmark Identification and Landmark Integration

The inclusion of landmark references in automatically generated navigation instructions requires two steps: (1) the identification of features that may serve as landmarks in principle. In the following, these features will be referred to as *landmark candidates*; (2) the selection of some of these candidates to be included in the instructions. Often, these two steps are seen as independent (Elias et al. 2005). Consequently, most approaches that will be presented in the following either focus on the identification of landmark candidates or on the selection of features from a set of landmark candidates that are then integrated into the generated instructions.

1.2.1 Landmark Identification

In general, landmark identification is performed by specifying a region in which landmarks are to be sought (e.g., an area around an intersection), and then identifying outliers relative to other features in this region, i.e., finding salient features (Sadeghian and Kantardzic 2008).

The first approach to the automatic identification of landmarks was presented by Raubal and Winter (2002). It inspired several extensions and further approaches. Their approach reflects the three landmark characteristics of Sorrows and Hirtle (1999) by taking into account different attributes of building façades (e.g., area, color, signs, visibility) in a weighted sum for calculating individual buildings' salience. These façades serve as point-like landmarks along a route; the required data is supposed to be stored in a spatial database (GIS). Employing a user survey, weights for the individual parameters were set for specific situations, accommodating for differences between day and night (Winter et al. 2005). New situations require an adaptation of these weights, which likely requires new user studies.

In Winter (2003), calculation of salience accounts for advance visibility, i.e., how soon and for how long a façade is visible when considering the direction of travel. This is further refined in Klippel and Winter (2005), where locations of landmark candidates along a route are taken into account—termed structural salience by the authors. The location of a landmark influences the ease of conceptualizing turning actions and, thus, determines the ease of understanding instructions (Richter and Klippel 2007).

A similar approach to Raubal and Winter (2002) is taken by Elias (2003). She uses machine learning techniques to identify the most salient objects in a spatial data set. These objects are considered to be point-like entities. Winter et al. (2008) combine the two approaches of Raubal and Winter and of Elias to construct a hierarchy of landmarks based on each individual candidate's salience. This hierarchy is used in the generation of destination descriptions (Tomko and Winter 2009), which, accordingly, then is an example for integrating landmarks into wayfinding instructions.

Others have explored data mining approaches to identify landmark candidates for navigation services. Tomko (2004) used requests to Internet search engines looking for street names and subsequent filtering mechanisms to identify potential salient features (buildings) along a previously calculated route. Both search and filtering of results were done manually in this case, but may be automated with specifically tailored web services. In Tezuka and Tanaka (2005), text mining methods are used to mine WWW documents in order to identify prominent point-like features; prominence is based on how authors of these documents refer to the features. Mining of landmark information is further discussed below.

1.2.2 Landmark Integration

Caduff and Timpf (2005) presented an algorithm that calculates a route through a network based on the presence of point-like landmarks at decision points (nodes). It tries to navigate a wayfinder along a route that has a landmark at every decision point. They did not specify how these landmarks are identified, but rather assume their existence. The same holds for the approach by Richter (Richter 2007; Richter 2008; Richter and Klippel 2007), which integrates landmarks into an abstract specification of route directions that follow cognitive principles of direction giving. His approach selects those landmarks from a set of landmark candidates that are best suited to describe actions to be performed (cf. Klippel and Winter 2005). In a similar line, Elias and Sester (2006) used a modified Dijkstra shortest path algorithm to find a route through a network that integrates landmarks. Weights in the network are adapted according to the permanence, visibility, usefulness of location, uniqueness, and brevity of description of landmarks. Landmarks are assumed to be point-like (buildings) and are determined using the approach by Elias (2003).

The CORAL system by Dale et al. (2005) produces natural language instructions for route following, mimicking human principles of direction giving. Integration of landmarks is based on work by Williams (1998), which employs common-sense rules for selecting landmarks in indoor environments. The approach is not well documented, but seems to use location of a landmark and travel direction as parameters.

Recently, Duckham et al. (2010) explored using categories of features instead of their individual properties to determine suitability as a landmark. They combined a category's general suitability, its uniqueness in an area and a feature's location along a route to select those features best suited to describe how to follow the given route. This approach is implemented in the *WhereiS* route service using categories taken from the yellow pages. A similar approach was taken by Wagner (2009).

2 Landmarks in Navigation Services: A Categorization

This section develops a categorization of the approaches presented in the previous two sections. A first, broad categorization is already done there: the distinction between landmark identification and landmark integration. This distinction is the top level of the proposed categorization. Further, some approaches focus on properties of the features themselves, i.e., how they differ from other features in their surrounding. Other approaches account for the location of landmark candidates along a route to assess their suitability as references in instructions. The former is a static view on landmarks, the latter a dynamic view. This difference in views is similar to the distinction between *structure* and *function* in wayfinding as introduced by Klippel (Klippel 2003).

The (assumed) source of data that landmark identification is based on also differs between the approaches. Some use spatial databases of the kind attached to a typical geographic information system (GIS), some use data from the web (general websites; or web catalogs, such as yellow pages), and others do not specify their data source (marked as *abstract* in Table 1). Finally, approaches differ in the conceptual geometry of landmark candidates [points or more complex features, i.e., polygons; Hansen (2006)] and in whether they aim to identify individual features (instances) or categories of features (types).

Table 1 shows a matrix that categorizes the approaches presented in the previous two sections according to these criteria.

The first observation to make when looking at this matrix is that approaches to landmark identification predominantly work on a structural level, while landmark integration is on a functional level. This supports the statement made previously that identification of landmark candidates and selection of landmarks to be integrated in wayfinding instructions are considered to be independent steps. Landmark identification needs to find all features that may serve as a landmark in principle, i.e., are sufficiently salient. For a given data set, this may be done in a preprocessing step. The resulting set of landmark candidates then can be used as a pool of potential landmarks to select from when generating route directions for any route through the environment. Further, salience is a local feature (Elias 2003), in that a feature needs to stick out from its neighboring features. Thus, for landmark identification this static view on features' properties is useful as it allows determining a feature's general suitability. The two approaches that (also) are on a functional level already assume a specific given route for which landmarks are to be identified. They also partly cover the integration step, particularly Klippel and Winter (2005).

Landmark integration, on the other hand, needs to ensure that the referenced landmarks are actually useful in a navigation context. Landmarks need to be visible in the direction of travel, sensibly describe a (turning) action, and support conceptualization of the instructions. These characteristics are functional, as they depend on the specific route at hand. In the integration step, the landmarks chosen are not necessarily the most salient landmarks, but those that are most relevant for

Table 1 Matrix of approaches to landmark identification and integration

	Identification													
	Structure							Function						
	Data Source			Geometry				Data Source			Geometry			
	GIS	WWW	Abstract	Point	Polygon	Individual	Category	GIS	WWW	Abstract	Point	Polygon	Individual	Category
Elias (2003)	■			■		■								
Klippel and Winter (2005)										■	■		■	
Raubal and Winter (2002)	■			■		■								
Tezuka and Tanaka (2005)		■		■		■								
Tomko (2004)		■		■		■								
Winter (2003)	■			■		■		■			■		■	
Winter et al. (2008)	■			■		■								
	Integration													
	Structure							Function						
	Data Source			Geometry				Data Source			Geometry			
	GIS	WWW	Abstract	Point	Polygon	Individual	Category	GIS	WWW	Abstract	Point	Polygon	Individual	Category
Caduff and Timpf (2005)										■	■		■	
(Elias and Sester 2006)								■			■		■	
Dale et al. (2005)								■			■		░	░
Duckham et al. (2010)		■		■	░		■		■		■	░		■
Klippel and Winter (2005)										■	■		■	
Richter (2007), Richter and Klippel (2007)										■		■	■	

the given route. Consequently, approaches to landmark integration work on a functional level only (except for Duckham et al. 2010, discussed below); they usually take a set of landmark candidates to be given.

The separation between identification and integration also becomes apparent when looking at the chosen data sources. Each approach for landmark identification uses a concrete data source, mostly spatial databases. For landmark integration, many approaches are not specific regarding the kind of data source underlying their approach. Only Duckham et al. (2010) explicitly use a database of POIs in their case study that is taken from the *WhereiS* map server. Likewise, Dale et al. (2005) claim to base their approach on existing GIS data.

It can further be observed that with the exception of Duckham et al. (2010), all approaches employ individual features rather than categories. For the CORAL system (Dale et al. 2005), this is not really known, but it most likely uses individuals tagged manually based on common-sense assumptions about suitable categories (thus, the light gray marking in the table for this aspect). Finally, almost all approaches for identification and integration assume landmarks to function as point-like entities along a route, very much as defined by Lynch (1960). Duckham et al. (2010) acknowledged that other kinds of landmarks may be useful and presented some ideas on how to integrate them. Richter (Richter 2007; Richter and Klippel 2007) took this idea the furthest. He argued for the need to integrate linear and area-like objects in structuring route information (cf. Hansen et al. 2006) and developed a uniform approach to determining the functional role of landmarks with different geometries.

3 Challenges: Why are Landmarks Not Used in Commercial Systems?

Several challenges have prevented the integration of landmark references into commercial systems up till today. The calculation and generation of directions in these systems are based on simple, efficient algorithms. Metric distances and references to street names, as they are used today in commercial navigation software, are easily calculable from a geo-referenced network representation of the street layout. Landmarks need to be embedded into this existing network structure in a seamless way, i.e., the graph needs to be annotated with additional features such that they are easily integratable into the directions, ideally already in the path search. Some systems combine metric distances with references to traffic lights to provide additional context.[2] In some systems, points of interest (POIs), such as hotels or gas stations, are accessible. While these POIs could be used as sets of

[2] Often, however, this is done without taking into account the presence of other traffic lights. It is not uncommon to get instructions, such as ‘in 500 m, at the traffic lights, turn left,’ with another set or two of traffic lights before the one referred to.

landmark candidates in principle, they are hardly ever used for describing the route to take, but rather as commercial announcements or selectable destinations. Also, given the commercial nature of POIs, there will be a bias of employing specific types of landmarks only, such as fast food restaurants or gas stations, and their distribution and density will likely lead to great variations in the quality of landmark-based navigation services, as can be seen from the analysis below.

The seamless integration of landmarks requires a suitable data structure; the Urban Knowledge Data Structure (Hansen et al. 2006; Klippel et al. 2009) that is based on OGC's OpenLS specification[3] might be such an approach that can deal with different types of landmarks and offers mechanisms for structuring route information.

Given such a data structure, there is still the need to identify landmark candidates and then to integrate suitable candidates into route directions. However, as can be seen in Table 1, these two kinds of approaches often lack integration. Elaborate approaches to landmark integration either ignore the problem of identifying landmark candidates (Caduff and Timpf 2005; Richter 2007) or do not provide any details on how this is done (Dale et al. 2005). Some of the approaches to identification, namely Raubal and Winter (2002), provide some ideas on integrating landmarks into formal specifications of turning actions, but are restricted in the way references may be created and also fail to discuss situations where no landmarks are present.

Klippel and Winter (2005) explicitly combined identification and integration of landmarks by extending the Wayfinding Choreme grammar (Klippel 2003)—a formal specification of movement behavior in wayfinding—with landmark annotations. Consequently, this approach is listed both under identification and integration in Table 1. Winter et al. (2008) used the machine learning approach of Elias (2003) to identify landmark candidates, which are then used in generating destination descriptions (Tomko and Winter 2009). While these integrated processes work in theory, they are highly data intensive. They use individuals, i.e., identify individual features that may serve as a landmark. To gain useful results, these individuals need to be described in great detail, which is especially true for the calculation of façade salience in Raubal and Winter (2002). The required information is hard to collect automatically and, therefore, labor-intensive, will need to be specifically collected for each town and will result in large amounts of data. This makes it unlikely that it ever will appear in commercial databases due to the attached immense collection efforts and costs.

Therefore, looking at categories rather than individuals seems to be the more promising way, as can be seen with the implementation of Duckham et al.'s (2010) approach in the *WhereiS* web service. Using categories, properties of individual features do not need to be known since they are inferred by some heuristics from a general assessment of a specific category's suitability as landmark. Much less data is required; relevant information comprises location, geometry, and type of feature.

[3] http://www.opengeospatial.org/standards/ols

Table 2 Example of Route Directions generated with whereis.com.au

	Distance	Time
Directions A		
Start: Bourke St, Melbourne, VIC 3000		
1. Continue on Royal La, Melbourne—head towards Bourke St at Red Violin	1 km	
2. Turn right onto Bourke St, Melbourne	0.6 km	1 min
3. Turn left onto Spring St, Melbourne *at Imperial Hotel*	0.1 km	14 s
4. Continue along Nicholson St, East Melbourne *at Princess Theatre @ Marriner Theatres*	0.7 km	1 min
5. Turn right onto Palmer St, Carlton *at Melbourne Museum*	14 m	2 s
6. Turn right onto Nicholson St, Fitzroy *at Academy Of Mary Immaculate Catholic*	0.1 km	8 s
7. Arrive at Nicholson St, Fitzroy		
Sub Total:	1.5 km	3 min
End: Melbourne Museum, 11 Nicholson St, Carlton, VIC 3053		
Total:	1.5 km	3 min
Directions B		
Start: Melville Rd, Brunswick West, VIC 3055		
1. Continue on Melville Rd, Brunswick West—head towards Bakers Pde	0.1 km	12 s
2. Turn right onto Moreland Rd, Brunswick West	1.6 km	3 min
3. Turn left onto Sydney Rd, Brunswick *at Moreland Hotel*	0.6 km	1 min
4. Turn right onto Rennie St, Coburg	0.8 km	1 min
5. Turn left onto Darlington Gr, Coburg	0.3 km	46 s
6. Turn right onto Carlisle St, Coburg	0.1 km	9 s
7. Arrive at Carlisle St, Coburg		
Sub Total:	3.5 km	6 min
End: Carlisle St, Coburg, VIC 3058		
Total:	3.5 km	6 min

Directions A from Bourke St to the Melbourne Museum, the route used as an example in Duckham et al. (2010); Directions B from Brunswick West to Coburg, two urban residential districts in Melbourne

Table 2 shows two sample route directions including landmark references that were generated using the *WhereiS* web service.[4] Directions A (from Bourke St to Melbourne Museum) contain several references to landmarks, which illustrates that this approach has great potential for commercial systems (note that the actual integration of landmarks, i.e., the generation of directions may still be improved for better conceptualization of the turning actions). However, as directions B (from Melville Rd to Carlisle St), which lead through two of Melbourne's urban residential districts close to the city center, illustrate, landmark candidates are not evenly distributed across the environment. The route described by directions B is comparable in length and complexity to the route of directions A, and they are not far apart from each other. Still, for route B, far less landmark candidates are available than for route A. Duckham et al. state that in the current *WhereiS*

[4] Accessed on March 29, 2010.

implementation for all of Australia only 170,000 features from 66 categories can be used as landmarks.[5]

This results in a sparse distribution of landmark candidates throughout the country; it can also be expected that the density is significantly higher in inner-city areas compared to suburbs or rural areas. Comparable results were found in a diploma thesis at the University of Bremen (Wagner 2009) that used a similar approach. An informal evaluation showed that all selected landmark candidates are sensible (i.e., landmarks are visible and identifiable along the route), but the geographic data set used contains too few features to properly cover large parts of an environment.

To sum up, while generating landmark references based on category information rather than on individual landmark properties seems to be the most prominent way to go in automatic landmark identification, a remaining challenge is to pool sufficient information about a sufficient number of features from a sufficient number of useful categories such that enough landmark candidates emerge to cover all parts of an environment.

4 Outlook: User-Generated Landmark Information

The more promising option to get at the missing landmark data is to tap into the vast and ever increasing repositories of user-generated content, a lot of which is geographic in nature (Goodchild 2007; Krumm et al. 2008; Sui 2008). User-generated content refers to data that is contributed to a service by its users. Usually, this data collection happens without a central authority managing or supervising the collection process. The individual approaches to data collection vary and cover a spectrum from conscious, dedicated user action ('volunteered') to rather passive modes ('citizens as sensors'). These approaches are made possible by the recent advent of new web technologies—commonly termed 'Web 2.0', or 'GeoWeb' in the spatial domain—and the ubiquity of network connectivity (see also Hirtle and Raubal, this volume).

These approaches to user-generated content can either be *indirectly* or *directly* exploited in landmark identification. Indirect approaches would tap into existing data sources of contributed data, similar to the web mining approaches discussed above, while direct approaches would create new sources specifically tailored to serve as sets of landmark candidates.

The GeoCAM project (Zhang et al. 2009), for example, aims at extracting meaningful parts from web documents containing route directions. These parts are the origin, the destination, and the instructions to get from one to the other. This

[5] To get a better idea of what this means: if landmark candidates were evenly distributed across Australia, there would be roughly 200 candidates within the area of Melbourne, or about 1 feature every 45 km^2.

extraction could be extended to also filter landmark information from these instructions, similar to Tezuka and Tanaka (2005), which is already hinted at in Zhang et al. (2009). Such landmark extraction from web documents would be an indirect approach. Others used geo-referenced (and/or) annotated photographs from photo sharing websites to identify landmarks; see also approaches to place identification from user-generated content that use similar mechanisms, e.g., Hollenstein and Purves (2010); Mummidi and Krumm (2008). For example, Schlieder and Matyas (2009) used the Panoramio photo database[6] to identify prominent sights in four European cities. Crandall et al. (2009) used Flickr[7] as a source to identify representative views of cities, which typically correspond to some salient geographic feature, such as the town hall or a cathedral. These identified sights are prominent, outstanding features in these cities, given that they have been photographed multiple times by different users. Thus, they can be expected to be salient, and may be used as landmark candidates. However, such an approach to landmark identification requires places actually being photographed or otherwise captured in user-generated content, which, again, most likely will lead to a sparse, uneven distribution of candidates. The major cathedral in the center of town may be photographed thousands of times, while the neighborhood churches in the suburbs may never appear in any photo collection. Thus, indirect approaches of exploiting user-generated content for landmark identification, while not suffering from the insurmountable costs of data collection (users essentially provide the data for free), still suffer from too few landmark candidates in large areas of an environment to be useful for navigation services.

Direct approaches to user-generated landmark content may result in a more even distribution of landmark candidates. For example, OpenStreetMap collects user-generated content to provide topographic data of the world. While accuracy and completeness is not the same everywhere, overall this project has managed in the last few years to create a data set that is comparable with authoritative data sets in at least the more densely populated areas of the Western world (Haklay 2010; Zielstra and Zipf 2010).

Further, several dedicated services providing spatial information for specific user groups have been suggested in the literature. Priedhorsky et al. (2007) proposed a Wiki-like service for bicyclists. Here, users directly contribute semantic information to enhance the bike riding experience. CityFlocks proposed to exploit detailed knowledge of people living in a neighborhood to annotate places of interest in that neighborhood (Bilandzic et al. 2008). The latter is not particularly geared towards navigation information, but rather to find and judge places to get food and other daily needs.

It is conceivable that applications similar to CityFlocks can provide landmark information (Richter and Winter 2011). They could tap into locals' knowledge and expertise to identify landmarks for navigation services. Such services would need

6 http://www.panoramio.com

7 http://www.flickr.com

to be designed such that users stay motivated to contribute (for a discussion of why people contribute, see e.g., Budhathoki et al. (2010) and would require carefully crafted instructions of what to do in order to avoid biasing users in what they contribute. Another direct way of identifying landmark candidates through user-generated content may be to ask users of a website to describe intersections seen on photographs of that intersection (e.g., taken from Google StreetView). This may be implemented either as a photo tagging game similar to Google Image Labeler[8] (Ahn et al. 2006) or as a (low-)paid job on websites for human intelligence tasks, such as Amazon Mechanical Turk.[9] Such approaches directly tap into humans' semantic knowledge of an environment. They mark some geographic features of a neighborhood as landmarks and, depending on how the user interface is designed, also collect reasons as of why these features are seen to be landmarks. However, as with most user-generated content, there is no guarantee that the provided information is actually useful. Thus, these approaches require the incorporation of trust and reputation mechanisms (Alfaro et al. 2011; Flanagin and Metzger 2008) in the creation of landmark candidate sets. They may also incorporate mechanisms to 'follow' landmarks of specific users (e.g., because they turn out to be especially effective for some users), this way enabling user-specific landmarks in navigation instructions.

In summary, research over the last decades has clearly established the important role landmarks play in our understanding of and communication about space. Empirical findings have inspired several computational approaches to the identification of landmark candidates and their integration into (automatically generated) route directions. However, these advances in basic research failed to find their way into commercial applications; landmarks are hardly ever considered in of-the-shelf navigation services. This failure can be attributed to two aspects: (1) the immense effort and, thus, costs attached to the acquisition of the required data for many of the approaches; (2) the highly skewed distribution of landmark candidates in available spatial data, which leaves large parts of an environment without suitable candidates. These challenges may be tackled by exploiting principles and methods of crowd-sourcing. In light of current developments in user-generated content, where users participate in building up and improving the (web) services they use, instead of investing in ever more complex computational approaches that rely on infeasible top-down, authoritative data collection methods, computational intelligence and smart interface design should be invested to achieve sustainable crowd-sourced landmark collection services that exploit human intelligence of (local) experts.

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[8] http://images.google.com/imagelabeler/

[9] https://www.mturk.com/mturk/welcome

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References

Ahn L, Liu R, Blum M (2006) Peekaboom: a game for locating objects in images. In: CHI '06: Proceedings of the SIGCHI conference on human factors in computing systems. ACM, New York, pp 55–64

Alfaro LD, Kulshreshtha A, Pye I, Adler BT (2011) Reputation systems for open collaboration. Commun ACM 54(8):81–87

Bilandzic M, Foth M, De Luca A (2008) CityFlocks: designing social navigation for urban mobile information systems. In: DIS '08: Proceedings of the 7th ACM conference on designing interactive systems. ACM, New York, pp 174–183

Budhathoki NR, Nedovic-Budic Z, Bruce B (2010) An interdisciplinary frame for understanding volunteered geographic information. Geomatica 64(1):11–26

Burnett G, Smith D, May A (2001) Supporting the navigation task: characteristics of 'good' landmarks. In: Hanson MA (ed) Contemporary ergonomics 2001. Taylor & Francis, London, pp 441–446

Caduff D, Timpf S (2005) The landmark spider: representing landmark knowledge for wayfinding tasks. In: Barkowsky T, Freksa C, Hegarty M, Lowe R (eds) Reasoning with mental and external diagrams: computational modeling and spatial assistance—papers from the 2005 AAAI spring symposium, Menlo Park, pp 30–35

Couclelis H, Golledge RG, Gale N, Tobler W (1987) Exploring the anchor-point hypothesis of spatial cognition. J Environ Psychol 7:99–122

Crandall DJ, Backstrom L, Huttenlocher D, Kleinberg J (2009) Mapping the world's photos. In: Proceedings of the 18th international conference on world wide web. ACM, Madrid, pp 761–770, 1526812

Dale R, Geldof S, Prost J-P (2005) Using natural language generation in automatic route description. J Res Pract Inf Technol 37(1):89–105

Denis M (1997) The description of routes: a cognitive approach to the production of spatial discourse. Cahiers Psychologie Cognitive 16(4):409–458

Duckham M, Winter S, Robinson M (2010) Including landmarks in routing instructions. J Locat Based Serv 4(1):28–52

Elias B (2003) Extracting landmarks with data mining methods. In: Kuhn W, Worboys M, Timpf S (eds) Spatial information theory. Lecture notes in computer science. Springer, Berlin, pp 375–389

Elias B, Paelke V, Kuhnt S (2005) Concepts for the cartographic visualization of landmarks. In: Gartner G (ed) Location based services & telecartography. Geowissenschaftliche Mitteilungen, TU Vienna, pp 1149–1155

Elias B, Sester M (2006) Incorporating landmarks with quality measures in routing procedures. In: Raubal M, Miller H, Frank A, Goodchild M (eds) Geographic information science. Lecture notes in computer science. Springer, Berlin, pp 65–80

Flanagin A, Metzger M (2008) The credibility of volunteered geographic information. GeoJournal 72(3):137–148

Goodchild M (2007) Citizens as sensors: the world of volunteered geography. GeoJournal 69(4):211–221

Haklay M (2010) How good is volunteered geographic information? A comparative study of OpenStreetMap and ordnance survey datasets. Environ Plan B Plan Des 37(4):682–703

Hansen S, Richter K-F, Klippel A (2006) Landmarks in OpenLS—a data structure for cognitive ergonomic route directions. In: Raubal M, Miller H, Frank AU, Goodchild MF (eds) Geographic information science. Lecture notes in computer science. Springer, Berlin, pp 128–144
Hirtle SC, Jonides J (1985) Evidence of hierarchies in cognitive maps. Mem Cogn 13(3):208–217
Hollenstein L, Purves R (2010) Exploring place through user-generated content: Using Flickr to describe city cores. J Spat Inf Sci 1:21–48
Klippel A (2003) Wayfinding choremes. In: Kuhn W, Worboys M, Timpf S (eds) Spatial information theory. Lecture notes in computer science. Springer, Berlin, pp 320–334
Klippel A, Hansen S, Richter K-F, Winter S (2009) Urban granularities—a data structure for cognitively ergonomic route directions. GeoInformatica 13(2):223–247
Klippel A, Richter K-F, Hansen S (2005) Structural salience as a landmark. In: Workshop mobile maps 2005, Salzburg
Klippel A, Winter S (2005) Structural salience of landmarks for route directions. In: Cohn AG, Mark D (eds) Spatial information theory. Lecture notes in computer science. Springer, Berlin, pp 347–362
Krumm J, Davies N, Narayanaswami C (2008) User-generated content. Pervasive Comput 7(4):10–11
Lovelace KL, Hegarty M, Montello DR (1999) Elements of good route directions in familiar and unfamiliar environments. In: Freksa C, Mark DM (eds) Spatial information theory. Lecture notes in computer science. Berlin, Springer, pp 65–82
Lynch K (1960) The image of the city. The MIT Press, Cambridge
May AJ, Ross T, Bayer SH, Tarkiainen MJ (2003) Pedestrian navigation aids: information requirements and design implications. Pers Ubiquit Comput 7(6):331–338
Michon P-E, Denis M (2001) When and why are visual landmarks used in giving directions? In: Montello DR (ed) Spatial information theory. Lecture notes in computer science. Springer, Berlin, pp 400–414
Mummidi L, Krumm J (2008) Discovering points of interest from users' map annotations. GeoJournal 72(3):215–227
Presson CC, Montello DR (1988) Points of reference in spatial cognition: stalking the elusive landmark. Br J Dev Psychol 6:378–381
Priedhorsky R, Jordan B, Terveen L (2007) How a personalized geowiki can help bicyclists share information more effectively. In: WikiSym '07: Proceedings of the 2007 international symposium on wikis. ACM, New York, pp 93–98
Raubal M, Winter S (2002) Enriching wayfinding instructions with local landmarks. In: Egenhofer M, Mark D (eds) Geographic information science. Lecture notes in computer science. Springer, Berlin, pp 243–259
Richter K-F (2007) A uniform handling of different landmark types in route directions. In: Winter S, Duckham M, Kulik L, Kuipers B (eds) Spatial information theory. Lecture notes in computer science. Springer, Berlin, pp 373–389
Richter KF (2008) Context-Specific Route Directions - Generation of Cognitively Motivated Wayfinding Instructions, DisKi 314 / SFB/TR 8 Monographs Volume 3. IOS Press, Amsterdam, The Netherlands
Richter K-F, Klippel A (2007) Before or after: prepositions in spatially constrained systems. In: Barkowsky T, Knauff M, Ligozat G, Montello DR (eds) Spatial cognition V. Lecture notes in artificial intelligence. Springer, Berlin, pp 453–469
Richter K-F, Winter S (2011) Citizens as database: conscious ubiquity in data collection. In: Pfoser D, Tao Y, Mouratidis K, Nascimento M, Mokbel M, Shekhar S, Huang Y (eds) Advances in spatial and temporal databases. Lecture notes in computer science. Springer, Berlin, pp 445–448
Ross T, Burnett G (2001) Evaluating the human-machine interface to vehicle navigation systems as an example of ubiquitous computing. Int J Hum Comput Stud 55:661–674
Ross T, May A, Thompson S (2004) The use of landmarks in pedestrian navigation instructions and the effects of context. In: Brewster S, Dunlop M (eds) Mobile computer interaction-MobileHCI 2004. Lecture notes in computer science. Springer, Berlin, pp 300–304

Sadeghian P, Kantardzic M (2008) The new generation of automatic landmark detection systems: challenges and guidelines. Spat Cogn Comput Interdisc J 8(3):252–287

Schlieder C, Matyas C (2009) Photographing a city: an analysis of place concepts based on spatial choices. Spat Cogn Comput Interdisc J 9(3):212–228

Siegel AW, White SH (1975) The development of spatial representations of large-scale environments. In: Reese HW (ed) Advances in child development and behaviour. Academic Press, New York, pp 9–55

Sorrows ME, Hirtle SC (1999) The nature of landmarks for real and electronic spaces. In: Freksa C, Mark DM (eds) Spatial information theory. Lecture notes in computer science. Springer, Berlin, pp 37–50

Sui DZ (2008) The wikification of GIS and its consequences: or Angelina Jolie's new tattoo and the future of GIS. Comput Environ Urban Syst 32(1):1–5

Tezuka T, Tanaka K (2005) Landmark extraction: a web mining approach. In: Cohn AG, Mark DM (eds) Spatial information theory. Lecture notes in computer science. Springer, Berlin, pp 379–396

Tomko M (2004) Case study—assessing spatial distribution of web resources for navigation services. In: 4th international workshop on web and wireless geographical information systems W2GIS04, Koyang

Tomko M, Winter S (2009) Pragmatic construction of destination descriptions for urban environments. Spat Cogn Comput Interdisc J 9(1):1–29

Wagner DB (2009) Bestimmung von Landmarken aus räumlichen Daten. Diploma thesis, Universität Bremen

Williams S (1998) Generating pitch accents in a concept-to-speech system using a knowledge base. In: Proceedings of the 5th international conference on spoken language processing, Sydney

Winter S (2003) Route adaptive selection of salient features. In: Kuhn W, Worboys M, Timpf S (eds) Spatial information theory. Lecture notes in computer science. Springer, Berlin, pp 349–361

Winter S, Raubal M, Nothegger C (2005) Focalizing measures of salience for wayfinding. In: Meng L, Zipf A, Reichenbacher T (eds) Map-based mobile services—theories, methods and implementations. Springer, Berlin, pp 127–142

Winter S, Tomko M, Elias B, Sester M (2008) Landmark hierarchies in context. Environ Plan B Plan Des 35(3):381–398

Zhang X, Mitra P, Xu S, Jaiswal AR, Klippel A, Maceachren A (2009) Extracting route directions from web pages. In: Twelth international workshop on web and databases (WebDB 2009), Providence

Zielstra D, Zipf A (2010) A comparative study of proprietary geodata and volunteered geographic information for Germany. In: Painho M, Santos MY, Pundt H (eds) Geospatial thinking: Proceedings of 13th AGILE international conference on geographic information science 2010

Landmarks and a Hiking Ontology to Support Wayfinding in a National Park During Different Seasons

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Abstract This chapter describes the results of an empirical study aiming to provide additional knowledge on human verbal descriptions of routes and landmarks. The purpose of the present study is also to provide a theoretical basis for the design and implementation of our terrain navigator — a Location Based Service (LBS) for hikers. The central question regarding a terrain navigator concerns what kinds of spatial concepts and terms people use when hiking, and whether the concepts and terms are different from previous studies on route descriptions that have mostly been carried out in urban environments. We are also interested in what kind of role the seasons play in navigating; whether we would need remarkably different navigational instructions during winter compared to

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summertime. Altogether ten subjects participated in our thinking aloud experiment during summer conditions and another ten during snowy winter conditions. The landmarks were included in most of the propositions (79 % in the summer and 70 % in the winter). The analyzed propositions were classified into landmark groups and formalized as a hiking ontology, that also covers modalities. The results of this empirical study emphasize the role of landmarks in wayfinding when hiking during both summer and winter.

Keywords Landmark · Ontology · Hiking · LBS · Wayfinding · Season

1 Introduction

In many countries it has become trendy to pursue outdoor leisure activities such as hiking and, for example, Finnish national parks have become increasingly popular during the past decades. Maps have always played a dominant role not only during hiking, but also in planning the hike. Until now paper maps have been the main media for providing the map to a hiker, but gradually, new technologies have also been adopted in this usage area. There are several applications for smartphones that allow the user to view and browse outdoor maps. However, outdoor leisure activities still lack useful services for personal navigation, even though many users would need easy-to-use mobile guidance while hiking in the forest.

Although many research findings confirm the important role of landmarks for navigating, the use of landmark information is still rare in commercial navigation applications (Sarjakoski et al. 2012). Studies about landmark information focus mainly on urban areas. To implement an application for personal navigation related to such leisure-time activities as hiking, the question is whether the spatial concepts and terms used and the environment information needed for successful navigation are different for hiking in the forest compared to when people walk in built urban environments. The aim of our study is to collect and analyze the spatial descriptions people use when hiking, and to examine which kinds of landmarks they rely upon in a national park environment.

The population is ageing and more and more people have some kind of restrictions on their ability to move. In order to increase the potential for mobility impaired persons to move around and navigate independently, more detailed information on the environment should be supported by map services and delivered together with spatial information to their personal navigation devices (Laakso et al. 2011). For example, information about the difficulty of routes and one's restricted ability to move is needed when the LBS suggests suitable walking routes for elderly people. This information needs to be structured and represented consistently. These observations have raised two additional issues related to landmarks in a national park environment: first, the role and importance of landmarks may vary depending on the abilities and disabilities of the user group, second, the creation of ontologies could serve as a useful formalization step when designing the representation of the landmark information.

This study is part of two ongoing research projects. The goal of the HaptiMap project is to make LBSs and map applications accessible for user groups with various disabilities, including aging people with reduced mobility and visual impairments (Magnusson et al. 2009; HaptiMap 2008). The second project, UbiMap, focuses on the interactive map that is explored as a user interface between the user and the surrounding environment. The case studies for these projects are related to hiking in the forest. From the user studies, we established that, in addition to visual representation, an audio channel could potentially be valuable for supporting hikers. We are continuing the research by implementing a mobile application (which we call a terrain navigator) that will provide users with additional voice-based navigation instructions (Kovanen et al. 2010) on top of a visual map in an LBS in order to increase the hikers' safety and ensure that they are on the right trail. We will utilize the results of the present study for this purpose.

After reviewing previous research on the topics of route descriptions, landmarks and wayfinding, as well as ontologies for geospatial applications, Sect. 3 presents an empirical study that we repeated both during the winter and summer seasons in a national park with the same test set-up. The results are presented in Sect. 4 along with a comparison between the seasons. In Sect. 5, we present an ontology for hiking, based on the results from the recognized and categorized features in the forest. Finally, a discussion and conclusions are given.

2 Building Blocks to Support the Navigation Task

The current study approaches the problem of describing the national park environment in such a way that hikers would receive optimal support for navigation. In certain situations and for certain user groups this means that more detailed information about the environment is needed. Three topics are relevant within this context: wayfinding and landmarks, verbal route descriptions, and formalizing the knowledge about the environment as ontologies. In the following literature review we touch upon the most important findings from our perspective.

2.1 Wayfinding and Landmarks

Montello (2005) describes navigation as a coordinated and goal-oriented movement through the environment, which involves both planning and the execution of movements. He considers navigation to consist of two components: locomotion and wayfinding. Locomotion is the movement of one's body around an environment. There are various modes of locomotion, including either when people move about unaided by machines (such as climbing, walking, running), or aided by machines (such as planes, trains, cars). According to Montello, in contrast to locomotion, wayfinding is goal-oriented and involves decision making and the planned movement of one's body around an environment in an efficient way.

Elias et al. (2005) state that humans prefer to communicate navigational instructions in terms of landmarks that are the prominent objects along their route. Therefore, in their study, similar to an earlier study by Raubal and Winter (2002), the routing directions are enriched with landmarks. Snowdon and Kray (2009) address the importance of natural landmarks when navigating in the wild. They used a video-based approach that resulted in a visual simulation of the nature. According to their results, the most frequently used landmarks were peaks and watercourses. Already, in the study of Pick et al. (1995) in which map readers were dropped off in the wild and had to localize themselves with a plain topographic map, landforms proved to be sufficient features to localize oneself.

Raubal and Winter (2002) state that research on spatial cognition has shown that people use landmarks for spatial reasoning and to communicate routes. Whether or not an object is considered a landmark is a relative property, and the saliency of a landmark feature depends on the extent to which some of its attributes are distinctive compared to those of surrounding objects. Blades (1991) goes a step further and suggests that to be a landmark, a feature needs to be more than just an isolated place and has to be linked in memory to information which indicates how the individual should act when approaching the landmark. Ishikawa and Montello (2006) regard spatial knowledge as knowledge about the identities of discrete objects or scenes that are salient and recognizable in the environment. Landmark salience has been discussed in several studies (Caduff and Timpf 2008; Klippel and Winter 2005; Nothegger et al. 2004; Sorrows and Hirtle 1999). Caduff and Timpf (2008) claim that the salience of a landmark is not an inherent property of the feature, but a product of the relationship between the feature itself, the surrounding environment and the observer's cognitive and physical point of view. Sorrows and Hirtle (1999) place landmarks in three categories: visual, cognitive, and structural landmarks. As regards the salience of the landmark, they point out that the strongest landmarks contain all three elements.

While Golledge (1999) states that the landmarks may support wayfinding at decision points, Janzen and van Turennout (2004) showed this through brain imaging. Landmark objects at decision points activated the objects-in-place -related brain region of participants significantly more often than landmarks at non-decision points, even if the participants did not precisely remember having seen the objects.

Ross et al. (2004) showed the importance of landmarks for pedestrian route instructions in an experiment in which half of the participants were given traditional vehicle navigation instructions (e.g., "Turn left after 50 m onto Street Road") and the other half received instructions enriched with landmarks (e.g., "Turn left after 50 m onto Street Road, after the statue"). The participants made significantly less turning errors in the experiment when landmarks were embedded in the instructions probably because the users could identify the decision points earlier with landmarks. Rehrl et al. (2010) also discovered that landmarks eliminate the errors caused by ambiguous turning directions that occur with metric instructions.

2.2 Route Descriptions

Route-like spatial knowledge is tightly linked to the task of wayfinding, which is one of the most frequent human activities performed through spatial cognition. During the process of wayfinding, the strategic link is the environmental image, and the need to recognize and pattern our surroundings is crucial (Lynch 1960). Route knowledge is procedural knowledge in the form of a sequence of locations and their characteristics. The route-like organization of spatial knowledge is identified as part of the human spatial mental model and often as an alternative for the survey-like model (Thorndyke and Hayes-Roth 1982; Jacobson 1998; Tversky 1993, 2003). The structure of route knowledge in the human mind can be experimentally studied through analyzing verbal route descriptions. Route descriptions can be collected while proceeding on the route or when the user is far from the route, for example in laboratory situations.

Analyzing verbal route descriptions is a linguistic task. Denis (1997) observed that his collection of descriptions consisted mainly of propositions that introduced actions and landmarks. Based on his data, he created a five-class classification of spatial propositions: (1) action only, (2) action with reference to a landmark, (3) landmark introduction, (4) landmark description, and (5) commentary. Denis's classification provides a general framework for analyzing route descriptions and it has been used in several comparable studies (see, for example, Rehrl et al. 2009).

Le Yaouanc et al. (2010) used verbal descriptions of a landscape scene from panoramic photographs to build a structure-based model of an environment. Urban and nature environments essentially differ from one another in that the former mainly consists of distinguishable objects with clear boundaries, whereas the latter is full of fuzzy objects with indeterminate boundaries. So far, few studies have been done in a non-urban environment. Brosset et al. (2008) collected their route descriptions in nature and found that the portion of landmark descriptions was larger than in preceding comparable studies on urban environments. However, they found fewer landmark introductions that might be peculiar to nature environments where landmarks are often combined with actions in order to specify the direction.

2.3 Ontologies for Geospatial Applications

In recent years, ontologies have become popular in the field of computer and information science (Stigmar 2010). The term ontology refers to a branch of philosophy and the science of what is. Ontologies deal with the semantic characteristics of objects, properties, processes and relations, and how they are structured in reality, and try to create classifications for these characteristics. The classifications should be well-defined and unambiguous (Bittner et al. 2005; Gruber 1993; Guarino 1998).

Today, the information science community widely accepts the use of the term ontology to refer to a conceptual model, and the term has little to do with the original question of ontological realism (searching for the truth). It has become pragmatic (Smith 2003). According to Guarino (1998), the philosophical language-independent perspective of ontologies can be termed conceptualization, whereas the information-science, language-dependent perspective should be the one that the term ontology is used for.

Ontologies are classified as high-level ontologies and low-level ontologies, which is done depending on the content. High-level ontologies have concepts with rich semantics and define general concepts that have foundational roles in nearly every discipline (e.g., "equals", "is part of"). Respectively, low-level ontologies define concepts for a specific domain or task. Top-level ontologies are the "highest" high-level ontologies. Domain ontologies, on the other hand, are low-level ontologies specified for a specific domain. Task ontologies are similar to domain ontologies, but they focus on a specific task or activity instead of a domain. Application ontologies are even more specific and define the concepts for a specific application depending both on a specific domain and a specific task (Kavouras and Kokla 2008, Bittner et al. 2005, Guarino 1998).

The different types of ontologies are often classified according to their formality, contents, or structure. Regarding the formality, there are informal ontologies and formal ontologies and a wide range in between. Informal ontologies use natural language to express the meaning of the terms, while formal ontologies use an artificial formal language, often with formal semantics, theorems, and proofs. However, it should be noted that ontologies often have both formal and the informal parts in which the formal parts support automated processing and informal parts support human understanding (Kavouras and Kokla 2008). In order to represent the information in the ontologies, ontology languages are used. An example of an ontology language is Web Ontology Language (OWL) (Dean and Schreiber 2004), which is used in the Semantic Web. It is expressive and prevalent in the creation of task ontologies (Dean and Schreiber 2004).

The creation of geo-ontologies is a priority research theme in the geospatial domain. However, creating a domain ontology for the geospatial world would be very complex, as the ontology would have to be enormous in order to contain a sufficient amount of taxonomical concepts and be neutral among different communities. This would not be possible without making major compromises. Therefore, the creation of an upper-level and a number of sub-level ontologies is more feasible.

Paepen and Engelen (2006) constructed an ontology for pedestrian navigation in order to implement a language-independent system for authoring hiking route instructions. They noted that pedestrians need much more detailed route instructions than do those driving cars and that human authoring is still needed for satisfying instructions.

After we describe our own study in the following section, and present the results in Sect. 4, we present the collection and formalization of important landmarks for hiking, with the final formalization having been done in the ontology language OWL.

3 Study Outline

We collected verbal route descriptions in an empirical study in which 20 participants were taken into a national park where they each had to follow and describe a route and the nearby landmarks (Fig. 1). Altogether, ten people participated in the experiment during summer conditions and the other ten in snowy winter conditions. In this section, we briefly describe how the experiments were carried out and how we analyzed the results in order to study differences between the seasons in route descriptions and the landmarks used in the descriptions. The experimental set-up is briefly presented here, but it is documented in more detail in Sarjakoski et al. (2012) and McGookin et al. (2011).

3.1 Collection of Route Descriptions

Prior to the test session, we asked the participants for some background information, such as their year of birth, profession, and previous hiking experience. The participants, aged 19 to 54, spoke Finnish as their mother tongue. They reported hiking in nature, on average, a few times a month.

We carried out the experiments in Nuuksio National Park in southern Finland. The test route was 1.2 km long and there were 24 decision points along the route (Fig. 1). All the path crossings where the user had to decide which way to take were treated as decision points. The test route ran through a thick forest that included many uphill and downhill stretches. It took about half an hour to walk the route. Half of the route consisted of marked hiking routes, while the other half consisted of small non-marked paths in the forest.

The following assignment was given to the participants before they began their test session: "Describe everything you find remarkable in the surroundings and explain their locations. Stop when you have to make a decision about which route

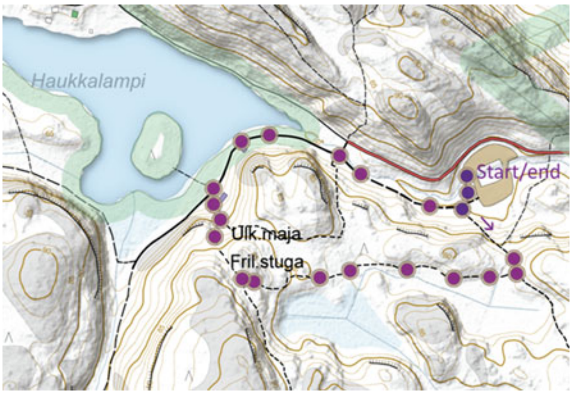

Fig. 1 Participants followed a route defined prior to the experiment

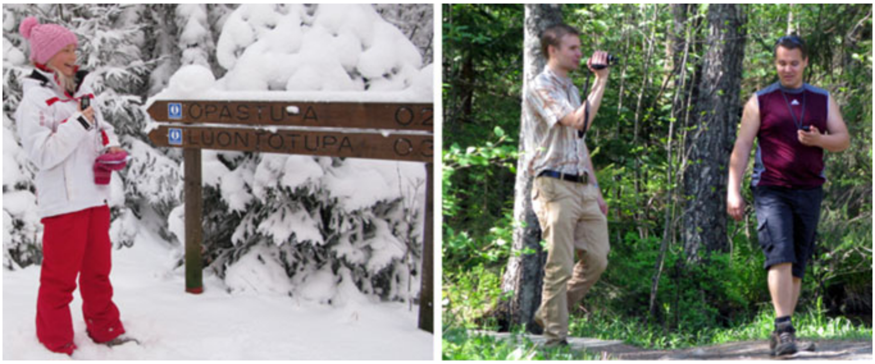

Fig. 2 Each test session was documented with audio and video recordings. The participants described their surroundings at and between the decision points

to take. Describe the options in detail." At the decision point, the participant had to describe the possible options by thinking out loud, a method described by Boren and Ramey (2000). After the participant introduced the possible alternatives, the instructor pointed out the direction in which to continue. When the description was very brief, the instructor asked the participant to elaborate and keep talking; otherwise, the instructor kept quiet. The participants did not use any navigation equipment such as maps, compasses or navigators. Each test session was documented with audio and video recordings (Fig. 2).

3.2 Classification of Propositions

In the first phase of the route description analysis, we split the transcripts into propositions, that is, into basic units of speech in which participants introduced individual easily distinguishable statements (Sarjakoski et al. 2012). In splitting the transcripts, we applied Denis's (1997) method of dividing the propositions into five classes:

1. action propositions without landmarks, such as "I continue forward";
2. propositions using both actions and landmarks, such as "I pass a red sign";
3. landmark propositions without actions, such as "I see two huts on the left";
4. landmark descriptions, such as "The spruce is close to the path";
5. commentaries, such as "Birds are singing loudly."

In order to analyze the contents of route descriptions at the decision points and between them, we registered for every proposition, with the help of the audio and video recordings, whether it was spoken at a decision point or not. The classification of propositions allowed us to calculate the proportions of the route description classes from among the total number of propositions. We compared the proportions of the proposition classes between the summer and winter experiments and also analyzed whether the proportions at decision points were different than the proportions between the decision points.

3.3 Calculating Landmarks

We continued our analysis by focusing on the landmarks in the thinking aloud route descriptions. We wanted to know which kinds of landmarks the participants used in their descriptions and how often they used the different landmarks. To accomplish this task, we applied methods of Natural Language Processing (NLP) (Manning and Schütze 1999) to the thinking aloud transcripts.

The Finnish language abounds with fluctuations, making NLP difficult because calculations can only be done for the basic forms of the words. Therefore, our first task was to transform the transcripts into basic form words for which we used Helsinki Finite-State Transducer Technology (HFST 2011). Next, we counted the words from the transcripts in their basic form. We made the calculations using the Python programming language and the Natural Language Toolkit (NLTK 2011) Python library, which provides core functionalities for NLP analysis. We first calculated the total number of times each word appears in its basic form in the summer and winter experiments in order to make comparisons between the seasons. We then created a list of landmark words by picking out the words from the basic form list denoting the landmarks. For a word to refer to a landmark, we required that it represents a physical and clearly distinguishable permanent feature in the environment. We did not include snow, spoors, flowers, and similar temporary and changing objects in the list of landmark words. In the Finnish language there are several synonyms that denote the same landmark. In order to calculate how often the participants used the different landmarks, we gathered the synonyms for the landmark words into groups that represented the same landmark.

4 Results

4.1 Distribution of Propositions

The number of decision points that the participants recognized during the experiment varied from 7 to 18. On average, the participants recognized about 11 decision points out of the 24 possible decision points both in the winter and in the summer experiments.

The analysis of Denis's classifications showed that "Landmark description" was the most frequently used proposition class both in the winter and summer experiments (Fig. 3), followed by "Commentary" in the winter and "Landmark" in the summer. The "Action and landmark" class was fourth in terms of occurrence,

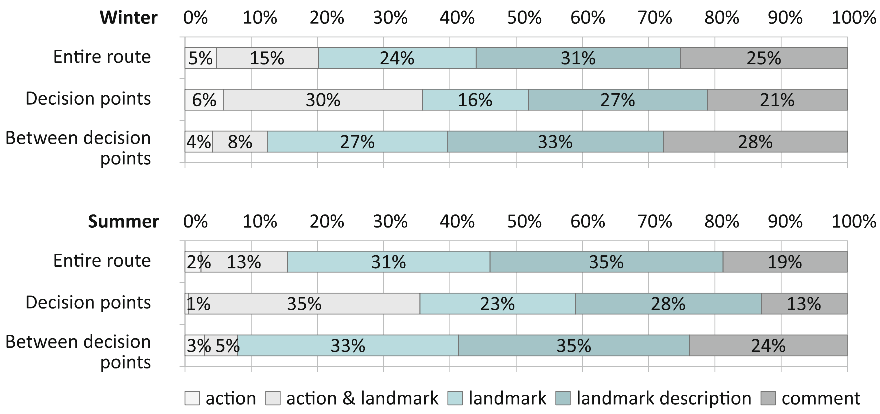

Fig. 3 Distributions of propositions in the winter and summer experiments along the different parts of the route

whereas the "Action" class occurred the least. The large number of commentaries in winter arose from many propositions concerning snow. Landmarks were involved in most of the propositions in both seasons but more frequently in the summer season, when 79 % of the propositions were landmark-related ("Action and landmark." "Landmark" and "Landmark description" classes), whereas the portion was 70 % in the winter. In contrast, action-related propositions ("Action," "Action and landmark") were more frequent in the winter experiment, with a portion of 20 % as opposed to 15 % in the summer experiment.

At decision points, the participants most frequently introduced "Action and landmark" propositions both in the winter and in the summer (Fig. 3). The large number of "Action and landmark" propositions originated mainly from the introductions of route alternatives at decision points, such as "I can take the small path to the right." The task assignment asked for route alternatives, so this was a natural result. There were very few "Action" propositions at decision points in the summer (only 1 %), and they comprised the least frequent proposition class in the winter as well — actions were mostly linked to landmarks at decision points. The landmark-related proposition classes were even more predominant at decision points than along the entire route: 73 % of propositions in the winter and 86 % in the summer. The importance of action-related classes was also higher at decision points, with 36 % both in the winter and in the summer, mainly due to the introduction of route alternatives.

When ranking the proposition classes between decision points, their order of magnitude was similar to that of the entire route both in the winter and in the summer experiments (Fig. 3). "Landmark description" propositions were the most common ones, which was due to the lengthy verbal descriptions that the participants gave of their surroundings while walking. Landmark-related classes decreased slightly in frequency between the decision points compared to the entire route, with 68 % in the winter and 73 % in the summer, whereas action-related propositions decreased more, with 12 % in the winter and 8 % in the summer.

The number of propositions varied considerably between participants, and the distribution of propositions into Denis's classes also varied. In particular, the frequency of commentaries varied significantly between participants: 2–51 %. Despite the variance in distributions, the vast majority of participants used the "Landmark" and "Landmark description" proposition classes more frequently (excluding the irrelevant "Commentary" class).

When comparing the distributions of each of Denis's classes among participants during the summer and winter experiments, we could see differences in class frequencies. We observed the largest difference along the entire route in the "Landmark" class, for which the mean frequency decreased 7.16 percentage points (pp) from summer to winter. The statistical test (two-tailed Wilcoxon rank sum test) for equality of locations between the summer and winter distributions showed the difference to be significant ($W=80$, $p=0.020$). Another large and statistically significant ($W=23$, $p=0.043$) difference occurred in the "Action" class, the mean of which increased 2.80 pp from summer to winter. These statistically significant differences were also present at decision points where the differences were larger: a decrease of 7.53 pp in the mean for the "Landmark" class ($W=23$, $p=0.043$) and an increase of 5.88 pp in the mean for the "Action" class. Between the decision points, the statistical tests did not show significant variations for class frequency differences, meaning that the decision points were the main source of difference between the seasons.

The variances among single classes between seasons differed to a statistically significant degree only for the "Action" class ($F(9.9)=0.1457$, $p=0.008$). This supports our observation that the participants introduced "Action" propositions randomly, and without any regularity, such as "Here we go forward."

The distribution of propositions into the four landmark- and action-related classes was similar along the entire route and between the decision points, both when looking at the class frequencies and their differences between the seasons. The similarity reflects the fact that the participants articulated the predominant number of their propositions between the decision points, with such propositions representing approximately two-thirds of all propositions. At the decision points, the distribution was considerably different due to the larger number of landmark-related propositions. The difference between the seasons was also large, as the frequency of the landmark-related classes decreased considerably from summer to winter, whereas, at the same time, the frequencies of the "Action" and "Commentary" classes increased considerably.

4.2 Use of Landmark-Related Words

The total length of the thinking aloud transcripts was 26505 words, with 11092 words captured from the winter experiment and 15413 from the summer experiment. The total number of separate words was 2357, which we calculated using the basic form conversions of the transcripts. The total number of separate landmark words was 295, and the grouping of synonyms resulted in a total of 62 separate landmark features used by the participants in their descriptions. Of these, they used 59 landmarks in the winter and 60 in the summer. The participants used these landmarks 1129 times in the winter experiment and 1560 times in the summer experiment, which represents 10.18 % and 10.12 % of all the words per season, respectively.

There were four landmarks that every participant used during the experiment: a house, a lake, a parking lot, and a creek. These are clearly distinctive landmarks during both winter and summer. In the winter, every participant also used “uphill” and “info board” as landmarks in the descriptions. They used the landmark “uphill” quite often due to presence of slippery slopes along the footpaths. Throughout the season, participants used “spruce,” “path,” “fallen tree,” “cliff,” “bridge,” and “anthill” as landmarks, many of which were distinctive in the summer but not in the winter, when they were covered by snow. There were three landmarks that participants repeatedly used in only one season: “witch’s broom,” “pit,” and “marsh.” These three landmarks were clearly distinct only during either the winter or summer. Except for “path,” the nine most commonly used landmarks were the same in the winter and in the summer (Table 1): “house,” “road,” “lake,” “spruce,” “creek,” “parking lot,” “road,” “birch,” and “fallen tree.” In Table 1, thick horizontal lines separate the landmarks that had statistically significant use frequency ($p<0.05$ in one-tail binomial test, in the winter B(11092, 1129/11092), and in the summer B(15413, 1560/15413)).

The distribution of landmarks was different between the seasons: in the winter season, the participants used 13 landmarks with significant frequency, which represented 61.29 % of the total use of landmarks. In the summer season, they used 17 landmarks with significant frequency, which represented 74.17 % of the total use of landmarks. In addition, there were more users per significantly frequent landmark in the summer season. The more varied use of significantly frequent landmarks in the summer season resulted mainly from the appearance of objects in the forest that were covered by snow in winter: paths, crossings, cliffs, and boulders.

There were six statistically significant differences between the summer and winter experiments among the twenty largest landmark frequency differences: “path,” “uphill,” “crossing,” “anthill,” “shore,” and “fence barrier” ($p < 0.05$ in two-tail Wilcoxon rank sum test, emphasized in Table 2). For all these significant differences, there was also a difference of two or more participants between the seasons in terms of the number of users. Participants used “path,” “crossing,” “anthill,” and “shore” more often in the summer experiment; all of these objects are covered by snow during the winter. Participants used “uphill” and “fence barrier” more in the winter. The use of “uphill” can be explained by the slipperiness of the slopes and “fence barrier” by its distinctiveness in the snowy surroundings. The use of “road” distinctly had the largest difference in usage frequency between the summer and winter experiments, but the statistical significance of the difference was only suggestive ($p=0.0588$). “Birch trees” was another landmark for which a similarly suggestive significant difference appeared ($p=0.0588$). Participants used “road” and “birch trees” more frequently in the

Table 1 The 20 most used landmarks in the summer and in the winter.

	Winter landmarks				Summer landmarks			
No. of part.	*P* value bin. test	Freq./ landmarks (%)	Landmark	Rank	Landmark	Freq./ landmarks (%)	*P* value bin. test	No. of part.
10	0.000000	8.86	House	1	Road	9.49	0.000000	10
10	0.000000	7.09	Creek	2	House	7.44	0.000000	10
10	0.000000	6.47	Lake	3	Spruce	6.35	0.000000	10
9	0.000000	6.02	Spruce	4	Lake	6.28	0.000000	10
10	0.000000	5.49	Parking lot	5	Creek	5.77	0.000000	10
8	0.000000	4.07	Route mark	6	Parking lot	5.64	0.000000	10
8	0.000001	3.90	Road	7	Path	5.19	0.000000	10
8	0.000017	3.54	Birch	8	Birch	3.40	0.000002	9
9	0.000037	3.45	Fallen tree	9	Fallen tree	3.14	0.000031	10
8	0.000037	3.45	Spruce trees	10	Crossing	3.01	0.000116	9
10	0.000079	3.37	Uphill	11	Cliff	2.88	0.000399	10
7	0.002271	2.92	Ditch	12	Route mark	2.82	0.000717	8
8	0.012246	2.66	Pine	13	Marked passage	2.76	0.001262	7
6	0.050466	2.39	Path	14	Boulder	2.63	0.003657	9
8	0.050466	2.39	Guidepost	15	Ditch	2.50	0.009686	8
8	0.110946	2.21	Cliff	16	Spruce trees	2.44	0.015229	8
9	0.110946	2.21	Bridge	17	Pine	2.44	0.015229	9
7	0.156765	2.13	Boulder	18	Bridge	2.18	0.073383	10
10	0.214433	2.04	Info board	19	Guidepost	2.18	0.073383	9
8	0.214433	2.04	Thicket	20	Anthill	2.12	0.102321	10

The heading "No. of part." denotes "the number of participants who used the landmark"

summer when they were more visible, since the road was not covered by snow and the birches had leaves.

In order to reach an overall view of the usage of landmarks in our route description experiments, we gathered the extracted landmarks into distinct homogeneous main groups. We ended up with eight landmark groups in which the landmarks within each particular group resembled each other more than did the landmarks between the groups:

1. structures (man- and animal-made constructions: house, electricity line, bridge, anthill, bird's nest, etc.)
2. passages (routes or parts of routes intended for movement: road, path, crossing, etc.)
3. trees and parts of trees (trees and their parts: spruce, witch's broom, stump, etc.)
4. waterways (parts of water systems: lake, ditch, shore, etc.)
5. land cover (vegetation type: spruce trees, clearing, marsh, etc.)
6. rocks (rocky features: stone, bare rock area, crack, etc.)
7. signs (man-made signs: guidepost, information board, route marker, etc.)
8. landforms (parts of topography: upward slope, hill, pit, etc.)

Table 2 The 20 largest differences in landmark usage between summer and winter

Rank	Landmark	Freq./ landmarks(pp)	Difference in No.of partcipants	*p* value Wilcoxon	Rank	Landmark	Freq./ landmarks(pp)	Difference in No.of partcipants	*p* value Wilcoxon
1	Road	−5.59	−2	0.058782	11	Marked passage	−0.90	−2	0.449692
2	Path	−2.80	−4	0.006502	12	Clearing	0.83	0	0.449692
3	Uphill	2.40	3	0.006502	13	Brich trees	−0.76	−5	0.058782
4	Crossing	−1.68	−2	0.025748	14	Shore	−0.76	−4	0.025748
5	House	1.42	0	0.173617	15	Thicket	0.76	−1	0.198765
6	Creek	1.32	0	0.650147	16	Cliff	−0.67	−2	0.427355
7	Route mark	1.25	0	0.449692	17	Info board	0.63	1	0.096304
8	Anthill	−1.23	−7	0.006502	18	Fence barrier	0.57	3	0.041250
9	Hill	1.06	0	0.427355	19	Stump	0.56	3	0.226476
10	Spruce trees	1.02	0	0.705457	20	Downhill	0.50	3	0.185877

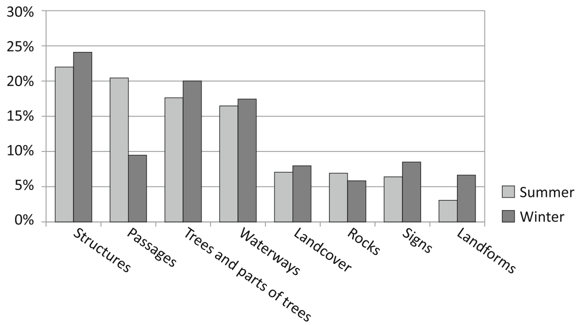

Fig. 4 Frequencies of landmark groups in the summer and in the winter

The "structure" was the most commonly used landmark group both in the summer and in the winter experiment (Fig. 4). "Trees and parts of trees" and "waterways" were large groups in both seasons, but otherwise, the distribution of landmark groups differed between the seasons.

When looking at the differences in usage frequency between the landmark groups, the group termed "passages" differed most between the seasons (Table 3). Participants used the "passages" landmarks 11.0 pp less in the winter season than in the summer season, and statistical testing rated the difference in participant-wise distributions to be clearly significant (p=0.0009 in two-tail Wilcoxon rank sum test). The landmarks grouped together as "passages", which included roads, paths and crossings, were more visible in the summer season when they were not covered by snow, which seemed to lead to the participants mentioning them more often.

"Landforms" was another landmark group that showed a statistically significant difference in usage frequency between the summer and winter experiments (p=0.0494, Fig. 4).

The participants used the "landforms" group 3.6 pp more often in the winter experiment. The difference may result from the snow coverage, which makes large landforms more visible, as the ground details are hidden, but also because slopes were slippery during the winter experiment, which the participants mentioned

Table 3 Differences in the usage of landmark groups in the summer and winter experiments.

Landmark	Frequency/ landmarks(pp)	Difference in No.of partcipants	No of landmarks	*p* value Wilcoxon
Passages	−10.97	−1	0	0.0009
Landforms	3.57	2	−1	0.0494
Trees and parts of trees	2.39	0	3	0.9397
Structures	2.10	0	0	0.1509
Signs	2.09	0	0	0.2265
Rocks	−1.08	0	0	0.5454
Waterways	0.97	0	−1	0.7055
Landcover	0.92	−1	−2	0.7055

The significant differences are highlighted ($p < 0.05$ in two-tail Wilcoxon rank sum test) often. Besides the "passages" and "landforms" landmarks, the other landmark groups showed no significant differences in usage frequencies between the summer and winter experiment.

5 Creating a Landmark Ontology for Hiking

The landmarks and landmark groups that we extracted from the thinking aloud experiments formed the basic framework for an ontology of hiking. As we are aiming at an automated use of landmark knowledge in the terrain navigator, we need a formalized ontological presentation of the landmarks. We used Protégé ontology editor (Protégé 2011) to formalize the ontology and chose an open standard ontology language OWL, as a means of formalizing it. The formalization is briefly presented in the following section, and some more details are given in Kettunen and Sarjakoski (2011).

The 62 landmarks that we extracted from the thinking aloud test session transcripts formed the bottom-level ontology classes for a landmark taxonomy, of which the eight landmark groups formed the top-level classes. While formalizing the taxonomy in Protégé, we added mid-level ontology classes between the landmarks and landmark groups where necessary. For example, we placed the landmarks "bare rock area" and "cliff" in a new mid-level class, "rockSurface", in the taxonomy. At the end of the taxonomy formalization, there were 22 new mid-level classes in the taxonomy. Figure 5 shows a part of the created ontology.

The landmarks that the participants used in the route description sessions represented only a subset of all landmarks in Nuuksio National Park. We wanted our landmark ontology to contain a rather complete set of the landmarks found in Nuuksio National Park and, therefore, it was necessary to expand the experiments-based taxonomy. We expanded the taxonomy using additional sources, such as legends and the specifications of topographic and orienteering maps, and the experience of the research group. The expansion of the taxonomy resulted in 42 new landmarks and one new mid-level class, after which the taxonomy contained 108 landmarks, 23 mid-level classes, and eight landmark groups. The depth of the taxonomy became five levels at maximum, including a top class "landmark", which meant two mid-level classes at most between the landmark group classes and the landmark classes. We refined our hiking landmark taxonomy towards a more complete ontological model by making the ontology classes correctly disjoint to each other and by inserting object properties in order to describe the characteristics of the landmarks. We added a "season" class as well as an object property to denote the seasonal characteristics of landmarks. The disjoint ontology classes and object properties allowed us to create defined classes in the ontology, the subclasses of which can be solved automatically based on the existing ontological relations. We created a class, called "unreliableWinterLandmark", for landmarks that are unreliable for use in the winter season.

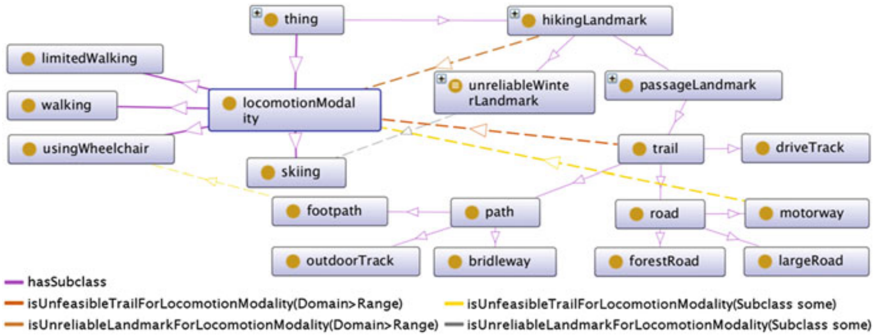

Fig. 5 Modeling locomotion modalities in the landmark ontology for hiking in relation to landmarks and trails. The figure shows a part of the created ontology using the graphical notation of Protégé

Within the context of pedestrian navigation, the term modality is often used to denote the usage of different types of locomotion, such as movement and transportation for a single journey (Montello 2005; Liu 2010; Navteq 2011). In urban pedestrian routing the typical modalities include walking, use of public transportation (such as bus, tram, and subway), and driving a car. In the present study, we extend the notion of modality to include a person's ability to move and a person's way of moving. This view of locomotion modality is motivated by the assumption that the modality affects which landmarks are suitable for him or her when moving and navigating in the nature. For example, our user group of elderly persons with limited walking ability may need to look at their feet on a rough surface so often that they cannot observe the minor landmarks.

We included four locomotion modalities in our hiking ontology, while taking into account both seasons ("walking" and "skiing") and the moving constraints in movement faced by a particular user ("limited walking" and "usingWheelchair") (Fig. 5). Subsequently, we set up object properties for denoting when a landmark is not suited for locomotion modality and that a trail landmark (such as a path or a road) is unfeasible for locomotion modality (Fig. 5).

6 Discussion and Conclusions

Our results confirm the importance of landmarks in route descriptions in a national park environment. The results also confirm that the effect of season should to some extent be considered when developing LBSs for purposes such as hiking (see Sarjakoski and Sarjakoski 2008). The importance of landmarks appears to be more significant in the summer (79 % landmark-related propositions), when more landmarks are visible, than in the winter (70 %), when terrain and many landmarks are covered by snow. The dominance of landmark-related propositions is similar to earlier experiments in which Denis's classification method was applied (Denis

1997; Daniel and Denis 2004; Brosset et al. 2008; Rehrl et al. 2009). However, the overall proportion of landmark-related proposition classes was smaller in our experiments since the "commentaries" class covered a larger proportion of classes. The large number of commentaries partly arose from the unrestricted flow of speech due to the thinking aloud method, and partly, during the winter season, from the snow that inspired many commentaries.

The statistical analyses of our classification of propositions highlighted two classes that differed significantly between summer and winter in terms of their usage. The participants used the "action" class significantly more often in the winter and the "landmark" class significantly more often in the summer. The differences originated from the propositions given at the decision points. The differences in the "action" class resulted from introducing the route alternatives at the decision points, which contained both actions and landmarks in the summer, while in the winter participants did not include the landmarks as often. The significantly larger number of "landmark" propositions in the summer originated from the elaborate landmark descriptions, probably because there were more visible landmarks in the summer.

The analysis of the landmarks showed that "structures" was the most frequently used landmark group both in the summer and in the winter. The "structures" were good and reliable landmarks because they were clearly visible in the national park in both seasons. Consequently, "structures" should always be included when providing route instructions in this kind of environment. Other important landmark groups during both seasons were "trees and parts of trees" and "waterways". The most important single landmarks in our experiments were "house," "lake," "parking lot," and "creek," since all of the participants used them and they were among the six most commonly used landmarks both in the summer and in the winter seasons. We also recognized seasonally important landmarks that were used by all of the participants in one season.

We detected significant quantitative differences between the summer and winter seasons in terms of the usage of the "passages" and "landforms" landmark groups. Participants used the "passages" group significantly less often in the winter season, mainly because the footpaths were not visible. The result suggests that footpaths should not be given a large role in creating route descriptions during the snowy wintertime. Participants used the "landforms" group significantly more often in the winter than in the summer season, which appeared to originate from the fact that landforms are more visible in the winter due to snow. Hence, landforms could be used for route descriptions in a national park environment, especially in the winter. In the summer, the use of landforms as navigational landmarks must be considered more carefully. Also, consideration should be given to the question of whether or not the hiking environment affects the use and subsets of the landmarks; are they different when moving in the forest or in open areas, such as in mountains?

Interestingly, the use of the "trees and parts of trees" landmark group increased in winter compared to summer, and, at the same time, the number of "land cover" landmarks decreased. The "trees and parts of trees" landmark group consisted of single trees and the "land cover" landmark group consisted of amalgamated vegetation objects. In the summer season, people's visual attention seems to focus on the plant patterns, but in the winter season, when there are no leaves or undergrowth, people focus more on individual plants such as trees. Route instructions in a national park environment should be adapted to vegetation conditions involving the respective season.

We took the extracted landmarks and landmark groups as the basis for a hiking landmark ontology, for which the landmarks and landmark groups provided a taxonomical framework based on empirical observations. We added mid-level ontological classes between the landmarks and landmark groups, and we expanded the ontology with additional landmarks collected from map legends and from our group's expertise. The resulting ontology came to contain 108 landmark classes, 23 mid-level classes, and eight landmark group classes which can be used in creating route descriptions for hiking in a national park environment. We included associative relations in the ontology in order to model the character of landmarks in relation to seasonal differences and the locomotion modalities of the users.

To conclude, the results of this empirical study emphasized the role of landmarks in wayfinding when hiking during both summer and winter, supporting the findings of previous studies that have been conducted in urban environments. The study identified the most commonly used hiking-related landmarks. Future work will include identifying the spatial relationships that need to be incorporated into the comprehensive hiking ontology. We will also continue studying landmarks and examine their use on a per participant base. The navigation instructions for hiking should be adapted to some extent to the respective season and the user's locomotion modality.

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References

Bittner T, Donnelly M, Winter S (2005) Ontology and semantic interoperability. In: Zlatanova S, Prosperi D (eds) Large-scale 3D data integration, Taylor & Francis Ltd, London, pp 139–160

Blades M (1991) Wayfinding theory and research: the need for a new approach. In Mark DM, Frank AU (eds) Cognitive and linguistic aspects of geographic space, NATO ASI Series, Series D: behavioural and social sciences, vol 63. Kluwer, Dordrecht, pp 137–165

Boren MT, Ramey J (2000) Thinking aloud: reconciling theory and practice. IEEE Trans Prof Commun 43(3):261–278

Brosset D, Claramunt C, Saux E (2008) Wayfinding in natural and urban environments: a comparative study. Cartographica 43(1):21–30

Caduff D, Timpf S (2008) On the assessment of landmark salience for human navigation. Cogn Process 9:249–267

Denis M (1997) The description of routes: a cognitive approach to the production of spatial discourse. Cahiers de Psychologie Cognitive 16(4):409–458

Daniel M-P, Denis M (2004) The production of route directions: investigating conditions that favour conciseness in spatial discourse. Appl Cognitive Psychol 18(1):57–75

Dean M, Schreiber G (eds) (2004) OWL web ontology language reference. W3C. Online. http://www.w3.org/TR/owl-ref/ Accessed 30 April 2011

Golledge R (1999) Human wayfinding and cognitive maps. In: Golledge R (ed) Wayfinding behaviour. John Hopkins University Press, Baltimore, pp 5–46

Gruber TR (1993) A translation approach to portable ontology specifications. Knowl Acquis 5(2):199–220

Guarino N (1998) Formal ontology and information systems. Formal ontology and information systems (FOIS'98). IOS Press, Amsterdam, pp 3–15

Elias B, Hampe M, Sester M (2005) Adaptive visualisation of landmarks using an MRDB. In: Meng L, Zipf A, Reichenbacher T (eds) Map-based mobile services, theories, methods and implementations. Springer, New York, pp 73–86

HaptiMap (2008) HaptiMap, haptic, audio and visual interfaces for maps and location based services. Online. http://www.haptimap.org/ Accessed 18 Nov 2011

HFST (2011) Helsinki finite-state transducer technology (HFST). University of Helsinki, Department of Modern Languages. Online. http://www.ling.helsinki.fi/kieliteknologia/tutkimus/hfst/index.shtml Accessed 12 April 2011

Ishikawa T, Montello DR (2006) Spatial knowledge acquisition from direct experience in the environment: individual differences in the development of metric knowledge and the integration of separately learned places. Cogn Psychol 52:93–129

Jacobson RD (1998) Cognitive mapping without sight: four preliminary studies of spatial learning. J Environ Psychol 18:289–305

Janzen G, van Turennout M (2004) Selective neural representation of objects relevant for navigation. Nat Neurosci 7(6):673–677

Kavouras M, Kokla M (2008) Theories of geographic concepts: ontological approaches to semantic integration. Taylor & Francis Ltd, Boca Raton

Kettunen P, Sarjakoski LT (2011) A context-sensitive wayfinding ontology for hiking based on an empirical study. In: Moratz R, Giudice N (eds) Extended abstracts from the poster session of the conference on spatial information theory, COSIT'11, 12–16 Sept 2011, Belfast, Maine

Klippel A, Winter S (2005) Structural salience of landmarks for route directions. In: Cohn AG, Mark DM (eds) Spatial information theory—COSIT05. Springer, Ellicottville, pp 347–362

Kovanen J, Sarjakoski T, Sarjakoski LT (2010) A client-server architecture for audio supported mobile route guiding for hiking. Proceedings of UPINLBS 2010, Ubiquitous positioning, Indoor navigation and location-based service, 14–15 Oct 2010, Helsinki (Kirkkonummi) Finland, CD-ROM. Online. http://dx.doi.org/10.1109/UPINLBS.2010.5654302

Laakso M, Sarjakoski T, Sarjakoski LT (2011) Improving accessibility information in pedestrian maps and databases. Cartographica 46(2):101–108

Le Yaouanc J-M, Saux É, Claramunt C (2010) A semantic and language-based representation of an environmental scene. Geoinformatica 14:333–352

Liu L (2010) Data model and algorithms for multimodal route planning with transportation networks. Dissertation, Technische Universität München

Lynch K (1960) The image of the city. The MIT Press, Cambridge

Magnusson C, Brewster S, Sarjakoski T, Roselier S, Sarjakoski LT, Tollmar K (2009) Exploring future challenges for haptic, audio and visual interfaces for mobile maps and location based services. Proceedings of the CHI 2009 –locweb workshop, April 4–9, Boston. ACM 978-1-60558-247-4/08/04

Manning C, Schütze H (1999) Foundations of statistical natural language processing. Massachusetts Institute of Technology, Cambridge

McGookin D, Sarjakoski LT, Anastassova M, Ferguson S (eds) (2011) Final prototypes and final report on the perceptualization of map data, context sensing and reasoning, and hardware development. Public report, Deliverable 2.2, HaptiMap, haptic, audio and visual interfaces for maps and location based services, FP7-ICT-224675, 29 April 2011, p 196

Montello DR (2005) Navigation. In: Shah P, Miyake A (eds) The cambridge handbook of visuospatial thinking. Cambridge University Press, Cambridge, pp 257–294

Navteq (2011) Online. http://corporate.navteq.com/products_data_advanced_discover_cities.html. Accessed 12 April 2011

NLTK (2011) Natural language toolkit. Online. http://www.nltk.org/. Accessed 12 April 2011

Nothegger C, Winter S, Raubal M (2004) Computation of the salience of features. Spat Cogn Comput 4:113–136

Paepen B, Engelen J (2006) Using a walk ontology for capturing language independent navigation instructions. Proceedings of ELPUB 2006 conference on electronic publishing, June 2006, Bansko, Bulgaria

Pick HL, Heinrichs MR, Montello DR, Smith K, Sullivan CN, Thompson WB (1995) Topographic map reading. In: Hancock PA, Flach JM, Caird J, Vicente KJ (eds) Local applications of the ecological approach to human-machine systems. Erlbaum, New York, pp 255–284

Protégé (2011) Protégé ontology editor. Online. http://protege.stanford.edu/. Accessed 18 Nov 2011

Raubal M, Winter S (2002) Enriching wayfinding instructions with local landmarks. Geographic information science, vol 2478. Springer, Heidelberg, pp 243–259

Rehrl K, Leitinger S, Gartner G, Ortag, F (2009) An analysis of direction and motion concepts in verbal descriptions of route choices. In: Hornsby KS, Claramunt C, Denis M, Ligozat G (eds) COSIT 2009. LNCS, vol 5756. Springer, Heidelberg, pp 471–488

Rehrl K, Häusler E, Leitinger S (2010) Comparing the effectiveness of GPS-enhanced voice guidance for pedestrians with metric- and landmark-based instruction sets. In: Fabrikant, S, Reichenbacher T, van Kreveld M, Schlieder C (eds) Geographic information science, vol 6292. Springer, Berlin, pp 189–203

Ross T, May A, Thompson S (2004) The use of landmarks in pedestrian navigation instructions and the effects of context. In: Brewster S, Dunlop M (eds) Mobile human-computer interaction—Mobile HCI 2004, LNCS, vol 3160. Springer, Berlin, pp 1–5

Sarjakoski LT, Sarjakoski T (2008) User interfaces and adaptive maps. In: Xiong H, Shekhar S (eds) Encyclopedia of GIS. Springer, Berlin, pp 1205–1212

Sarjakoski LT, Kettunen P, Flink H-M, Laakso M, Rönneberg M, Sarjakoski T (2012) Analysis of verbal route descriptions and landmarks for hiking. Pers Ubiquit Comput 16(8):1001–1011. Online. http://dx.doi.org/10.1007/s00779-011-0460-7. Accessed 21 Sept 2011

Smith B (2003) Ontology. In: Floridi L (ed) Blackwell guide to the philosophy of computing and information. Blackwell, Oxford, pp 155–166

Snowdon C, Kray, C (2009) Exploring the use of landmarks for mobile navigation support in natural environments. Mobile HCI 2009, Sept 15–18, Bonn. ACM 978-1-60558-281-8/09/09

Stigmar H (2010) Making twenty first century maps legible—methods for measuring and improving the legibility and usability of real-time maps. Doctoral thesis, Lund University. ISBN 978-91-7473-039-5

Sorrows ME, Hirtle SC (1999) The nature of landmarks for real and electronic spaces. In: Freksa C, Mark DM (eds) Spatial information theory: cognitive and computational foundations of geographic information science, International Conference COSIT'99. Springer, Stade, pp 37–50

Thorndyke PW, Hayes-Roth B (1982) Differences in spatial knowledge acquired from maps and navigation. Cogn Psychol 14:560–589

Tversky B (1993) Cognitive maps, Cognitive Collages, and Spatial Mental Models. COSIT 1993. LNCS, vol 716. Springer, Heidelberg, pp 14–24

Tversky B (2003) Structures of mental spaces: how people think about space. Environ Behav 35(1):66–80

Talking About Place Where it Matters

Stephan Winter and Marie Truelove

Abstract This chapter poses questions towards a smart geographic communication: What is required to allow a person to talk to a machine in a natural way about geographic space, without learning a particular interface or structured form of dialog? And can the machine respond in a manner that a person would accept as human-like communication in its capacity of considering context? Where are the gaps in our current knowledge, for example as implemented in current systems, and where is more research needed?

Keywords Spatial cognition · Place · Human computer interaction

1 Introduction

Spatial language is now an accepted research challenge in geographic information science (e.g., Mark and Frank 1991; Frank and Mark 1991). Considering the progress in the past twenty years, we have recently suggested a *spatial Turing test*: a restricted Turing test limiting the scope of conversation to geographical space (Winter and Wu 2009). If a person can talk to a machine in a natural way about geographic space, without learning a particular interface or structured form of dialog, and if the machine can talk to a person in a way they easily understand

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without further cognitive effort than they would spend on human communication, then the machine would be called intelligent in Turing's sense. This means two tasks are involved, as far as machines are concerned: to *understand* human spatial descriptions or queries, and to *generate* spatial descriptions that are understood by people.

Already Turing was aware that intelligence for a machine is a hard problem, and *spatial* intelligence will continue to be a challenge for some time. Spatial communication, as with any communication, requires grasping the tenor of the conversation, catching the context, complying with the communication purpose at hand, adjusting to the partner in the communication, and considering the location of the partner (Janelle 2004) and the time of the communication. In addition, and beyond Turing's idea of general conversation, spatial communication is about information in support for decision making or problem solving. This means the machine must be able to identify what is most useful in a particular context. These factors influence the selection of references to places (Winter 2003; Tomko and Winter 2009), the selection of spatial relations (Herskovits 1986; Tversky and Lee 1998), and the frame of reference for these relations (Retz-Schmidt 1988; Levinson 1996; Marchette and Shelton 2010).

In this chapter we restrict ourselves to the communication of human place descriptions within a service, i.e., a machine's task to *understand* a human spatial description or query. This part of the general problem with spatial intelligence is already felt ubiquitously: it matters in all user interaction with services currently available. People expect to be understood in local search ("childcare centre in Fitzroy"), navigation ("to work"), or social media ("news relevant for Carlton"), but also in specialist services such as in crime analysis, disaster response, or geo-marketing. A human spatial description can be given in free speech or free text, and this is obviously more complex to interpret than structured interfaces (e.g., Fig. 1). However, structured interfaces are constraining the user and typically limiting the discourse. We also exclude the study of *generating* human-like place descriptions. This means in particular that in the case studies presented we accept the response of the machine in any form, and only search for indications of their current capacity to understand the user.

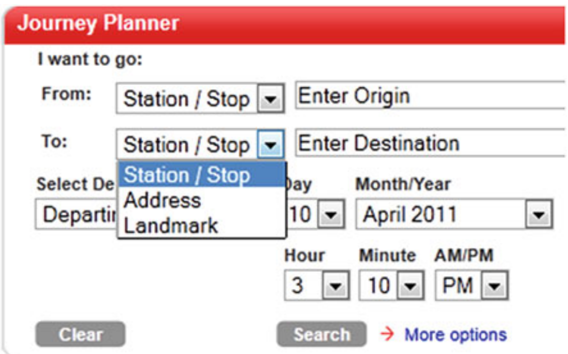

Fig. 1 Structured communication of a destination to a machine (© Metlink, 2011)

Our interest is to see whether resolving human place descriptions is still a hard problem, a continuing long-term research program even after two decades or more of research in this area, or whether the problem has become rather trivial, perhaps solved by current knowledge already. Thus the research question is: Can a machine nowadays understand place descriptions intelligently? And if this is not the case, what are the current barriers, the hard questions, preventing machines from understanding place descriptions?

This chapter is contributing a review of the research on cognitive and linguistic aspects of geographic space. It is structured in the following way. Section 2 explores the challenge for the machine to deal with a cognitive and linguistic concept of place and why this is important. Section 3 continues this line with case studies, identifying these challenges by examples. In Sect. 4 the findings are compared with the current state of knowledge, such that in Sect. 5 the chapter can conclude with a research agenda.

2 Talking about Place

People naturally talk about place: where they are, where resources are, where they want to meet, or where events have happened. In their communication they use single placenames, and also construct aggregated place descriptions from placenames and the relations between places.

Place is a polysemic concept, which is in addition subject to context. In this chapter the focus is on places in vista and environmental scale (Montello 1993), i.e., to places that can be learned from a single viewpoint or from locomotion and integration. This limitation excludes places of table-top and smaller scales (e.g., "under the newspaper"), geographic and larger scales (e.g., "in Australia"), and any metaphorical forms of places (e.g., "in heaven"). Place descriptions are context-dependent: the same location can be described differently depending on perspective, purpose and time. We would describe our current location by *in Vienna* for colleagues in Melbourne, *in a coffeehouse* for a friend with whom we plan to meet, or *at table 5* for the waiter for paying the bill. Talking to a machine also happens in particular contexts. Linguistic imprecision comes in where no distinction is made between a reference to an object and its place, while place is clearly a function (role) of the object, or a group of objects. *Central Station* is an object in the environment, but it has also a place, and *I am in Central Station* means that my place is part of the place of Central Station, but not that I am part of Central Station.

Even after fifty years of geographic information systems (Coppock and Rhind 1991) this elementary (human) concept of place has no equivalent in spatial databases.

- Raster databases can represent features by enumerating the elements of the interior of the feature, a variant of constructive solid geometry. But while people have no difficulties to use placenames in communication and to communicate meaning by these names, they may have difficulties to enumerate in a Boolean manner which elements exactly belong to a place.

- Vector databases can represent features by polygons, basically outlining the boundary of the feature, a variant of boundary representations in computational geometry. Similarly to the argument above, people may find it difficult—and may actually disagree with each other—when drawing exact boundaries around places they have no difficulty using in their verbal communication (Montello et al. 2003).
- Gazetteers are depositories, often maintained by authoritative agencies, of georeferenced and typed geographic names. The georeference is typically a point in a geographic reference system (Hill 2006). For example, Melbourne is gazetteered by "*type*: towns or localities, *latitude*: −37.818, *longitude*: 144.976" in the register of geographic names of the State of Victoria. Similar databases exist for business directories or (postal) addresses. Georeferenced and typed names provide comparatively poor structure (e.g., between points only two topological relations can be distinguished) and spatial semantics (e.g., points do not provide a sense of extent). Linking gazetteers with other spatial databases is non-trivial because of the lack of semantics to establish the link.

A few examples may illustrate why talking about place in geographic information science matters:

- Emergency call center operators deal with calls from stressed people. An operator has to find out where the accident happened quickly and unambiguously. Misunderstandings which have resulted in the most serious of consequences are often reported in the media.
- Post services around the world rely on authoritative address systems and automated delivery processes. Deviations from conforming postal addresses reportedly lead to billions of dollars[1] in additional costs.
- Users of geographic information services (e.g., local search services, car navigation services, or public transport planners) are frequently frustrated by a restrictive user interface or weak interpretation capabilities of the input. The functionality of these services to interpret user place descriptions is still quite limited as illustrated in the use cases presented in this chapter.

People are increasingly reliant on such services. In 2009 it was estimated internet mapping sites have 300 million unique visitors monthly, and that this number will continue to increase annually by 15 %.[2] This means the ability of the machine to understand (or generate) place descriptions should be an issue for geographic information science.

In the following section we will present use cases of local orientation and local search in a webmapping service. The use cases will identify and highlight shortcomings of services that by and large are text-based and supported by gazetteers

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[1] E.g., http://www.eworldwire.com/pressreleases/18186

[2] http://www.abiresearch.com

for geocoding. Shortcomings identified in these use cases will then be discussed further in Sect. 4.

3 Challenges in Talking About Place

The following two case studies have been undertaken to illustrate current challenges when people talk to machines about place. One conversation is from a tourist's perspective looking for *local orientation*, and one is from a local resident's perspective realizing *local search*. The conversations were made with a leading webmapping service, carried out in March 2010.

The methodology has properties that have to be acknowledged. First, such case studies provide only anecdotal evidence. Some underlying problems will be discovered, others not. This means, our investigation does not and can not claim completeness. Secondly, findings are not necessarily reproducible. The custom-made maps of these services depend on constantly evolving search ranking mechanisms, and also on some context factors such as the query country of origin and the query history. This observation is uncritical for this chapter since we can safely assume that the observed problems appear similarly in other contexts. We further do not focus on the rankings as such. Thirdly, current commercial implementations do not necessarily reflect all current knowledge in the discipline. However, we have made sure that the reported results are representative. Competitors show by and large a similar behavior. A few services allow free text search in maps, and they all override any given spatial relation by *near*. Other services allow a semi-structured search by separating *what* and *where*, which means there is no way of specifying a spatial relation in the first instance, and the search results are also generally *near* the specified location. Today's smartest computational knowledge engine, which is not specialized on maps or spatial information, is usually so occupied by resolving the location that it forgets about the *what*, i.e., it does not come to an answer of the original question. In addition to identifying problems in commercial implementations, these problems also need a careful consideration of the corresponding scientific literature to confirm or reject the need for further research (Sect. 4).

3.1 Local Orientation: Tourist Landmarks

Let us take a tourist's perspective and query places of touristic interest. For example, querying a mapping service for *Federation Square, Melbourne* leads to a map at some default zoom level that shows the area of Federation Square together with a list of interesting places around Federation Square (Fig. 2). But there are some challenges.

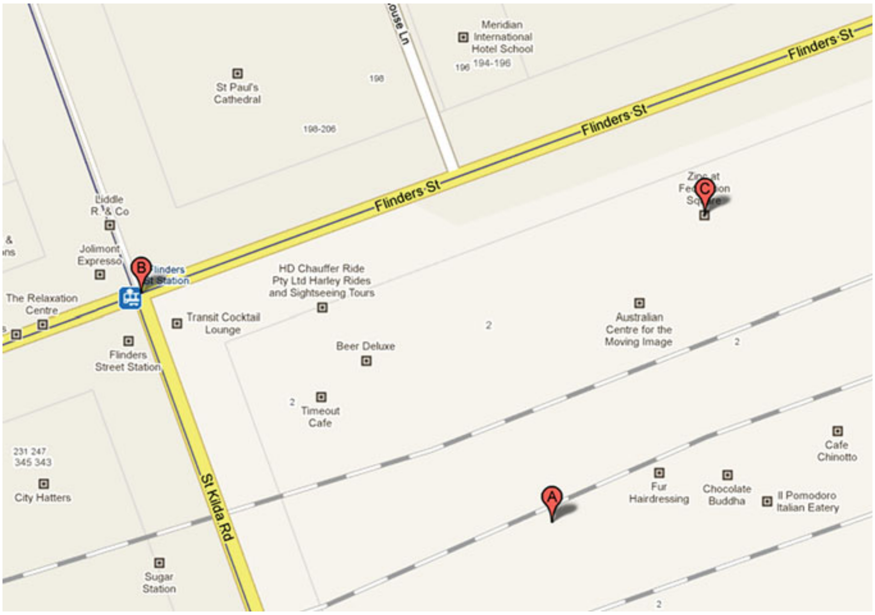

Fig. 2 Section of a service's response to *Federation Square, Melbourne* (© Google, 2010)

The first observation is that the service parses any query string for known placenames, and links them by a *near* relation. Hence, *Federation Square, Melbourne* becomes *Federation Square* near *Melbourne VIC, Australia*. It is ignored that here the proper spatial relation would be *within*. Any existing formal model of spatial relationships between spatially extended objects like Federation Square and Melbourne would reject that Federation Square is near Melbourne. However, both places, when queried individually, are points for the service. Between points the nearness relation is defined, however it is context dependent and not necessarily symmetric (Worboys 2001). Some context-dependency must be assumed for the service's reasoning as well, since some threshold distance is applied that may vary with object types or the default zoom level. We also observe that parsing ignores generally spatial relationships in query strings.

Secondly, *Federation Square, Melbourne* is resolved to the three top-ranked search results, all represented as points on the map. Assuming without further discussion that places always have extent (Aristotle 350BC), a point is quite a limited representation of the spatial semantics of a place. Three points for one place are even more confusing. Neither individually nor together do these points convey the sense of place that would be associated with a city square.

Thirdly, zooming in Fig. 2, the point labeled *A* (*Federation Square*) is located in the middle of railway lines where one would not expect a city square (Federation Square is built above train lines). Point *B* (*Charmaine's at Federation Square*) is located on the center of a street intersection outside of Federation

Square, a location where one would not expect to find a restaurant. Point C (*Zinc at Federation Square*) is on a building located at Federation Square and refers properly to another restaurant. The relationships of these points to the query vary largely, and we can conclude that search based on string similarity is semantically limited, and geocoding features by points adds to the complexity of the interpretation process by the user. Semantically more informed search methods are required.

Fourthly, it is not transparent what ranked *B* and *C* higher than other features at Federation Square, and this is a matter for page ranking algorithms, which are constantly evolving. The map, for example, shows other named places as well, some of them related to Federation Square. Among these other places are candidates of more relevance to tourists, such as the Australian Centre of the Moving Image (the National Gallery of Victoria is missing). Thus, the ranking is of limited context awareness.

To explore spatial relations further, let us query *Westgarth, Melbourne*. Westgarth is a vernacular placename for a locality within Melbourne's suburb of Northcote. The map returned shows *Westgarth Station*. Westgarth is certainly not equal to Westgarth Station, although common reasoning will assume that Westgarth Station is either in an area called Westgarth, or at least close to it. None of this is indicated on the map. However, typing *Wstgarth, Melbourne*—the typo is intentional here—one gets asked: "Did you mean: *Westgarth, Northcote VIC 3070*?" So the service knows a place called Westgarth, i.e., it knows vernacular placenames, but it does not treat them equally to official placenames. Also, since the query asked for the Westgarth in Melbourne there should be no need to ask back since Westgarth in Northcote is the only Westgarth in Melbourne, and Melbourne is in Victoria. Apparently, and confirming previous observations, the service cannot handle part-of hierarchies or spatial reasoning.

To explore the issue of context-dependency further, assume our tourist is looking for information about the Brandenburg Gate in Berlin. The results are as expected. Next our tourist searches for information about *Mt Everest, Tibet*. The service will attempt to interpret this request in the context of the previous one (Fig. 3), presenting restaurants and other categories near the Brandenburg Gate that contain references to Mt Everest or Tibet. Although interpreting query context seems desirable, the obvious choice—immediate query history—leads to failure.

These challenges already point to some fundamental research questions beyond the current state of knowledge. These are on linking placenames with spatial semantics of the places characterized by these names, in form of spatial extent, spatial relations and spatial reasoning. While formal models of relations and reasoning exist for crisp polygons, places do not necessarily have crisp boundaries—think of vernacular places, for example. In addition to being applied to vaguely defined places, the spatial relations carry uncertain and context-dependent meanings. The capture and modeling of context are an open area for research, and so is the question of relevance of the information provided in response to a query.

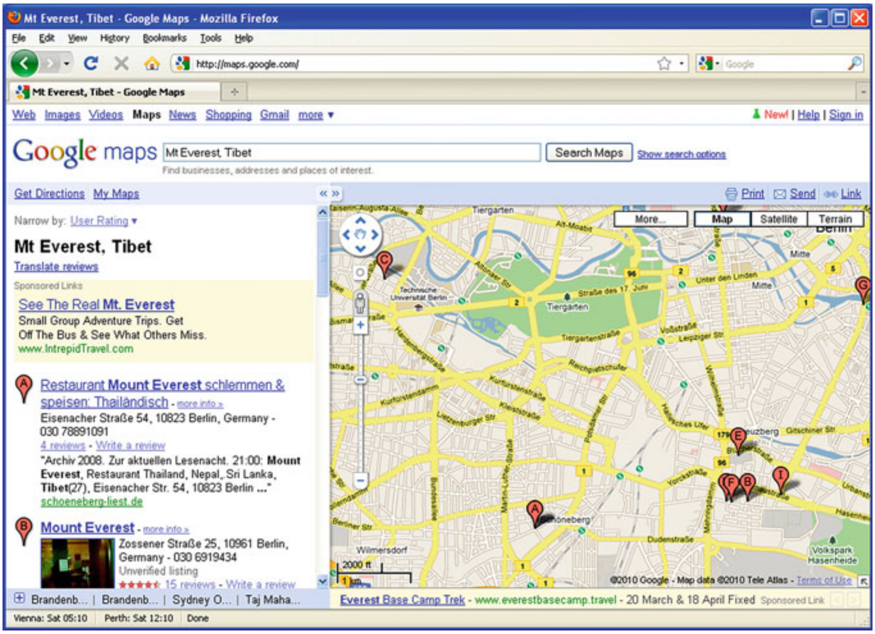

Fig. 3 The query *Mt Everest, Tibet* placed after a query *Brandenburger Tor, Berlin* interprets this query in the context of the first (© Google, 2010)

3.2 Local Search: Childcare

Local search is another (typical) communication context: a person is searching for a service rather than a place. In this case study, the map service was used in March 2010 by parents to search for childcare centers, for which there is a strong motivation to find a service near home or work.

To provide context at the beginning of the session, a valid street address in North Fitzroy was provided. The search is successful with an exact match listing the suburb name as *Fitzroy North* (rather than *North Fitzroy* which is a common vernacular name). Underneath the result the label *near Fitzroy* appears in parenthesis, providing a clue as to the results to come. In this context the search for *childcare centres in north fitzroy* is resolved to *childcare centres near Fitzroy, VIC, Australia* (Fig. 4). None of the ten links listed on the first page are in Fitzroy North, but in Fitzroy and the two adjacent suburbs to the east and west (Carlton and Collingwood respectively). The second page of links reveals a significant broadening of the search radius. Cardinal directions incorporated in placenames are neither taken as direction relations (see our discussion above), nor recognized as part of placenames when given in vernacular variations.

Assuming the parents recognize their ‘mistake’, and restructure their query to *childcare centres in fitzroy north*, they will be presented with a map of the four services *in* Fitzroy North—they must be closest to the point characterizing Fitzroy

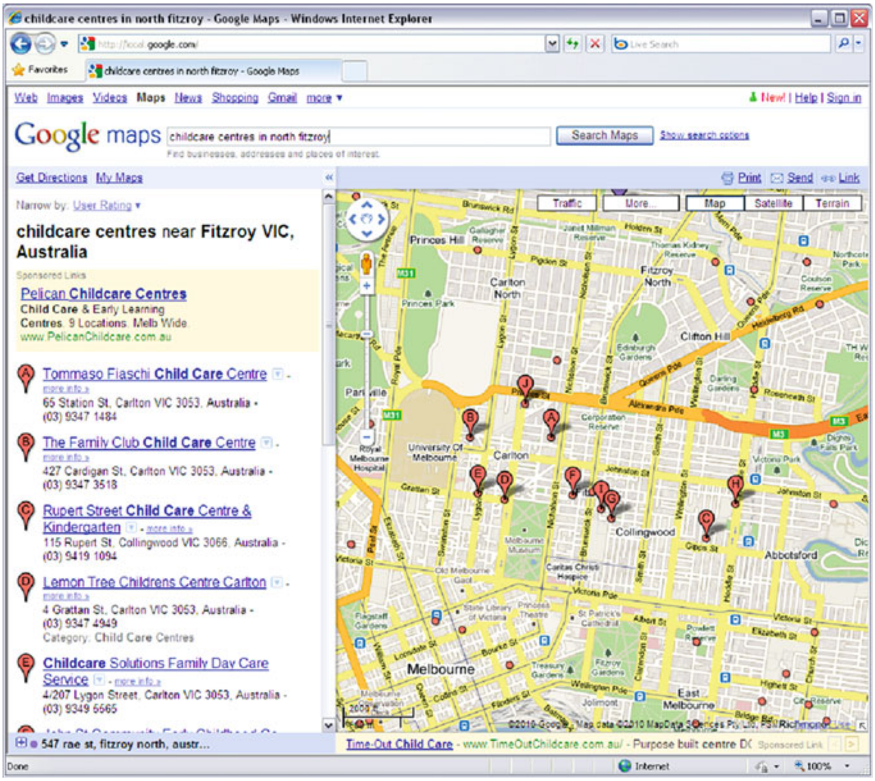

Fig. 4 The service's response to *childcare centres in north fitzroy* returns results for Fitzroy (© Google, 2010)

North after our findings above, or their string matching is superior, distinguishing from those that are merely *near* Fitzroy North. Figure 5 provides a further insight. The first result listed is an example of what can be referred to as a vanity address. A vanity address is one where a person or business reports their address differently from their official address, typically to one with perceived superior status (ANZLIC 2009). In this example, *Kids on Queens Parade Child Care Centre & Registered Kindergarten* lists its street address as *476 Queens Pde, Clifton Hill, VIC*. However, querying this street number and name directly in the service, it resolves to Fitzroy North not Clifton Hill. Therefore, we can assume vanity addresses are being accepted for business listings, which presents challenges for data mining Web resources for place descriptions.

To test for capabilities of managing spatial hierarchies next-up the query *childcare centres in the city of yarra* is attempted. Childcare services are managed at a local government level, and increasingly they are implementing policies to provide residents and workers in their jurisdiction preferential treatment on waiting lists. Fitzroy North is in the *City of Yarra*. Knowing these policies it is

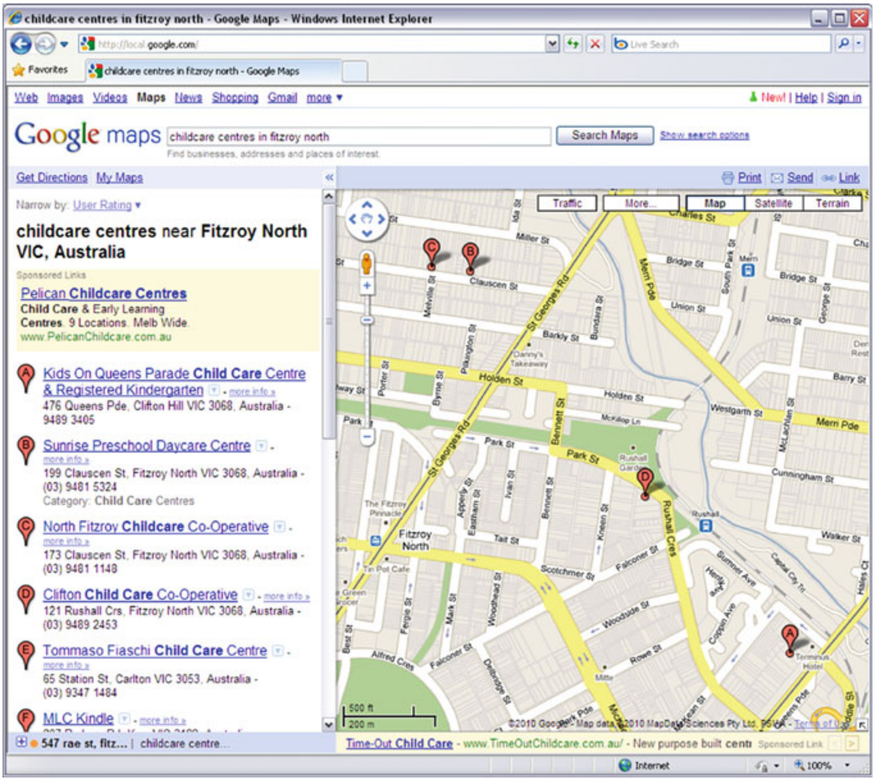

Fig. 5 The four childcare centers found in Fitzroy North, provide examples of vernacular placenames incorporated in business names and a vanity address (© Google, 2010)

logical for parents to widen their search to the entire local government area to better guarantee a place. However, this query is resolved to *childcare centres near Yarra NSW, Australia*. We can hypothesize that, as local government areas are not used in addresses, they are not integrated as a data source.

To test for more complex place descriptions, the parents try *childcare centres in the inner north of Melbourne*. With the already observed lack of abilities to deal with spatial relations, the response shows that *inner* is attempted to be interpreted as a street name, and the ranked placenames are addresses that include this name. It is also a spatial relation that challenges formal models of relationships by its uncertainty. In contrast, the responses to the final request *childcare centres in fitzroy north and surrounding suburbs* held more promise, but the ranked placenames refer to places clearly beyond the directly surrounding suburbs (Fig. 6). With the lack of topological knowledge it appears that the service translates this request to provide all childcare centres within a configured distance of Fitzroy North. In many cases this heuristic approach may yield acceptable results, in

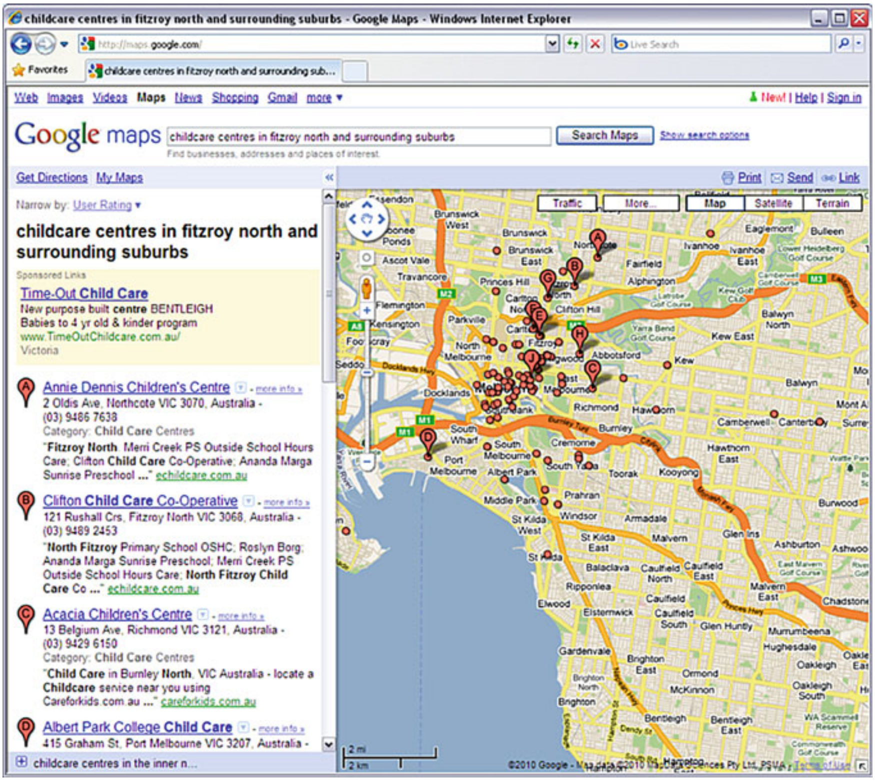

Fig. 6 Responses for *fitzroy north and surrounding suburbs* (© Google, 2010)

particular for vaguely defined places, but suburbs have well defined extents, and thus this request is not ambiguous.

In conclusion, the parents in this case study cannot rely on a conversation with the service to determine what childcare services are in their area. They would be forced to pan and zoom the map, defining their personal context, clicking on the services that meet their criteria as they find them.

3.3 Identified Shortcomings

Identified shortcomings from the case studies include:

- The spatial semantics of places is not sufficiently captured by gazetteers and the like. Linking between databases is challenging with lack of semantic information and other deficiencies in the capture and representation of places.
- Aggregated place descriptions use explicit or implicit spatial relations, especially containment but also topological, directional and qualitative distance relations.

Understanding aggregated place descriptions is impossible with point-like georeferences.

- Spatial reasoning between places is challenged further by the nature of places and the gradual, vague, and context-dependent interpretations of placenames in conversation.
- Language tools need improvement to deal with vernacular variations of placenames, including mistyped or abbreviated placenames, but also about the category (semantics) of placenames.
- Related places in place descriptions are chosen to disambiguate places in a particular communication context, but from the many possible ways to do this the chosen places feature salience, and the structure of place descriptions show salience hierarchies—from the prominent to the less prominent. This is not reflected in current databases or reasoning.
- Sensitivity for language and culture is lacking in global systems and services.
- Understanding the query context is limited. In particular the query history can be a simple indicator for spatial context, but can also fail just as easily.

In summary current technology is far from being able to talk about place intelligently.

4 Review of the State of Knowledge

Case studies can only highlight shortcomings in current systems. In this section the findings will be matched with the current state of knowledge, such that open questions for a research agenda can be identified.

4.1 Technological Progress

Compared to twenty years ago the urgency of machine understanding of place descriptions has risen dramatically by current technological progress. GPS and mobile phones were in infancy twenty years ago. Nowadays we have cyber-infrastructures, mobile ubiquitous access to information, and the web as an inexhaustible resource of data. A few statements shall illustrate the fundamentally changed technological environment.

Ubiquitous positioning of a person is solved (Kolodziej and Hjelm 2006; Retscher and Kealy 2006): developments ensure a machine never again needs to ask a person for their current location. This *location-awareness* (e.g., Want and Schilit 2001) is the current state of the technology.

Ubiquitous access to spatial data is solved. In principle, data is abundant and redundant, and a machine—including a mobile device, smart vehicle, or smart environment—can find and access any spatial data through some spatial data infrastructure. Management principles (custodianship, licensing, pricing, metadata management and exchange formats) have been addressed outside science. Only semantic interoperability between spatial data from different resources remains a research challenge (Kuhn 2005).

Despite an abundance of data, data about place, including appropriate data models, is missing. The typical georeference is a point (in some coordinate system), and further spatial semantics is neither captured nor clear how to describe. As data has become more accessible and inexpensive, and with the evolution of the social web, indirect methods of data capture become available: data mining, web harvesting, or crowd sourcing are currently explored to capture placenames and their spatial meaning as they evolve and change. These methods are all text-based, not spatial, and spatialized by points, either derived from placename databases, or directly from geotags (text tagged with a georeference). Results are either points or point clouds.

4.2 Scientific Progress

While geographic information science is experiencing an emerging interest in place (Winter et al. 2009), in human geography place has been a fundamental and well researched concept for a long time (e.g., Cresswell 2004; Tuan 1977; Relph 1976; Harvey 1993; Rodaway 1994). Traces can be found in linguistic and cognitive research on everyday communication (e.g., Jarvella and Klein 1982; Tversky 2003; O'Keefe 2003; Pylyshyn 2007). Geographic information science has seen ontological approaches to characterize place (e.g., Couclelis 1992; Casati and Varzi 1999; Agarwal 2004; Bennett and Agarwal 2007; Donnelly 2005), affordance-based approaches (Scheider and Janowicz 2010), mobility based approaches (e.g., Miller 2005; Schmid and Richter 2006), and space syntax approaches (e.g., Dalton 2007; Dalton 2006).

Independently, and with no reference to place, work has been done on representing objects of uncertain or indefinite boundaries (e.g., Burrough and Frank 1996). The prominent representations and logics of approximate reasoning are fuzzy sets (Zadeh 1965), rough sets (Pawlak 1982), and supervaluation (Kulik 2001; Bennett 2001). None of them has been systematically applied to deal with place in our limited sense of the word. They are also not well supported by the data models of current spatial databases. However, they will form natural representations for current work trying to capture the spatial extent of an area in which a placename is used within a community (e.g., McGranaghan 1991; Schmidtke 2003; Tezuka et al. 2004; Jones et al. 2001; Jones et al. 2008; Ahlers and Boll 2008; Scharl et al. 2008; Twaroch et al. 2008; Edwardes and Purves 2007; Davies et al. 2009; Schlieder and Matyas 2009).

Research on salience and prominence of features in an environment has emerged recently (e.g., Nothegger et al. 2004). A first commercial navigation service using salience-based selection of landmarks in their route directions has been launched (Duckham et al. 2010).

Research on qualitative spatial relations has produced now well-established knowledge (e.g., Randell et al. 1992; Egenhofer and Franzosa 1991; Freksa 1991) and tools implementing this knowledge for qualitative reasoning (Wallgrün et al. 2007).

Small-screen cartography is now an established research area (e.g., Agrawala and Stolte 2001; Schmid 2008; Schmid et al. 2010). As far as talking about place is concerned, mobile you-are-here maps (local orientation) are available commercially, and are researched to improve their usability. The last ten years have also seen the evolution of *mapping for the masses* by web and mobile applications (e.g., Hudson-Smith et al. 2009). The ubiquity of maps has made consumer and business expectations increasingly sophisticated, demanding support for familiar places in everyday conversation contexts.

All the advances discussed have largely been with respect to Western concepts of place and addressing systems. Recent research in linguistics and anthropology has also addressed the ways how different spatial experiences and organizations have shaped spatial language between cultures and language groups (Mark et al. 1999, 2007). For example, for many indigenous cultures language including placenames and spatial relations are owned, and access is a privilege (e.g., Hodges 2007; Windsor 2009), and these additional cultural complexities have yet to be considered.

This review reveals that much previous research is relevant when it comes to characterizing, modeling and reasoning with place, but also that place, placenames and place descriptions are not a systematically researched area.

5 A Research Agenda for Talking about Place

Place is an emerging problem for geographic information science that has multiple roots, some of them in Las Navas 1990 (Nunes 1991; McGranaghan 1991). However, place as such is rarely recognized as a particular challenge within the various published research agendas (e.g., Virrantaus et al. 2009; Goodchild 2010 for recent reviews). It is rather hidden in issues such as *Cognition*, *Geographic Representation*, or *Uncertainty*. In Goodchild's triangle between *the human*, *society* and *the computer* (2010, p. 7) talking about place would be located in the centre between the human and the computer, as long as we talk about human–computer interaction, but linguists might also look at the edge between the human and society. We argue that place must be fully recognized, or made explicit in the agenda, to make progress towards intelligent systems, and this despite the weak definition of place.

This chapter has focused on *understanding* human place descriptions, to create a case, but the complementary task of an intelligent machine is also part of talking about place: generating place descriptions similar to those produced by humans.

So given the identified shortcomings (3.3) and the relevant technological (4.1) and scientific progress (4.2), what are the particular topics for a research agenda on place? We can identify:

- Defining place:
  In this part—the first topic of any research agenda on place—the community must agree on a concept, potentially several concepts of place, as the subject of study, and how to represent them, i.e., *place* as a function of x and y.
- Capturing place:
  Once the first topic has been sufficiently addressed, methods to capture places as a function of x and y can be developed. As laid out these methods must be richer than current gazetteers, to enable more intelligent spatial reasoning. Early work in this direction can be found in geographic information retrieval (Janowicz et al. 2011; e.g., Alazzawi et al. 2010) and in mobile location based gaming (Richter and Winter 2011), both of them relying on capturing common sense knowledge.
- Generating place descriptions:
  Given that some research has been done already in this area (Tomko and Winter 2009; Richter et al. 2008), the main stumbling blocks for progress might be the two topics above.
- Understanding place descriptions:
  The challenges related to understanding place descriptions are well laid out in this chapter. Richer databases than current gazetteers will facilitate the development of novel methods in this area. Related, and contributing, are research efforts to capture the salience of geographic features, their relevance for various contexts, and the notion of context itself. Here at least aspects of context related to the spatial neighborhood of the geographic features, the affordances exerted by the environment, the individuals interacting with the environment, and their activities or purposes. What can be learned here, can also inform the generation of place descriptions.
- Dialog about locations with place:
  The combination of the previous two research topics will finally enable smart dialog, or the intelligent system (Winter and Wu 2009) to support human problem solving.

Furthermore, dealing with place will challenge some of the developed knowledge. For example, representations and reasoning tools for spatial relationships were designed for spatial data types of crisply bounded features (points, lines, and polygons). The spatial semantics of places will rarely be properly or completely described by points, lines and polygons, and also has a temporal component. This means that research on spatial relations has to be combined with research on place and place descriptions to finally converge and contribute to intelligent systems talking about place.

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References

Agarwal P (2004) Contested nature of place: knowledge mapping for resolving ontological distinctions between geographical concepts. In: Egenhofer M, Freksa C, Miller HJ (eds) Geographic information science, vol 3234., Lecture notes in computer science. Springer, Berlin, pp 1–21

Agrawala M, Stolte C (2001) Rendering effective route maps: improving usability through generalization. In: SIGGRAPH 2001, ACM, Los Angeles, pp 241–250

Ahlers D, Boll S (2008) Retrieving address-based locations from the web. In: Jones CB, Purves R (eds) Second international workshop on geographic information retrieval, ACM Press, Napa Valley, pp 27–34

Alazzawi AN, Abdelmoty AI, Jones CB (2010) An ontology of place and service types to facilitate place-affordance geographic information retrieval. In: Purves R, Clough P, Jones CB (eds) Proceedings of the 6th workshop on geographic information retrieval, ACM, Zurich, Paper 4 (2 pages)

ANZLIC (2009) National address management framework—glossary of terms. ANZLIC, Australia

Aristotle (350BC) Physics (trans: Hardie RP, Gaye RK). eBooks@Adelaide. The University of Adelaide, Adelaide, South Australia

Bennett B (2001) Application of supervaluation semantics to vaguely defined spatial concepts. In: Montello DR (ed) Spatial information theory, vol 2205., Lecture notes in computer science. Springer, Berlin, pp 108–123

Bennett B, Agarwal P (2007) Semantic categories underlying the meaning of ‘place’. In: Winter S, Duckham M, Kulik L, Kuipers B (eds) Spatial information theory, Lecture notes in computer science, vol 4736. Springer, Berlin, pp 78–95

Burrough PA, Frank AU (eds) (1996) Geographic objects with indeterminate boundaries, vol 2. ESF-GISDATA. Taylor & Francis, London

Casati R, Varzi AC (1999) Parts and places: the structures of spatial representation. The MIT Press, Cambridge

Coppock JT, Rhind DW (1991) The history of GIS. In: Maguire DJ, Goodchild MF, Rhind DW (eds) Geographical information systems: principles and applications, vol 1. Longman Scientific & Technical, Harlow, pp 21–43

Couclelis H (1992) Location, place, region, and space. In: Abler RF, Marcus MG, Olson JM (eds) Geography’s inner worlds. Rutgers University Press, New Brunswick, pp 215–233

Cresswell T (2004) Place: a short introduction. Blackwell Publishing Ltd., Oxford

Dalton NS (2007) Is Neighbourhood measurable? In: Kubat AS (ed) 6th international space syntax symposium, Istanbul, Turkey

Dalton NSC (2006) Configuration and neighbourhood: is place measurable? In: Hölscher C, Conroy Dalton R, Turner A (eds) Space syntax and spatial cognition, SFB TR8 Spatial Cognition, Bremen, Germany, pp 53–64

Davies C, Holt I, Green J, Harding J, Diamond L (2009) User needs and implications for modelling vague named places. Spatial Cognit Comput 9(3):174–194

Donnelly M (2005) Relative places. Appl Ontol 1(1):55–75

Duckham M, Winter S, Robinson M (2010) Including landmarks in routing instructions. J Locat-Based Services 4(1):28–52

Edwardes AJ, Purves R (2007) A theoretical grounding for semantic descriptions of place. In: Web and wireless geographical information systems, Lecture notes in computer science, vol 4857. Springer, pp 106–120

Egenhofer MJ, Franzosa RD (1991) Point-set topological spatial relations. Int J Geograph Inf Syst 5(2):161–174

Frank AU, Mark DM (1991) Language issues for geographical information systems. In: Maguire DJ, Goodchild MF, Rhind DW (eds) Geographical information systems: principles and applications, vol 1. Longman, London, pp 147–163

Freksa C (1991) Qualitative spatial reasoning. In: Mark DM, Frank AU (eds) Cognitive and linguistic aspects of geographic space. NATO ASI series d: behavioural and social sciences. Kluwer Academic Press, Dordrecht, pp 361–372

Goodchild MF (2010) Twenty years of progress: GI Science in 2010. J Spatial Info Sci 1(1):3–20

Harvey D (1993) From space to place and back again: reflections on the condition of postmodernity. In: Bird J, Curtis B, Putnam T, Robertson G, Tickner L (eds) Mapping the futures: local cultures. Global Change, Routledge, pp 3–29

Herskovits A (1986) Language and spatial cognition. Cambridge University Press, Cambridge

Hill LL (2006) Georeferencing: the geographic associations of information. Digital Libraries and Electronic Publishing, The MIT Press, Cambridge

Hodges F (2007) Language planning and place naming in Australia. Curr Issues Lang Plan 8(3):383–403

Hudson-Smith A, Batty M, Crooks AT, Milton R (2009) Mapping for the masses: accessing Web2.0 through crowdsourcing. Soc Sci Comp Rev 27(4):524–538

Janelle DG (2004) Impact of information technologies. In: Hanson S, Giuliano G (eds) The geography of urban transportation. Guilford Press, New York, pp 86–112

Janowicz K, Raubal M, Kuhn W (2011) The semantics of similarity in geographic information retrieval. J Spatial Info Sci 1(2):29–57

Jarvella RJ, Klein W (eds) (1982) Speech, place, and action. Wiley, Chichester

Jones CB, Alani H, Tudhope D (2001) Geographical information retrieval with ontologies of place. In: Montello DR (ed) Spatial information theory, vol 2205., Lecture notes in computer science. Springer, Berlin, pp 322–335

Jones CB, Purves RS, Clough PD, Joho H (2008) Modeling vague places with knowledge from the web. Int J Geograph Info Sci 22(10):1045–1065

Kolodziej KW, Hjelm J (2006) Local positioning systems. CRC Press, Boca Raton

Kuhn W (2005) Geospatial semantics: why, of what, and how? In: Spaccapietra S, Zimanyi E (eds) Journal of data semantics III, vol 3534., Lecture notes in computer science. Springer, Berlin, pp 1–24

Kulik L (2001) A geometric theory of vague boundaries based on supervaluation. In: Montello DR (ed) Spatial information theory, vol 2205., Lecture notes in computer science. Springer, Berlin, pp 44–59

Levinson SC (1996) Frames of reference and molyneux's question: crosslinguistic evidence. In: Bloom P, Peterson MA, Nadel L, Garrett MF (eds) Language and space. MIT Press, Cambridge, pp 109–169

Marchette SA, Shelton AL (2010) Object properties and frame of reference in spatial memory representations. Spatial Cogn Comput 10(1):1–27

Mark DM, Frank AU (1991) Cognitive and linguistic aspects of geographic space, vol 63., Nato ASI series d: behavioural and social sciences. Kluwer Academic Publishers, Dordrecht

Mark DM, Smith B, Tversky B (1999) Ontology and geographic objects: an empirical study of cognitive categorization. In: Freksa C, Mark DM (eds) Spatial information theory, vol 1661., Lecture notes in computer science. Springer, Berlin, pp 283–298

Mark DM, Turk AG, Stea D (2007) Progress on yindjibarndi ethnophysiography. In: Winter S, Duckham M, Kulik L, Kuipers B (eds) Spatial information theory, vol 4736., Lecture notes in computer science. Springer, Berlin, pp 1–19

McGranaghan M (1991) Matching representations of geographic locations. In: Mark DM, Frank AU (eds) Cognitive and linguistic aspects of geographic space, vol 63., NATO ASI series d: behavioural and social sciences. Kluwer Academic Publishers, Dordrecht, pp 387–402
Miller HJ (2005) Place-based versus people-based accessibility. In: Levinson D, Krizek KJ (eds) Access to destinations. Elsevier, London, pp 63–89
Montello DR (1993) Scale and multiple psychologies of space. In: Frank AU, Campari I (eds) Spatial information theory, vol 716., Lecture notes in computer science. Springer, Berlin, pp 312–321
Montello DR, Goodchild MF, Gottsegen J, Fohl P (2003) Where's downtown? behavioral methods for determining referents of vague spatial queries. Spatial Cogn Comput 3(2&3):185–204
Nothegger C, Winter S, Raubal M (2004) Computation of the salience of features. Spatial Cogn Comput 4(2):113–136
Nunes J (1991) Geographic space as a set of concrete geographical entities. In: Mark DM, Frank AU (eds) Cognitive and linguistic aspects of geographic space, vol 63., NATO ASI series d: behavioural and social sciences. Kluwer Academic Publishers, Dordrecht, pp 9–33
O'Keefe J (2003) Vector grammar, places, and the functional role of the spatial prepositions in english. In: van der Zee E, Slack J (eds) Representing directions in language and space. Oxford Linguistics. Oxford University Press, New York, pp 69–85
Pawlak Z (1982) Rough sets. Int J Comput Inform Sci 11(5):341–356
Pylyshyn ZW (2007) Things and places: how the mind connects with the world. The Jean Nicod lectures. The MIT Press, Cambridge
Randell DA, Cui Z, Cohn A (1992) A spatial logic based on regions and connection. In: Brachmann R, Levesque H, Reiter R (eds) Third international conference on the principles of knowledge representation and reasoning. Morgan-Kaufmann, Los Altos, pp 165–176
Relph EC (1976) Place and placelessness. Pion Ltd., London
Retscher G, Kealy A (2006) Ubiquitous positioning technologies for modern intelligent navigation systems. J Navigation 59(1):91–103
Retz-Schmidt G (1988) Various views on spatial prepositions. AI Magazine 9(2):95–105
Richter K-F, Tomko M, Winter S (2008) A dialog-driven process of generating route directions. Comput Environ Urban Syst 32(3):233–245
Richter K-F, Winter S (2011) Citizens as database: conscious ubiquity in data collection. In: Pfoser D, Tao Y, Mouratidis K et al (eds) Symposium on spatial and temporal databases (SSTD), vol 6849., Lecture notes in computer science. Springer, Berlin, pp 445–448
Rodaway P (1994) Sensouous geographies: body, sense, and place. Routledge, London
Scharl A, Stern H, Weichselbraun A (2008) Annotating and visualizing location data in geospatial web applications. In: Boll S, Jones CB, Kansa E et al (eds) First international workshop on location and the web, ACM Press, Beijing, pp 65–68
Scheider S, Janowicz K (2010) Places as media of containment. In: GIScience 2010 extended abstracts, University of Zurich, Zurich, 2010
Schlieder C, Matyas C (2009) Photographing a city: an analysis of place concepts based on spatial choices. Spatial Cogn Comput 9(3):212–228
Schmid F (2008) Knowledge-based wayfinding maps for small display cartography. J Locat Based Services 2(1):57–83
Schmid F, Kuntzsch C, Winter S, Kazerani A, Preisig B (2010) Situated local and global orientation in mobile you-are-here maps. In: de Sa M, Carrico L, Correia N (eds) 12th international conference on human computer interaction with mobile devices and services (MobileHCI), ACM Press, Lisbon, pp 83–92
Schmid F (2006) Richter K-F extracting places from location data streams. In: Zipf A (ed) Second international workshop on ubiquitous geographical information services. Münster, Germany
Schmidtke H (2003) A geometry for places: representing extension and extended objects. In: Kuhn W, Worboys MF, Timpf S (eds) Spatial information theory, vol 2825., Lecture notes in computer science. Springer, Berlin, pp 221–238

Tezuka T, Yokota Y, Iwaihara M, Tanaka K (2004) Extraction of cognitively-significant place names and regions from web-based physical proximity co-occurrences. In: Zhou X, Su S, Papazoglou MP, Orlowska ME, Jeffrey KG (eds) Web information systems—WISE 2004, vol 3306., Lecture notes in computer science. Springer, Berlin, pp 113–124

Tomko M, Winter S (2009) Pragmatic construction of destination descriptions for urban environments. Spatial Cogn Comput 9(1):1–29

Tuan Y-F (1977) Space and place: the perspective of experience. University of Minnesota Press, Minneapolis

Tversky B (2003) Places: points, planes, paths, and portions. In: van der Zee E, Slack J (eds) Representing directions in language and space. Oxford Linguistics. Oxford University Press, Oxford, pp 132–143

Tversky B, Lee PU (1998) How space structures language. In: Freksa C, Habel C, Wender KF (eds) Spatial cognition, vol 1404., Lecture notes in artificial intelligence. Springer, Berlin, pp 157–175

Twaroch F, Jones CB, Abdelmoty AI (2008) Acquisition of a vernacular gazetteer from web sources. In: Boll S, Jones CB, Kansa E et al. (eds) First international workshop on location and the web, ACM Press, Beijing, pp 61–64

Virrantaus K, Fairbairn D, Kraak MJ (2009) ICA research agenda on cartography and GI science. The Cartograph J 46(2):63–75

Wallgrün JO, Frommberger L, Wolter D, Dylla F, Freksa C (2007) A toolbox for qualitative spatial representation and reasoning. In: Barkowsky T, Knauff M, Ligozat G, Montello DR (eds) Spatial cognition V: reasoning, action, interaction, vol 4387., Lecture notes in artificial intelligence. Springer, Berlin, pp 39–58

Want R, Schilit B (2001) Expanding the horizons of location-aware computing. IEEE Comp J 34(8):31–34

Windsor G (2009) The recognition of aboriginal placenames in New South Wales. In: Koch H, Hercus L (eds) Aboriginal placenames: naming and re-naming the Australian landscape. ANU E Press, Canberra, pp 70–86

Winter S (2003) Route adaptive selection of salient features. In: Kuhn W, Worboys MF, Timpf S (eds) Spatial information theory, vol 2825., Lecture notes in computer science. Springer, Berlin, pp 320–334

Winter S, Kuhn W, Krüger A (2009) Does place have a place in geographic information science? Spatial Cogn Comput 9(3):171–173

Winter S, Wu Y (2009) Intelligent spatial communication. In: Navratil G (ed) Research trends in geographic information science. Springer, Berlin, pp 235–250

Worboys MF (2001) Nearness relations in environmental space. Int J Geograph Info Sci 15(7):633–652

Zadeh LA (1965) Fuzzy sets. Inf Control 8:338–353

Many to Many Mobile Maps

Stephen C. Hirtle and Martin Raubal

Abstract The rapid development of mobile computing devices along with a variety of Web 2.0 social networking tools has led to a dramatic change in the way maps and other spatial displays are utilized. The evolution from stand-alone desktop GIS to the interactive, mobile devices, in which information from one or more sources and is sent to one or more sinks, is discussed. The result is access to real-time information, which is generated from both traditional sources, social networks, and other specialized geowikis. Both the benefits of many to many mobile maps and the emergence of new problems, such as understanding the needs of the user and providing appropriate context, are discussed.

Keywords Mobile computing · Social computing · GIS

1 Introduction

In the past 40 years, Geographic Information (GI), which was once the domain of paper and mechanical tools, has moved into the electronic domain with the development of Geographic Information Systems (GIS). More recently, electronic processing of spatial information has moved from stand-alone desktop systems to interconnected mobile devices. Such evolution in software and hardware has been

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characterized by Frank (2002) as a general shift from a reliance on general purpose geographic information systems (Big GIS) to access of specific geographic information (Small GI), which is relevant for the particular place and time. Big GIS was administered typically by non-end-users, often in a batch mode, for large problems, such as one would find in areas like urban planning, demographic analysis, or topographic mapping. The Small GI approach put the analysis in the hands of individual users and can solve problems that require iterative queries, such as found in logistics, tourism, real estate, or marketing. It is interesting to note that in historical terms, information was in the hands of users before the development of Big GIS. The shift to Small GI has returned spatial information to the hands of individuals.

Overall, the change to Small GI has been transformative and requires a reassessment of the field of geographic information science. Twenty years ago, every day spatial problems, such as determining the directions to a vacation resort or identifying a restaurant for dinner, were often solved in advance using static technologies including paper maps and guides. The use of electronic data was reserved for complex spatial problems, such as tracking the movement of a hurricane or locating the ideal location of a new store.

The shift to the use of spatially aware personal digital assistants over the last two decades has led to a change of the information-seeking behavior and created novel spatio-temporal decision situations due to the dynamic nature of mobility. This change has resulted in a shift of information needs: we often need to make decisions on the spot, for example, locating needed roadside services when traveling by car or making a flight connection inside a busy airport under time pressure. New technologies, such as Location Based Services (LBS), can help individuals make well-informed decisions. However, they can only do so if they take into account how people operate in dynamic and often complex situations, what kind of information they require, and how such information can be communicated effectively.

The result of these changes has been the increase of real-time information that can assist decision-making processes and a change to mobile decision-making that reflects current needs and current conditions. Mobile decisions are increasingly less likely to be made on the basis of centralized databases, but more likely to be supported through the Web 2.0 initiatives of social networking and distributed information sources. In terms of the temporal scale, mobile decisions are often made at the start of any actions and can change as the action progresses. Both push and pull technologies are possible, although push technologies have traditionally been viewed with concern for privacy and invasiveness (Raper et al. 2008; Kaasinen 2005).

To capture this new environment, we introduce the term *many to many mobile maps*, which can be defined as spatial displays that are geographically aware and shown on small portable devices connected to multiple sources and sinks. That is to say, the device can receive information that has been generated by many users or sensors, and can also send information to many users or act as sensor. For example, a GPS-based navigation system might do variable routing based on current traffic flows, while at the same time providing its own traffic speed information to update the data servers. The concept of *many to many* allows for *many to one*, such as a restaurant recommendation based on a social network of hundreds of reviews, and *one to many*, such as a single time-trace of a hike that is sent to a large archive of hikes that can be used to generate future recommendations. Furthermore, the map-like representations in many to many mobile maps can vary from a simple arrow indicating to turn here to photorealistic images of the immediate surround (Butz et al. 2001). At present, a two-dimensional graphical map would be the most common display and is typically displayed on small portable devices, such as an Android phone or iPhone. Satellite views, street-level images, and graphical mockups of the local environment (Agrawala et al. 2011) are also possible under the many to many mobile map framework, as well as both larger and small visual displays, sophisticated audio interfaces, or force-fed input devices.

2 How Has the Field Changed?

2.1 Access to Real-Time Information

Over the last years we have seen a tremendous change in how people access information and also with regard to the currency of such information. Most mobile decision situations require access to up-to-date information, such as in transportation, emergency response, or weather-related applications. We often think of this kind of information being accessed through mobile devices, but it can also include public information. For example, many public transportation systems offer information screens inside vehicles and/or at stops, which show the departure times of connecting buses, trams, and subways (Fig. 1). This information can also be accessed on mobile devices, which would facilitate to adjust trips in transit or plan alternative stops along the way.

Many to many mobile maps are greatly facilitated by the large amount of sensor data that is readily available through public databases. This includes common

Fig. 1 Public screen inside a tram in Zurich, Switzerland showing time estimates for the next three stops and the final destination, as well as connecting lines at the upcoming train station Bahnhof Oerlikon Ost

sources such as traffic sensor information or weather data. As just one example of traffic data, the California Department of Transportation maintains over 20,000 inductive loop sensors, which count the number of vehicles that pass over each highway sensor, as well as the time covered by each vehicle, to yield measures of flow and occupancy (Hutchins et al. 2010). Weather data is even more abundant with weather stations reporting a large variety of metaconditions at regular intervals. Efforts, such as the SensorMap project (Nath et al. 2007), provide general portals to both publish and retrieve sensor data. Furthermore, sensor information can be gathered using less traditional means. For example, Nericell (Mohan et al. 2008) is a prototype that uses the capabilities of smartphones, such as the accelerometer, microphone and GPS sensors to record potholes, bumps, braking, and traffic noise in Bangalore, India.

The cloud also allows for the sharing of additional data, computational resources, and specialized analysis programs (Lane et al. 2010). The use of the cloud raises potential privacy issues, especially when your own data is being spread to others without your explicit consent. More common is the ability to share informal sources of information through Twitter, Facebook, Flickr, and other social media, as discussed below, where there is more obvious control over some of the privacy settings through the personal management of your friend networks.

2.2 Traditional Decision-Making to Mobile Decision-Making

Clearly, a large part of the world's civilization has turned into a *mobile information society*, often requiring people to make decisions on the spot and in highly dynamic environments (Raubal 2011). There is still little knowledge about how mobile location-based decision-making is different from other types of decision-making. Much research has been done in the area of general decision theory covering a wide range of models with different foci on describing how decisions could or should be made and on specifying decisions that are made (Golledge and Stimson 1997). Behavioral decision theory has been emphasized in the cognitive literature due to the fact that human decision-making is not strictly optimizing in an economical and mathematical sense (Simon 1955). In order to investigate whether principles of generic decision-making can be transferred to mobile decision-making and find potential differences, researchers have developed tools to study the interaction between environments, individuals, and mobile devices (Li and Longley 2006).

Mobile decision-making involves a multitude of spatio-temporal constraints relating not only to people's spatio-temporal behavior in large-scale space (Kuipers and Levitt 1988) but also to their interaction with mobile devices, and perceptual, cognitive, and social processes. Space and time must therefore be considered from a broad perspective and as a context for understanding (Peuquet 2002). This includes actual physical spaces, multiple psychologies of space

(Montello 1993), and different types of times (Frank 1998). It is obvious that achieving progress in what may be called the evolving field of mobile Geoinformatics, requires multi- and interdisciplinary research. The overarching research question to be tackled is what is special about mobile decision-making?

2.3 Social Networking

Social networks have emerged in the decade as a major source of location-based information. Initially, social networking sites were designed both to facilitate communication among groups and to expand one's networks of friendships. Boyd and Ellison (2008) put SixDegrees.com, launched in 1997 and closed in 2000, as the first social network site. SixDegrees was followed by numerous other sites, such as LiveJournal, Friendster, MySpace, Flickr, Facebook, and Twitter. Location information became the focus of some sites, such as FourSquare. Recommendation sites, such as Yelp and Urbanspoon, include geographic pointers, and user-generated encyclopedias, such as Wikipedia and Wikimapia, include location coordinates where appropriate.

The consequence of the large amount of location-based social networking sites, is that one can gather both real-time information (e.g., the restaurant closed this afternoon due to a water main break) and aggregate information (e.g., travel times on Route 9 are typically 10 miles per hour under the posted limits during the lunch hour). In this rapidly changing arena, the following subsections highlight five different ways in which the social networking is being incorporated into spatial decision making and processing.

2.3.1 Volunteered Geographic Information

Volunteered geographic information (VGI) describes a large number of related activities in which collections of individuals provide geographic information for common consumption, in contrast to relying on the traditional authorities alone to provide maps and spatial information (Goodchild 2007). VGI allows individuals to mark information about locations that are of particular interest using either standalone applications or generic platforms. Generic platforms include websites such as OpenStreetMap or Wikimapia. After the devastating 2010 earthquake in Haiti, a group of international volunteers working abroad were able to remotely update OpenStreetMap, indicating passable roads, location of temporary shelters and the like. This was done in innovative ways by using not only current satellite imagery, but also ground reports, video captures and television news reports (Zook et al. 2010). The GeoCommons[1] project repository provided central storage for a

[1] http://geocommons.com/

variety of data sets, both official and unofficial. Zook et al. (2010) noted that the repository grew from less than two dozen to over 350 data sets in the weeks after the earthquake.

Other examples are more mundane, but also interesting. For example, the Wikimapia section for Pittsburgh, Pennsylvania indicates the location of the "food trucks," which appear on a daily basis near Carnegie Mellon University to sell food to students (Hirtle 2011). These trucks are part of an informal infrastructure that would not appear in yellow page directories, service listings, or other traditional maps, since they do not reside in permanent buildings with a fixed address. Yet, the information and location of the food trucks is quite useful for students looking for inexpensive meals at lunchtime and, thus, reflects in a GIS the common wisdom of the crowds.

2.3.2 Specialized Geowikis

As a subset of VGI, specialized geowikis also provide a platform for the sharing of certain kinds of spatial information. Here, we use the sense of geowiki that was given by Priedhorsky (2011) to refer to a specialized wiki that includes geographic information.[2] This goes beyond Wikipedia and Wikimapia, which are large-scale, generic repositories of generally unstructured text. As an example of a specialized geowiki, Priedhorsky et al. (2007a, b) demonstrated a bicycle route-finding system, which was based on information collected and stored in a geowiki. This application was challenging, as bicycle navigation systems are particularly difficult to automate. There are strong personal preferences with regard to topography, traffic, distance, and other factors. Priedhorsky et al. (2007a, b) presented a system that allowed for a wide range of personalized comments in terms of both the nature of the route to nearby amenities, such as the location of a pump to get air in your tires to an easy place to stop for refreshments. Building the system required a WYSIWYG web interface that made it easy to add information and bicycle paths. The project also includes a computational component where user-contributed knowledge was fed into selecting optimal routes.

2.3.3 Space–Time Trails

More recently, the explosion of GPS-enabled devices on smartphones, mp3 players, cameras, and other small mobile devices has led to the automatic recording and uploading of space–time trails. For example, Every Trail collects space–time trails in the same way that Flickr collects photographs or Delicious

[2] Our use of the term, geowiki, is in the generic sense of the concept. Geo-Wiki (with a hyphen) is the proper name of a separate project founded in 2009 through a collaboration of the International Institute for Applied Systems Analysis, University of Applied Sciences Wiener Neustadt and the University of Freiburg.

collects bookmarks. Uploaded trails on Every Trail have been categorized by mode of transportation and/or activity; a list which includes road biking, mountain biking, hiking, walking, running, driving, motorcycling, sightseeing, skiing, kayaking, canoeing, sailing, backpacking, roller skating, snowshoeing, horseback riding, snowboarding, ice skating, snowmobiling, hang gliding, skateboarding, bird watching, rock climbing, and even mountain unicycling. This information is publically available and can be easily mined for the collective information about popular routes, accurate estimates of travel times, and other spatio-temporal information. The large number of activities is critical to users, as what makes a good trail for mountain biking, backpacking, or rock climbing is based on a unique set of characteristics and constraints.

One method of aggregating space–time trails is through space syntax (Hillier 1996). Space syntax allows space–time trails to be aggregated across individuals to present the joint conception of space by activities, as shown in Fig. 2, where the time element is collapsed and no longer represented in an explicit fashion. Space syntax then provides a representation of the space by actual use. This might even include anomalies, such as traffic regulations (e.g., one-way streets or stop signs) that are being ignored on a regular basis (Turner 2009). The resulting "map" does not represent the legal truth, but instead the accepted reality of the collective wisdom of the crowd. Thus, space syntax can give a better understanding of the

Fig. 2 Space-time trails using space syntax measures from (Turner 2009). The area is from central London covering approximately 8 km × 6 km. Colors indicate trip duration

structure of a city as perceived by the residents who share their daily travels (Counts and Smith 2007; Turner 2009).

2.3.4 Place Concepts as Social Constructs

In addition to examining the information produced through VGI, one can use social tagging in an indirect way to understand the conceptualization that individuals have when referencing locations throughout the city. Social tagging is used as a way of marking entries in large collections (Gupta et al. 2010). The tags can be considered a folksonomy (Gruber 2008), which is not as formal or structured as an ontology, but allows individuals access to the content. The flexibility of social tagging makes it easier for individuals to implement and also allows for new tags to be incorporated into the folksonomy.

Using social tagging in an innovative way to answer deeper questions, Schlieder and Matyas (2009) analyzed a large collection of over 12,000 photographs of cities posted on Panoramio to show how cities are conceptualized by tourists. Schlieder and Matyas (2009) describe the approach as one of collaborative semantics, where the shared locations and terminology can be used to describe the structure of the city. This is not unlike the difference that one finds between the formal structure of a city as determined by city planners and engineers, and the common paths of travel that emerge through an analysis of walking patterns using space syntax (Hillier 1996).

2.3.5 Social Navigation Services

A more direct application of social networking can be found in social navigation services (Bilandzic et al. 2008). There is a wide range of services available on the web from location-based recommender systems to virtual post-it notes and graffiti (Espinoza et al. 2001). As with the previous examples, social navigation services can answer questions that require human judgment, such as the best place to find an inexpensive meal, or the best place to get fresh food for a picnic. Many traditional location-based services, such as Yellow Pages, are constructed without regard to quality of service. In contrast most current recommender systems, such as Yelp, reject this view and explicitly include a notion of social recommendation (Hearst 2008; Gupta et al. 2010).

3 What are the Challenges and Goals for Future Research?

3.1 Interaction Between Environments, Individuals, and Mobile Devices

In many ways, the ideal mobile device would act like an intelligent tour guide, who is knowledgeable of the immediate surroundings, knows the optimal route to get to a location, adjusts decisions with the current conditions and has intimate knowledge of all the shops, restaurants, and individuals in the area. This Orwellian view of technology in the near future will remain unrealized. Yet, at the same time, many individuals have already relinquished control of decisions to portable devices. We no longer have telephone numbers in memory, but depend on devices to recall them until lost. We now let GPS-based systems plan routes without confirming if the route makes sense in the local environment.

Future research must focus on the interaction possibilities between user, environment, and mobile device. Each of these 'components' can vary and the interaction depends on the specific task (Fig. 3). Different users perceive their environments differently and this should be reflected in the representation of the environment on the mobile device in order to facilitate user interaction. During an exploratory empirical study of interaction differences in the navigation services offered by Apple's iPhone and Google's Android smartphone a significant three-way interaction between the factors device, task, and environment could be demonstrated (Richter et al. 2010). This result implied that the number of wrong turns made by participants depended upon this combination. Further studies including different application scenarios, users, environments, and devices will shed more light on the complexity of this interaction and how to optimize it.

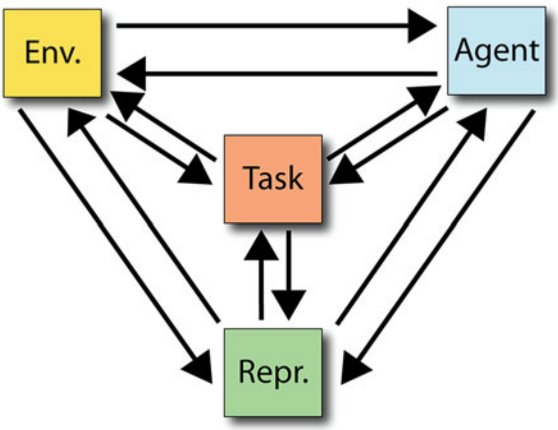

Fig. 3 Task-dependent interaction between agent (user), environment, and representation (mobile device) from (Richter et al. 2010)

Mobile eye-tracking studies (Grifantini 2010) can help find out whether users focus more on the environment or their mobile devices. The users' movement traces on their mobile device displays should indicate design problems with respect to symbol visualization, instructions, and other task-dependent spatio-temporal information. These studies will be of higher complexity compared to desktop eye-tracking experiments due to additional degrees of freedom (mobile device, movement, etc.).

3.2 Knowing the User

A key issue for the development of personalized services is knowing the user. Among the most important variables regarding differences between individual users and user groups (Raubal and Panov 2009) are age, gender, differences in spatial memory and reasoning abilities, preferred learning style, and attitude differences. Mobile decision-making requires fast access to spatial memory and the ability to make quick decisions on the spot. In addition, users have to cope with technological limitations regarding their mobile devices such as small screen size, and there is the general challenge of presenting information to someone on the move. We need studies that investigate for different domains how (different) people actually make decisions while on the move and how these decisions are impacted by technology and its current limitations. Intelligent user interfaces (Maybury and Wahlster 1998), which provide additional benefits to their users, such as adaptivity, context sensitivity, and task assistance, may be the way to go. But here, it is especially important to represent and exploit models of the user, the domain, tasks, and context. Adaptation is also required because it is practically impossible to anticipate the needs and necessities of each potential user in an infinite number of presentation situations.

3.3 Context

What is considered an optimal decision strongly depends on the context (Dey and Abowd 2000; Schmidt et al. 1999). Therefore, context elements must be captured for the particular user and task. What are relevant context elements and how can they be formalized (Raubal and Panov 2009)? These days, we have to cope with enormous loads of data, some of them helpful but most of them irrelevant to the task at hand. Much of these data automatically feed from sensors to the mobile device and support the mobile decision-making process. In addition, data can potentially be reused by others, such as when contributed and made available as VGI. Future research will have to address several issues in order to achieve context-sensitive location-based services, such as: How can we assure that only context-relevant data is taken into account? How can we filter these data for a particular user? How adaptive is such filtering process to the user's spatial and cognitive capabilities?

3.4 Impact on Spatial Learning

The use of technology for supporting people's mobile decision-making does not only impact their task performance but also their spatial learning of the environment. Studies have demonstrated that using mobile navigation devices may result in users turning off their brain (Munzer et al. 2006; Parush et al. 2007). They do not process the presented information and the information perceived in the environment to a sufficient level, and also lack the possibility to acquire survey knowledge. This is critical, especially in situations where technology fails and people must fully rely on their spatial knowledge and abilities.

In a human participants test using a multi-level virtual environment (Parush et al. 2007) demonstrated that reliance on automatic wayfinding systems can result in a degradation of spatial knowledge acquisition and learning. Participants had to perform way finding tasks and their current position was either indicated continuously or by request. In addition, they had to answer sporadic orientation quizzes. The results showed that those participants who had to request their position and who were more 'involved' through orientation quizzes also demonstrated better knowledge acquisition. The real-world study (Richter et al. 2010), described in Sect. 3.1, also indicated that differences in interaction with a mobile device during wayfinding can have an effect on people's spatial learning. More specifically, participants, who were required to actively zoom in at decision points when using a navigation service, made fewer wayfinding errors when later re-walking the same route without the help of the navigation service. Thus, participants showed an improvement in spatial learning with the active engagement of the navigational device.

As just one example of a non-geographic application, recent studies have looked at the role of spatial cognition in surgery and related fields (Hegarty et al. 2007, 2009). With minimally invasive surgical procedures, such as laparoscopy where a miniature video camera is directed to the surgical location, there is a loss of haptic cues that existed with the previous, more invasive forms of surgery. Keehner and Lowe (2009) have shown that haptic cues might reinforce the information gathered from visual cues in surgical settings. Thus, it might be incumbent on future interfaces to include a haptic component for the surgeons to respond. In a very different domain, an experimental interface, which combines auditory feedback and a force-feel joystick, allows blind sailors to direct a crew on a sailing vessel in tests off the coast of France (Simonnet et al. 2010). Thus, to the extent which spatial interfaces engage the user in the physical environment (Meilinger et al. 2008), there should be additional encoding and better memory of the environment.

Future research should investigate how differences in device design impact both navigation behavior and spatial learning. We have started to investigate how the functionality of a mobile navigation service can be adapted so that everyday users

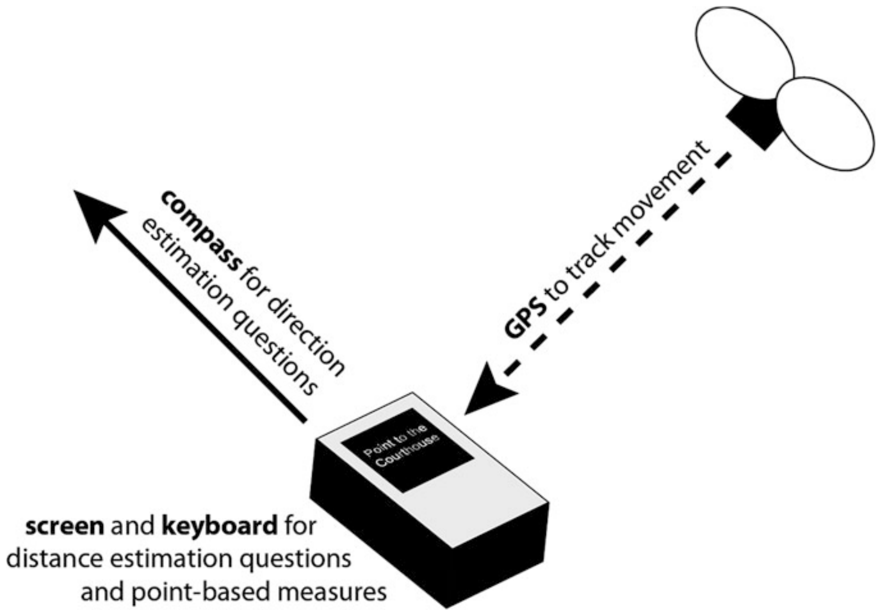

Fig. 4 The cognitive surveyor application supports mobile data collection (Dara-Abrams 2008)

of navigation services achieve both their immediate (finding their goal) and longer-term objectives (spatial learning) (Richter et al. 2010).

3.5 Innovative Tools

On the application side, we expect the future to bring novel and pioneering tools and services to the LBS market. Recent research has focused on the integration of digital and analog media (through the use of mobile phones that are equipped with digital cameras) (Rohs et al. 2007), the integration of different modes of communication (such as in navigation devices), and the development of LBS for group-decision-making (Espeter and Raubal 2009). Future mobile guides will be able to access knowledge from diverse online repositories, such as Wikipedia and Wikimapia, and use such content to generate educational audio tours starting and ending at stationary city maps (Schöning et al. 2007).

Innovative tools, such as the Cognitive Surveyor (Dara-Abrams 2008) (Fig. 4) will support future mobile data collection while people are actually performing tasks in the real world. Such data is necessary in order to analyze people's spatial knowledge and navigation practices. It will provide insights on when and where people make decisions, and how their acquired cognitive representations differ from the real world. This will help in the design of better services, which, in turn, should provide enhanced mobile decision support to their users.

4 The Future of Maps

One interesting question that emerges from the preceding analysis concerns the role of maps in the discourse. Consider, for instance, the iBurgh app for the iPhone (McNulty 2009). This application is designed for a single task of reporting a neighborhood problem to the city of Pittsburgh. For example, if you noticed a pothole in your street that has not been filled, you can use the iBurgh app to take a picture of the pothole. The application registers the location and then sends the picture with the geographical coordinates to the city's 311 complaint line. There is no need to describe the location in words or to draw a map of the location to later recall or transmit to the public works department. Spatial information is transmitted directly.

Directions seem like an obvious application for maps. However, maps suffer from the well-studied alignment problem that requires the observer to locate oneself on both the map and in the real world with the appropriate location and orientation (Davies and Peebles 2007). This had led to the needs to include complex instructions to get around the "tricky parts" of verbal directions (Hirtle et al. 2010). Furthermore, (Hirtle and Sorrows 1998) demonstrated that the images can be just as useful as either maps or a spatial description in locating oneself in an environment. A distinctive building would be an easy match in an image, when compared with the task of trying to identify which real-world building corresponds to a colored block representing the building on the map. Agrawala et al. (2011) have explored creating hybrid maps with some 3D sketches of useful landmarks that are of both visual and structural importance (Sorrows and Hirtle 1999).

The influx of image databases, such as Google Streetview, allows one to bypass the mapping process entirely and simply match the target location to an image. In fact, if one needs specific information, such as "Where do I turn to get to my hotel?," one needs no more than a voice telling you when you get near the appropriate intersection to turn in the appropriate direction. At best, this voice is accompanied by a small map. It is curious that on both websites and mobile screens, the 200 $\times$ 200 pixel map is becoming the norm for locating information.

The downside of providing limited spatial information is that it may impair the acquisition of spatial knowledge. For example, there appears to be a degradation in the ability to acquire spatial knowledge when using guided navigation systems, which results in continued to dependence on guidance systems for repeated trips along the same route (Ishikawa et al. 2008; Parush et al. 2007). The challenge for designers will be to provide effective visual displays that increase a user's engagement with the space, which in turn leads to a greater understanding of the environment (Agrawala et al. 2011).

5 Summary

In this review of literature, we traced a systematic change from centralized GIS platforms to individual GI platforms, which puts information and decision making into the hands of the individual, similar to how GI was viewed during thousands of years of mapmaking. Most of the related research discussed at Las Navas 1990, such as the sense-making investigation method for human wayfinding (Gluck 1991), the evidence that early environmental learning is not necessarily sequential (Blades 1991) as originally proposed by (Siegel and White 1975), or the image-schema-based formalization of interface metaphors by algebraic specifications (Kuhn and Frank 1991)—just to name a few examples—are still relevant today but the focus has changed due to our mobile information society. Unlike the past, the individual GI platforms are supported by a robust collection of real-time data sources, which can be broadcast to a large array of other users almost instantaneously. Thus, the *many to many mobile maps* concepts allow for heretofore unprecedented precision in the support of spatial decisions.

References

Agrawala M, Li W, Berthouzoz F (2011) Design principles for visual communication. Commun ACM 54(4):60–69

Bilandzic M, Foth M, De Luca A (2008) City flocks: designing social navigation for urban mobile information systems. In: 7th ACM conference on designing interactive systems, Cape Town, South Africa, 2008. ACM, New York, pp 174–183

Blades M (1991) Wayfinding theory and research: the need for a new approach. In: Mark D, Frank A (eds) Cognitive and linguistic aspects of geographic space. Kluwer, Dordrecht, pp 137–165

Boyd DM, Ellison NB (2008) Social network sites: definition, history, and scholarship. J Comput Med Commun 13(1):210–230

Butz A, Baus J, Krüger A, Lohse M (2001) A hybrid indoor navigation system. In: IUI2001: international conference on intelligent user interfaces. ACM Press, New York, pp 25–33

Counts S, Smith M (2007) Where were we: communities for sharing space-time trails. In: Proceedings of the 15th annual ACM international symposium on advances in geographic information systems (GIS '07), Seattle, WA, 2007. ACM, New York

Dara-Abrams D (2008) Cognitive surveying: a framework for mobile data collection, analysis, and visualization of spatial knowledge and navigation practices. In: Freksa C, Newcombe N, Gärdenfors P, Wölfl S (eds) Spatial cognition VI. learning, reasoning, and talking about space, LNCS 5248. Springer, Berlin, pp 138–153

Davies C, Peebles D (2007) Strategies for orientation: the role of 3D landmark salience and map alignment. In: Proceedings of the 29th annual conference of the cognitive science society, Nashville, TN, 2007. Erlbaum, New York, pp 923–928

Dey AK, Abowd GD (2000) Towards a better understanding of context and context-awareness. In: Conference on human factors in computing systems (CHI 2000), vol 4. The Hague, The Netherlands

Espeter M, Raubal M (2009) Location-based decision support for user groups. J Locat Based Serv 3(3):165–187

Espinoza F, Persson P, Sandin A, Nyström H, Bylund ECM (2001) GeoNotes: social and navigational aspects of location-based information systems. In: Abowd BS (ed) Ubicomp 2001: ubiquitous computing, international conference Atlanta, Georgia, September 30—October 2. Springer, Berlin, pp 2–17

Frank AU (1998) Different types of "times" in GIS. In: Egenhofer MJ, Golledge RG (eds) Spatial and temporal reasoning in GIS. Oxford University Press, Oxford, pp 40–62

Frank AU (2002) Big GIS/small GI—the commercialization of geographic information. In: Brazilian symposium on geoinformatics, Caxambu, Brazil, 2002

Gluck M (1991) Making sense of human way finding: review of cognitive and linguistic knowledge for personal navigation with a new research direction. In: Mark D, Frank A (eds) Cognitive and linguistic aspects of geographic space. Kluwer, Dordrecht, pp 117–135

Golledge RG, Stimson RJ (1997) Spatial behavior: a geographic perspective. Guilford Press, New York

Goodchild MF (2007) Citizens as sensors: the world of volunteered geography. GeoJ 69(4):211–221

Grifantini K (2010) Eye tracking for mobile control. MIT Technol Rev, Cambridge 24 May 2010

Gruber T (2008) Ontology of folksonomy: a mash-up of apples and oranges. Int J Semant Web Inf Syst 3:1–11

Gupta M, Li R, Yin Z, Han J (2010) Survey on social tagging techniques. SIGKDD Explor 12:58–72

Hearst MA (2008) UIs for faceted navigation: recent advances and remaining open problems. In: Workshop on human-computer interaction and information retrieval, Redmond, WA, USA, 2008

Hegarty M, Keehner M, Cohen C, Montello DR, Lippa Y (2007) The role of spatial cognition in medicine: applications for selecting and training professionals. In: Allen GL (ed) Applied spatial cognition: from research to cognitive technology. Erlbaum, Mahwah, pp 285–315

Hegarty M, Keehner M, Khooshabeh P, Montello DR (2009) How spatial abilities enhance, and are enhanced by, dental education. Learn Individ Differ 19(1):61–70

Hillier B (1996) A configurational theory of architecture. Cambridge University Press, Cambridge

Hirtle SC (2011) Geographical design: spatial cognition and geographical information science (synthesis lectures on human-centered informatics). Morgan & Claypool, San Rafael

Hirtle SC, Richter K-F, Srinivas S, Firth R (2010) This is the tricky part: when directions become difficult. J Sp Inf Sci 1(1):53–73

Hirtle SC, Sorrows ME (1998) Designing a multi-modal tool for locating buildings on a college campus. J Environ Psychol 18(3):265–276

Hutchins J, Ihler A, Smyth P (2010) Probabilistic analysis of a large-scale urban traffic sensor data set. In: Gaber MM, Vatsavai RR, Omitaomu OA, Gama J, Chawla NV, Ganguly AR (eds) Knowledge discovery from sensor data: second international workshop, Sensor-KDD 2008, LNCS 5840. Springer, Berlin, pp 94

Ishikawa T, Fujiwara H, Imai O, Okabe A (2008) Wayfinding with a GPS-based mobile navigation system: a comparison with maps and direct experience. J Environ Psychol 28:74–82

Kaasinen E (2005) User acceptance of location-aware mobile guides based on seven field studies. Behav Inf Technol 24:37–49

Keehner M, Lowe R (2009) Seeing with the hands and with the eyes: the contributions of haptic cues to anatomical shape recognition in surgery. In: Bertel S, Barkowsky T, Hölscher C, Shipley TF (eds) Cognitive shape processing. AAAI Press, Menlo Park, pp 8–14

Kuhn W, Frank AU (1991) A formalization of metaphors and image-schemas in user interfaces. In: Mark D, Frank A (eds) Cognitive and linguistic aspects of geographic space. Kluwer, Dordrecht, pp 419–434

Kuipers B, Levitt T (1988) Navigation and mapping in large scale space. Ai Mag 9(2):25–43

Lane ND, Miluzzo E, Lu H, Peebles D, Choudhury T, Campbell AT (2010) A survey of mobile phone sensing. Commun Mag IEEE 48(9):140–150

Li C, Longley P (2006) A test environment for location-based services applications. Trans GIS 10(1):43–61

Maybury MT, Wahlster W (1998) Readings in intelligent user interfaces. Morgan Kaufmann, San Francisco

McNulty T (2009) iBurgh lets you complain to city by cell phone. Pittsburgh Post-Gazette, Pittsburgh 18 Aug 2009

Meilinger T, Knauff M, Bülthoff HH (2008) Working memory in wayfinding: a dual task experiment in a virtual city. Cogn Sci 32:755–770

Mohan P, Padmanabhan VN, Ramjee R (2008) Nericell: Rich monitoring of road and traffic conditions using mobile smartphones. In: SenSys '08. ACM, Raleigh, North Carolina, pp 323–336

Montello DR (1993) Scale and multiple psychologies of space. In: Frank AU, Campari I (eds) Spatial information theory: a theoretical basis for GIS. Springer, Berlin, pp 312–321

Munzer S, Zimmer HD, Schwalm M, Baus J, Aslan I (2006) Computer-assisted navigation and the acquisition of route and survey knowledge. J Environ Psychol 26(4):300–308

Nath S, Liu J, Zhao F (2007) Sensormap for wide-area sensor webs. Computer 40:90–93

Parush A, Ahuvia S, Erev I (2007) Degradation in spatial knowledge acquisition when using automatic navigation systems. In: Winter S, Duckham M, Kulik L, Kuipers B (eds) Spatial information theory (COSIT 2007) vol LNCS 4736. Springer, Heidelberg, pp 238–254

Peuquet DJ (2002) Representations of space and time. Guilford Press, New York

Priedhorsky R (2011) Wiki, absurd yet successful: a position paper for CHI 2011 workshop on crowdsourcing and human computation. Paper presented at the CHI 2011. Vancouver, BC, Canada, Vancouver, BC, 7–12 May 2011

Priedhorsky R, Jordan B, Terveen L (2007a) How a personalized geowiki can help bicyclists share information more effectively. In Proceedings of the 2007 international symposium on Wikis. ACM, Montreal, Quebec, Canada, pp 93–98)

Priedhorsky R, Jordan B, Terveen L (2007b) How a personalized geowiki can help bicyclists share information more effectively. In: WikiSym'07, Montreal, Quebec, 2007, pp 93–98

Raper J, Gartner G, Karimi H, Rizos C (2008) A critical evaluation of location based services and their potential. J Locat Based Serv 1:4–45

Raubal M (2011) Cogito ergo mobilis sum: the impact of location-based services on our mobile lives. In: Nyerges T, Couclelis H, McMaster R (eds) The SAGE handbook of GIS and society. Sage, Los Angeles, pp 159–173

Raubal M, Panov I (2009) A formal model for mobile map adaptation. In: Gartner G, Rehrl K (eds) Location based services and telecartography II, selected papers from the 5th international symposium on LBS & Telecartography 2008, Salzburg, Austria. Springer, Berlin, pp 11–34

Richter KF, Dara-Abrams D, Raubal M (2010) Navigating and learning with location based services: a user-centric design. In: Gartner G, Li Y (eds) 7th international symposium on LBS & teleCartography. Guangzhou, China, pp 261–276

Rohs M, Schöning J, Raubal M, Essl G, Krüger A (2007) Map navigation with mobile devices: virtual versus physical movement with and without visual context. In: Proceedings of the ninth international conference on multimodal interfaces (ICMI 2007). ACM Press, Nagoya, Japan, pp 146–153

Schlieder C, Matyas C (2009) Photographing a city: an analysis of place concepts based on spatial choices. Sp Cogn Comput 9:212–228

Schmidt A, Beigl M, Gellersen HW (1999) There is more to context than location. Comput Graph 23(6):893–901

Schöning J, Hecht B, Rohs M, Starosielski N (2007) WikEar–Automatically generated location-based audio stories between public city maps. In: Proceedings of Ubicomp'07, pp 128–131

Siegel AW, White SH (1975) The development of spatial representations of large-scale environments. In: Reese HW (ed) Advances in child development and behavior, vol 10. Academic Press, New York

Simon HA (1955) A behavioral model of rational choice. Q J Econ 69(1):99–118

Simonnet M, Vieilledent S, Jacobson D, Tisseau J (2010) The assessment of non visual maritime cognitive maps of a blind sailor: a case study. J Maps 2010:289–301

Sorrows ME, Hirtle SC (1999) The nature of landmarks for real and electronic spaces. In: Freksa C, Mark D (eds) Spatial information theory. Springer, Berlin, pp 37–50

Turner A (2009) The role of angularity in route choice. In: Hornsby K, Claramunt C, Denis M, Ligozat G (eds) Sp Inf Theory vol LNCS 5756. Springer, Berlin, pp 489–504

Zook M, Graham M, Shelton T, Gorman S (2012) Volunteered geographic information and crowdsourcing disaster relief: a case study of the Haitian earthquake. World Med Health Policy 2(2):7–33

Cognitive and Linguistic Ideas in Geographic Information Semantics

Werner Kuhn

Abstract This chapter reviews ideas, rooted mostly in cognitive science and linguistics, to deal with semantics of geographic information. It discusses the following notions, dating roughly from the time between the two Las Navas meetings of 1990 and 2010: experiential realism, geographic information atoms, semantic reference systems, semantic datum, similarity measurement, conceptual spaces, meaning as process, and constraining the process of meaning. It shows why and how these ideas have been productive for semantics research and what future research they suggest.

Keywords Semantics of geographic information · Cognitive semantics · Experiential realism · Semantic reference systems

1 Introduction

Between 1987 and 1990, many researchers working on communication problems of some sort had discovered the work of cognitive linguists Len Talmy, Ron Langacker, and George Lakoff. At Las Navas 1990, in the presence of Len Talmy and George Lakoff, participants discussed how this body of work influenced their research on cognitive and linguistic aspects of geographic space. I had been doing research on metaphors in human–computer interaction for 10 years before and

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found the radically new notion of metaphor proposed by George Lakoff and by philosopher Mark Johnson (Lakoff and Johnson 1980) to perfectly fit the needs of user interface design. Furthermore, image schemas like CONTAINER or SURFACE promised to capture invariants in the metaphorical mappings of user interfaces, suggesting a potential for a formalization of these mappings. Metaphorical mappings establish correspondences between source and target domains (for example, desktop and computer, for the desktop metaphor), which are subject to image schematic constraints (for example, preserving the surface and container structures of both). My chapter, with Andrew Frank, in (Mark and Frank 1991) described an early attempt at applying and formalizing these ideas (Kuhn and Frank 1991).

In retrospective, Las Navas 1990 was the beginning of a long and continuing fascination of many semantics researchers with the challenge of formalizing ideas from the cognitive sciences in order to apply them to geographic information systems and science. Along this voyage, around 1994, it became obvious to me that metaphors are just one form of *semantic mappings*. Besides their obvious application to interaction design, problems like schema mappings in data transfers (Kuhn 1997) started to look like nails for the same hammer.

Around the time of Las Navas 1990, artificial intelligence researchers had started to explore an engineering notion of *ontology*, applying it to semantic problems. None of the chapters in the first Las Navas book contains the term "ontology". Yet two weeks before the 1990 meeting started, on June 22, 1990, I had noted the following observation on the connection between the two threads in my research journal:

> "The metaphor choice by the designer establishes the ontology of the interface."

When I published this idea in 1993 (Kuhn 1993), the term "ontology" was just starting to be applied to concept descriptions in knowledge representation (Bateman 1993; Gruber 1993; Guarino 1992). Considering the publication lag, the time of Las Navas 1990 can thus be considered a turning point for information semantics, with the almost synchronous emergence of a better understanding of formalizing semantic mappings and conceptualizations.

From today's perspective, (Mark and Frank 1991) is the first edited book on the *ontology of geographic space*, broadly conceived, though without yet using the term. In fact, the book's opening chapter by Joan Nuñes (1991) remains one of the best treatments of this topic until now, and many other chapters deal with deep ontological issues. The key thread of qualitative spatial and temporal reasoning, throughout Las Navas 1990 and 2010, can itself be seen as an ontological undertaking: to formally define the meaning of qualitative terms in order to enable automated reasoning on them.

In this chapter, I highlight some key ideas and insights gained in the past two decades and speculate on where research on them might lead over the next years. Note that this is not intended as a broader history of ideas in semantics research, only as a personal view of the influence that cognitive and linguistic ideas exerted on the research of some of us.

2 The Problem of Semantics

Before lining up solution ideas, a problem definition is in order. What exactly is the semantics of geographic information and what does it take to model it? The computer science and geographic information science literature is full of untenable or outdated notions of semantics and unrealistic claims about solutions. Many researchers in semantics seem to believe—and often explicitly say so—that one can define meaning as an object ("the meaning of x") or as a relationship between a term and things in the real world (the meaning of "building", for example, would be all the buildings in the world that exist, existed, and will exist). Apart from the vast literature in cognitive science and linguistics of the past 30 years refuting these believes, the very fact that there are semantic problems is evidence that these views are mistaken.

If terms had fixed meanings, one could simply write these down and share them with all information users. Feature-attribute catalogues of mapping agencies were such an attempt in the 1980s and 1990s, until it became clear that many potential users of the data saw the world quite differently and did not share the officially documented "meaning". This has not invalidated the careful cataloguing of features and attributes, but clarified their role as ontologies, i.e., as necessarily incomplete specifications of how the agencies use their vocabularies. These specifications now need to be mapped to other vocabularies and other ways of using the same vocabulary.

A recent paper (Bizer 2009), co-authored by the Semantic Web's father Tim Berners-Lee, claims that

> "meaning is explicitly defined"

for linked data (the latest incarnation of the semantic web). Such exaggerated expectations not only purport the mistaken view that there is an object-like form of meaning, inherent in the data, but also that it can be fully captured by some technology. The latter idea has long been recognized by practicing ontologists to be inadequate. Some of the most useful and widely adopted definitions of ontologies see these instead as *systems of constraints*, defining admissible uses and interpretations of vocabularies.

The problem of semantics of geographic information is, thus, best described as *designing and testing constraints on the use and interpretation of (geographic) terms* (Kuhn 2009). Ontologies and folksonomies state conditions on the use of terms. For example, if a hydrology ontology states that a river is a water body that flows into another water body, this is not an "explicitly defined meaning", but a prescription of how to use and interpret the term "river" in the given context. Many aspects of what users in the same context mean when they use the term can (and always will) remain unspecified. For example, the role of rivers as transportation routes would only be implicit in this specification. Users outside the intended context may apply slightly or entirely different constraints. For example, the European Water Framework Directive, which is meant to cover all member states of the European Union and underlies the current INSPIRE specifications, defines rivers as

> "A body of inland water flowing for the most part on the surface of the land but which may flow underground for part of its course."[1]

This implies that many rivers of southern Europe are either outside the intended context or need to be described by another term (Duce and Janowicz 2010).

The following sections line up eight ideas that many researchers found (and still find) useful in their work on geographic information semantics. In roughly chronological order of their appearance, these ideas are: experiential realism, geographic information atoms, semantic reference systems, semantic datum, similarity measurement, conceptual spaces, meaning as process, and constraining the process. The broad scope and limited space of this chapter only allow for brief overviews of key aspects with some examples and pointers to the literature. Since some ideas are already better understood than others, their account is not only a story about research results, but also one of remaining and emerging research challenges.

3 Experiential Realism

One of the key insights of cognitive linguists and philosophers in the 1980s was that human cognition needs to be taken seriously as a source of meaning, avoiding both semantic realism and its opposite, the denial of physical reality. This view of how our thoughts, actions, and languages relate to the world became known as experiential realism (Lakoff 1987). Its basic claim is that we conceptualize reality based on how we experience it through our bodies, sensing and acting in physical environments and in cultures. As Lakoff, Johnson, and others have shown with substantial linguistic, behavioral, and neural evidence, our physical existence and environment fundamentally shape our thoughts and language. From the experience of our bodies as containers through our standing on surfaces and distinguishing up and down, to the role of connections like links and paths, we build up a repository of experiential patterns, which have become known as *image schemas* (Johnson 1987). They are so basic to our cognition that they appear not only in our concepts of space and time, but also in abstract concepts, grounding them in physical reality. Thus, we conceptualize buildings and cities as containers, but also societies and crises; lakes and walls as surfaces, but also education levels and election programs; the sun as rising, but also prices; and buildings as connected to the Internet, but also to organized crime.

For an experiential realist, meaning results primarily from these patterns. Twenty years ago, this was not much more than a hypothesis, at least for information science. Since then, applications of the idea to the design of

[1] Directive 2000/60/EC Art. 2(4), see http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32000L0060:EN:NOT.

meaningful user interfaces (Kuhn and Frank 1991) and to geographic processes like navigation (Raubal et al. 1997) and transportation (Kuhn 2007) have shown their power as well as their suitability for formalization (Kuhn 2002; Raubal and Worboys 1999). A broader image-schematic ontology of geographic concepts, as sketched in (Kuhn 2007), remains an unfulfilled promise, but looks more feasible than ever. In particular, it would provide specific cases of the participation relation for objects in processes, in the form of the well-defined thematic roles of objects in image schemas. For example, transportation is characterized by the thematic roles of the transported item, the vehicle, the path, the origin and the destination. Such a role-based modeling of processes and their participating objects would be a very powerful ontological tool.

Apart from offering a useful understanding of semantics in general, experiential realism appears most productive for two specific problems: mappings from one conceptualization to another, and grounding of symbols. To semantic mappings, whether they are metaphors or database schema mappings or others, experiential realism contributes the *Invariance Hypothesis* (Lakoff 1990). This hypothesis says that the structure remaining invariant in a semantic mapping is image-schematic. For example, the invariant in the metaphor LIFE IS A JOURNEY as well as in a schema mapping from roads and ferry lines to transportation links is the PATH schema. Understanding and formalizing such mapping invariants is obviously helpful for user interface design and essential for data integration across multiple database schemas.

To symbol grounding, experiential realism contributes its core idea that symbols only become meaningful through bodily experience. Contrary to criticisms that experiential realism forgets reality in favor of language, it is actually more explicitly grounded in physical reality than so-called realist semantics, which has to pre-suppose a mind-independent existence of objects and categories as referents of terms. The grounding approach suggested by experiential realism is, instead, to produce ontological axiomatizations based on experiential (embodied) primitives of perceived reality, with a high chance of being universal due to our bodily and environmental constitution. The most recent attempt to work out a grounded theory, in this case for plane geometry, is (Scheider and Kuhn 2011). A meta-theory of the approach is worked out in (Scheider 2011).

To attendees of Las Navas 1990 who remember the fierce debates between George Lakoff and Zenon Pylyshyn, the following quote from Pylyshyn shows how much inroads experiential realism has made since then, primarily through the grounding argument:

> "If it were not for the existence of such nonconceptual processes, our concepts would not be grounded in experience and thus would not have the meaning that they do (Pylyshyn 2007)."

Meanwhile, the roots of these ideas in earlier work on Gestalt theory and ecological psychology have been traced in more detail (Scheider et al. 2009). One insight from this work is that perceptual ideas like affordances and the meaningful environment can go a long way toward grounding information, before we even need to resort to more complex (and less accepted) cognitive ideas like image schemas, metaphorical mappings, or blendings (Fauconnier and Turner 2003).

4 Geographic Information Atoms

An idea that has no special cognitive origins, but was proposed around the same time (Goodchild 1992) is that of atoms of geographic information. It answers the question whether there is a canonical form of geographic information to which all other forms can be reduced. Its simplest form is a tuple of location and attribute values:

$$< x, z >$$

where x describes a position in space–time and z the corresponding value of an attribute. For example, temperature data are such pairs of positions (in some spatial reference system) and temperature values (on some measurement scale). One needs to specify to what spatial reference system X the position x refers and what attribute Z is represented by the value z.

Extensions and refinements of the geographic information atom have been proposed, but do not change the basic idea: geographic information essentially consists of spatio-temporally referenced attribute values. One can formulate the atom with one or both of the types X and Z explicitly included, or state it in vector form, but these are just syntactic variations. Also, one can introduce "dipoles" for cases like distance information (Goodchild et al. 2007), which require two locations, but these can also be captured by generalizing x to complex geometries such as line segments or polygons.

The atom is highly relevant to semantics, because it suggests not only a canonical form of geographic information, but also a symmetry between its location and attribute components. This symmetry is the root of the analogy between spatial and attribute reference systems (Chrisman 1997) and of its generalization to semantic reference systems discussed in the next section: since we have theories and tools to interpret coordinates (namely, coordinate reference systems) and temporal data (calendars), together covering the x part of the atom, we need theories for referencing attributes, the z part. If geographic information atoms are a useful canonical form, such reference systems will solve most semantic problems. Otherwise, we will at least understand what is missing.

The geographic information atom does not capture processes, neither in the world (for example, climate change), nor in information systems (for example, computations). One can argue that processes in the world manifest themselves in changed values of atoms, and that computations use atoms as input and produce atoms as output. For example, if an image analysis procedure produces a pixel classification, its inputs and outputs are atoms. Similarly, climate models may take in time series of atoms and produce, for example, predictions of mean sea level rise (z) over a certain region and time (x). Yet, the inputs and outputs are not the whole story of computations, and snap shots are not good enough as process models (Worboys 2005). The semantics of computational operations (Riedemann 2005) remains a thorny issue that the atom does not capture. For example, an interpolation algorithm applied to a digital terrain model affects the interpretation of elevation data, and this is a separate semantic problem from that of its inputs and outputs (Kuhn 2005). How to capture processes and events in geographic information with well-defined semantics is an important current research issue (Devaraju 2012).

5 Semantic Reference Systems

While describing ontologies to colleagues and students as "reference systems for data that are *not* coordinates", I started to suspect around 2002 that there is more to this idea than a loose analogy. Since coordinate reference systems define the semantics of coordinates, both at the type level X (for example, interpreting latitude and longitude) and value level x (for example, interpreting degrees), other components of geographic information (Z and z in the atom, but also operators) seemed to ask for the same kind of conceptual and computational support. There is no a priori reason why specifying interpretations in a thematic domain should be fundamentally harder than specifying location, as one can use infinitely many descriptions to locate something. As suggested in (Kuhn 2003), location must have seemed equally hard to specify formally before Descartes invented coordinate systems.

Information communities have found ways to communicate successfully by making the semantics of their terms explicit (for example, through coordinate systems, gazetteers, or biological taxonomies). Reference systems make these specifications formal and ground them physically, so that transformations between them can be computed. Thus, location referencing *must* be a special kind of semantic referencing. This insight led me to the general idea of semantic reference systems, covering all aspects of geographic information. When I explained it in (Kuhn 2003), I was unfortunately unaware that its main novelty, attribute reference systems, had already been suggested in (Chrisman 1997).

The idea of semantic reference systems has reached some maturity meanwhile, but is still far from ready-to-use computational implementations for any non-trivial attributes like land use categories, not to mention operators. The hardest part, just as it was for location, is specifying the semantic datum, which grounds attributes and operations in reproducible observations (see next section). However, once a measurement scale for an attribute is defined and the corresponding datum is fixed, all ingredients for referencing attribute data and translating them from one reference system to another are in place. The semantics of operators, in turn, is best specified by standard software engineering methods, such as model-based pre- and post-conditions or algebraic specifications. For example, the behavior of an interpolation operator for values on a surface can be specified by algebraic properties of the interpolated values.

Note that there is nothing inherently spatial or even geometric about reference systems. Location in space is obviously well served by geometric specifications, either of coordinate systems and their anchoring in physical space or of footprints of places, in turn described by coordinates. Yet, soil or vegetation classes, for example, can be specified in any convenient form, as long as the primitives of such specifications are reproducible. The special and particularly intriguing case of a geometric specification of semantic reference systems will be discussed below, in the section on conceptual spaces.

6 Semantic Datum

A *geodetic* datum grounds a spatial reference system in reproducible observations of the physical earth. It anchors the axes of a coordinate system (ellipsoidal or Cartesian) in observations, such as the directions of the earth's axis of rotation and of gravity, and in monuments on the earth's surface (observatories, for instance). Thereby, it grounds the abstract mathematical concepts and values of coordinates in reproducible processes.

A *semantic* datum achieves such grounding for any concept, not just for location. It *fixes free parameters of measurement scales in observables*. For example, a semantic datum for temperature fixes the zero and unit of an interval scale (e.g., Celsius or Fahrenheit) or the unit of the ratio scale (Kelvin) for temperature measurements. A semantic datum for ordinal or nominal values has to ground every single value, typically through interval or ratio measurements that are themselves grounded. In remote sensing, for example, pixel classifications are typically defined based on ranges of frequency measurements in spectral bands, which in turn get their own datum from optics. Ongoing work on affordances (Ortmann and Kuhn 2010) shows that processes can also be grounded in observable qualities. For example, the ratio of step height to the leg length of a person climbing steps (Warren 1984) defines the semantic datum for climbability.

The main reason to seek a semantic datum is to enable *transformations* between different reference systems. As with a geodetic datum (which is just a special case for location), a semantic datum anchoring a concept in observable qualities allows for mappings from one reference system to another. For example, knowing the chemical properties of the saltwater solution that Fahrenheit used and of human body temperatures allows for precise mappings between Celsius and Fahrenheit temperatures. These mappings can then be standardized and implemented, as they have been for temperatures and many other cases.

The question how the idea of a semantic datum connects to foundational ontologies remains largely unexplored. Both ideas attempt to anchor and connect ontological specifications through a choice of primitives and their relations.

Both play somewhat complementary roles in semantic translation. Anchoring terminologies in foundational ontologies achieves rigor and clarity, but risks getting lost in meaningless abstractions (such as "thing") or hard to understand distinctions (such as endurants and perdurants) or both. Supplying semantic datums[2] , on the other hand, achieves a grounding in qualities of the environment and in human actions, but risks becoming complex in practice, even for relatively simple concepts.

Just as for coordinates, semantic translations do not always need the full power of datum transformations. Preserving semantic similarity relations may be good enough for many cases in practice. Ongoing research determines how to define and compute useful similarity transformations for semantic reference systems.

7 Similarity Measurement

The notion of semantic similarity is cognitively so fundamental that it is amazing how much it was ignored in the early days of the semantic web (Gärdenfors 2004). Even today, a lot of semantic reasoning is taxonomic, seeking crisp logical implications rather than best matches. The success of search engines has shown, however, that fast approximate results from exploiting similarities are often more useful. For example, when looking for accommodation in some place, one is more interested to find something similar to a hotel than only places classified as hotels. Such approximate results can be reached with statistical models alone, but involving semantic similarity measures increases recall and precision significantly (Schwering and Kuhn 2009). The main problem with brute force statistical methods is that they assume a term is always used to refer to the same thing. Therefore, in today's practice, search engines make heavy use of similarity reasoning as well as ontologies.

To achieve the full power of semantic similarity reasoning, it is necessary to combine logic-based with numeric or geometric methods (Andrea Rodríguez and Egenhofer 2004). Since similarity measures can only report similarities of *representations*, not of their referents, measures and reasoning methods are limited by the expressiveness of representations. The trick of going from plain syntactic similarities (based on text strings only) to semantic measures is to explicitly include semantics in representations. Recent measures take into account a variety of aspects, going far beyond graph distances in semantic networks or hierarchy levels in taxonomies and increasingly resembling sophisticated analogy models (Schwering and Kuhn 2009). Janowicz has implemented a series of similarity reasoners based on various description logics and organized them in a conceptual framework for semantic similarity reasoning (Janowicz et al. 2011).

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[2] The plural form of this technical term is "datums", as it is for geodetic datums (see, for example, http://en.wikipedia.org/wiki/Datum_(geodesy)).

Similarity values by themselves are meaningless. For example, one cannot say that a bed and breakfast is 80 % similar to a hotel. But it is meaningful to say that it is more similar than a camping ground in the context of accommodation search. Thus, similarity reasoning needs to be based on similarity *rankings*, not values. Given the strong *context-dependence* and the incompleteness of representations, it is safe to assume that similarity differences and ratios are also meaningless and only rank orders are informative. Similarity rankings, furthermore, allow for assessing the actual impact of context on queries (Keßler 2011). By determining changes in rankings resulting from different contexts, one gets a data-driven idea on context effects and can decide whether and how to deal with them.

Cognitive semantics makes it clear that *all semantics is context-dependent* and can generally not be modeled objectively or even standardized. Also, many of the cognitive semantics ideas discussed in this chapter (for example, experiential realism and semantic reference systems) address core aspects of context. However, the pragmatic methods of identifying *information communities* and bridging their vocabularies through shared concepts remain the best approaches to control and explicitly deal with context. As the examples of feature-attribute catalogues and of river concepts mentioned in the introduction have shown, specifying contexts in the form of information communities and validating concept definitions within them is essential, but often neglected.

8 Conceptual Spaces

If one takes the analogy between attribute and spatial reference systems literally, one is naturally led to conceptual spaces, and vice versa (Gärdenfors 2000). Conceptual spaces are spanned by axes representing simpler concepts and represent their target concept as convex regions in them. For example, color spaces (whether based on primary colors or on hue, saturation, and brightness) consist of three dimensions (some of them radial) and represent colors as regions in these three-dimensional spaces.

The main motivation to exploit conceptual spaces is that they support similarity reasoning elegantly through distance measures. Two concepts that are closer in a conceptual space are more similar than two that are further apart. Thus, even if Gärdenfors' theory about the cognitive reality of geometric concept representations in our minds does not hold, the representational mechanism of concepts in multi-dimensional quality spaces is extremely useful for similarity reasoning. It relates to the much older idea of multi-dimensional scaling in statistics, with the crucial difference that its axes are meaningful.

Florian Probst contributed the key insight that the dimensions of conceptual spaces can be separated from the symbols used to represent them. For example, a temperature dimension in a space for weather concepts expresses the conceptualization of temperature and its role in describing the weather, independently of whether temperature is measured in Celsius or Fahrenheit. Consequently, Probst proposed to partition the symbol-free conceptual spaces (also known as quality spaces) through symbol spaces, which he called reference spaces (Probst 2008).

The conceptual clarity and computational power of conceptual spaces raises an important methodological question for semantic problems: when should we solve a problem logically (through subsumption reasoning) and when geometrically (through spatial reasoning)? The field of qualitative spatial reasoning provides us with calculi to solve spatial problems through logic (Cohn and Hazarika 2001). Conceptual spaces provide us with structures to solve conceptual problems through geometry. We know very little, so far, about how to choose between the two options, much less how to combine them adequately, and there appears to be a trend to burden logic with tasks that geometry is better at.

9 Meaning as Process

As the saying *words don't mean, people do* expresses, it is people who mean something when they use a word, rather than the words having a meaning on their own. The consequence of this is that meaning needs to be understood as a process rather than as an object. This idea can be captured in the good old semiotic triangle (Ogden and Richards 1923), with the crucial addition of edges defined as human cognitive processes. Rather than linking three corners with edges that are undefined (or even undirected), human actions then connect the corners. One way of doing this (Fig. 1), is to say that people *conceptualize* reality to form ideas (thoughts) about it, which they *express* through words (symbols, terms, expressions) and use these to *refer* back to reality. For example, when seeing a shining light in the night sky, people conceptualize it as a celestial body and English speakers may refer to it with the word "star".

The so-called *conduit metaphor*, which has us believe that meaning gets packed into words by speakers and unpacked by listeners, has long been refuted (Reddy

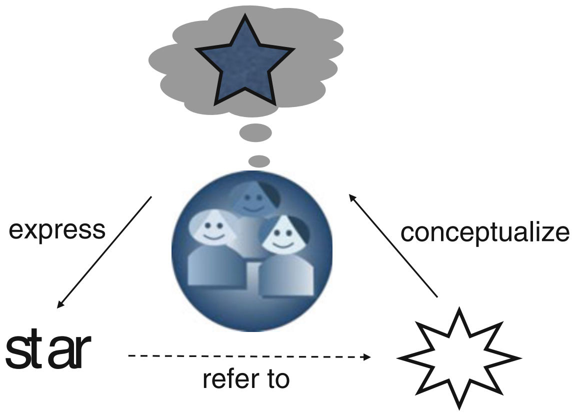

Fig. 1 The classical semiotic triangle, extended by human actions at its edges: people *conceptualize* reality and *express* the result through words, with which they *refer* to reality

1979). Yet, many information technologists seem to hold on to it, at least in practice, possibly because it may seem to simplify the task of semantic modeling, by positing well-defined meanings that can be defined and shared. In practice, it actually makes the task harder, as clashes between the supposed "well-defined" meaning of a term and its actual interpretation are the rule rather than the exception (remember the river example, again). Also, the idea of semantic content of words does not naturally accommodate vagueness and uncertainty in meaning. A process view of meaning dismisses such object-like contents. It suggests a view of ontologies (and other semantic techniques) as constraints on meaning and interpretation processes.

10 Constraining the Process

Once meaning is understood as a process, all semantic technologies and models become tools for constraining it. For example, *ontologies* constrain people in choosing a term to express an idea as well as in interpreting a term to find out what it refers to. Shared vocabularies (which can be seen as the simplest form of ontologies) also constrain the use and interpretation of terms, by their use in data. Vocabularies anchored in an axiomatization are more useful for interoperability and integration, because they support mappings. This is so because one can then define bridging axioms, which help compute translations from one vocabulary to another. This beneficial effect of ontological foundations is comparable to that of theory for other engineering tasks, like car design, where design constraints are not free floating, but anchored in mechanical, aerodynamic, and other theories. Another example is the traditional anchoring of local geodetic networks in national grids, to allow for a broader use and more rigorous testing of the resulting coordinates.

Complementing ontologies at various levels of sophistication (from vocabularies to full-fledged axiomatic specifications), *folksonomies* are another form of constraints that is becoming more and more useful. The tag clouds for information resources on the web show how people actually refer to something. Thereby, they observably constrain meaning, because the referent of a tag is explicit (in the form of the resource). They also demonstrate clearly that reference is not an authoritative process, but a pragmatic one. Of course, it is often ambiguous to what aspect of a resource a tag was meant to refer: does a picture tagged "Eiffel Tower" show the tower or a view from it? Like in any other constraint-based system, uncertainty and vagueness is therefore omnipresent (rather than an inconvenient topic for future work) in all semantic reasoning.

Folksonomies suggest a *data-driven approach* to semantics, which has been pushed to new levels through the social web and, in particular, through Volunteered Geographic Information (VGI, (Goodchild 2007)). Yet, bottom-up approaches can also be productive with traditional authoritative geographic data as well as for ontological (rather than semantic) questions, where classification rather than labeling is the goal. For example, (Scheider and Kuhn 2010) has shown how road intersections can be classified automatically, based on the geometry of incoming and outgoing links.

11 Conclusions

A key question in 1990, hotly debated in the long nights at Las Navas, was whether cognitive approaches to semantics admit formalization at all or whether "formal cognitive semantics" is an oxymoron. Twenty years later, one can confidently assert that formalization is not only possible, but useful and productive. Whether through logical, geometric or combined formalizations, cognitive theories have enabled reasoning that was simply not possible before. For example, semantic similarity measures have repeatedly been shown to be more adequate for information retrieval and other tasks (Schwering and Kuhn 2009).

Yet, while semantics research can use a growing stack of cognitive and linguistic ideas, these still form a patchwork and lack integration. As mentioned, we do not know how to distribute reasoning across logical and geometric models. At the level of languages and tools, we are stuck with set-based model-theoretic semantics and lack modeling environments with the expressiveness required for cognitively more adequate models (Kuhn 2010). From the practical perspective of solving semantic problems, we lack ontologies with strong enough foundations to enable their use in non-trivial semantic reasoning. For example, reasoning about changes in the environment (such as land use or climate change) requires a breadth of domains and depth of models (including processes and actors) that is not yet available and requires substantial efforts of ontology engineering.

Nevertheless, the many threads of cognitively oriented semantics research, of which I have only discussed a sample here, have become much stronger over the past two decades and are likely to grow further. While statistical methods still prevail in areas like vocabulary translation across natural languages, the satisfaction coming from building models that actually explain something (rather than just computing it) supports continued research on cognitive semantics (Sloman 2008). System building for the real world, of course, will always need clever combinations of multiple approaches.

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References

Bateman JA (1993) Ontology construction and natural language. In: Poli R (ed) International workshop on formal ontology. LABSEB-CNR, Padova (Italy), pp 83–93

Bizer C (2009) Linked data—the story so far. Int J Semant Web Inf Syst 5(3):1–22

Chrisman NR (1997) Exploring GIS, 1st edn. John Wiley College Division

Cohn AG, Hazarika SM (2001) Qualitative spatial representation and reasoning: an overview. Fundamenta Informaticae 46(1–2):1–29

Devaraju A (2012) Representing and reasoning about geographic occurrences in the sensor web. Dissertations in Geographic Information Science (GISDISS), vol 7. AKA, Verlag. ISBN:978-3-89838-673-9

Duce S, Janowicz K (2010) Microtheories for spatial data infrastructures-accounting for diversity of local conceptualizations at a global level. Geographic information science. Lecture notes in computer science, vol 6292. Springer, Berlin, pp 27–41

Fauconnier G, Turner M (2003) The way we think: conceptual blending and the mind's hidden complexities. Basic Books, New York

Gärdenfors P (2000) Conceptual spaces—the geometry of thought. Bradford Books, MIT Press, Cambridge

Gärdenfors P (2004) How to make the semantic web more semantic. In: Varzi A, Lieu L (eds) Formal ontology in information systems. IOS Press, Amsterdam, pp 17–34

Goodchild MF (1992) Geographic data modeling. Comput Geosci 18(4):401–408

Goodchild MF (2007) Editorial: citizens as voluntary sensors: spatial data infrastructure in the world of web 2.0. Int J Spatial Data Infrastruct Res 2:24–32

Goodchild MF, Yuan M, Cova T (2007) Towards a general theory of geographic representation in GIS. Int J Geogr Inf Sci 21(3):239–260

Gruber TR (1993) A translation approach to portable ontology specifications. Knowl Acquis 5(2):199–220

Guarino N (1992) Concepts, attributes and arbitrary relations: some linguistic and ontological criteria for structuring knowledge bases. Data Knowl Eng 8(3):249–261

Janowicz K, Raubal M, Kuhn W (2011) The semantics of similarity in geographic information retrieval. J Spatial Inf Sci 2:29–57

Johnson M (1987) The body in the mind: the bodily basis of meaning, imagination, and reason. The University of Chicago Press, Chicago

Keßler C (2011) What is the difference? A cognitive dissimilarity measure for information retrieval result sets. Knowl Inf Syst 30(2):319–340

Kuhn W (1993) Metaphors create theories for users. In: Frank AU, Campari I (eds) Spatial information theory a theoretical basis for GIS. Lecture notes in computer science, vol 716. Springer, Berlin, pp 366–376

Kuhn W (1997) Approaching the issue of information loss in geographic data transfers.Geogr Syst 4(3):261–276

Kuhn W (2002) Modeling the semantics of geographic categories through blendings. In: Lund SN, Turner M (eds) The way we think—research symposium on conceptual integration. University of Southern Denmark, Odense (Denmark)

Kuhn W (2003) Semantic reference systems (guest editorial). Int J Geogr Inf Sci 17(5):405–409

Kuhn W (2005) Geospatial semantics: why, of what, and how? J Data Semant (Special issue on semantic-based geographical information systems, Spring 2005) Lecture notes in computer science, vol 3534. Springer, Berlin, pp 1–24

Kuhn W (2007) An image-schematic account of spatial categories. In: Winter S, Duckham M, Kulik L, Kuipers B (eds) 8th international conference on spatial information theory (COSIT). Lecture notes in computer science, vol 4736. Springer, Melbourne, pp 152–168

Kuhn W (2009) Semantic engineering. Research trends in geographic information science. Lecture notes in geoinformation and cartography. Springer, Berlin, pp 63–76

Kuhn W (2010) Modeling vs encoding. Semant Web Interoperability Usability Appl 1(1):11–15

Kuhn W, Frank AU (1991) A formalization of metaphors and image-schemas in user interfaces. In: Mark DM, Frank AU (eds) Cognitive and linguistic aspects of geographic space (NATO ASI Series D, vol 63) Kluwer Academic Publishers, The Netherlands, pp 419–434

Lakoff GP (1987) Women, fire, and dangerous things. what categories reveal about the mind. University of Chicago Press, Chicago

Lakoff GP (1990) The invariance hypothesis: is abstract reason based on image-schemas? Cogn Linguist 1(1):39–74

Lakoff GP, Johnson M (1980) Metaphors we live by. The University of ChicagoPress, Chicago

Mark DM, Frank AU (1991) Cognitive and linguistic aspects of geographic space. NATO ASI Series D, vol 63 (519 pp) Kluwer Academic Publishers, The Netherlands

Nuñes J (1991) Geographic space as a set of concrete geographical entities. In: Mark DM, Frank AU (eds) Cognitive and linguistic aspects of geographic space (NATO ASI Series D, vol 63) Kluwer Academic Publishers, The Netherlands, pp 9–34

Ogden CK, Richards IA (1923) The meaning of meaning. Harcourt Brace Jovanovich, New York

Ortmann J, Kuhn W (2010) Affordances as Qualities. In: Galton A, Mizoguchi R (eds) 6th international conference on formal ontology in information systems (FOIS). IOS Press, Toronto (Canada), pp 117–130

Probst F (2008) Observations, measurements and semantic reference spaces. Appl Ontol 3(1):63–89

Pylyshyn ZW (2007) Things and places. How the mind connects with the world. The MIT Press, Cambridge

Raubal M, Worboys MF (1999) A formal model of the process of wayfinding in built environments. In: Freksa C, Mark DM (ed) Spatial information theory—cognitive and computational foundations of geographic information science (COSIT). Lecture notes in computer science, vol 1661. Springer, Berlin, pp 381–399

Raubal M, Egenhofer MJ, Pfoser D, Tryfona N (1997) Structuring space with image schemata: wayfinding in airports as a case study. In: Hirtle S, Frank A (eds) Spatial information theory—a theoretical basis for GIS, international conference (COSIT). Lecture notes in computer science, vol 1329. Springer, Berlin, pp 85–102

Reddy MJ (1979) The conduit metaphor: a case of frame conflict in our language about language. In: Ortony A (ed) Metaphor and thought. Cambridge University Press, Cambridge, pp 284–310

Riedemann C (2005) Matching names and definitions of topological operators. In: Cohn AG, Mark DM (eds) Spatial information theory: cognitive and computational foundations (COSIT). Lecture notes in computer science, vol 3693. Springer, Berlin, pp 165–181

Rodríguez AM, Egenhofer MJ (2004) Comparing geospatial entity classes: an asymmetric and context-dependent similarity measure. Int J Geogr Inf Sci 18(3):229–256

Scheider S (2011) Grounding geographic information in perceptual operations. PhD thesis, University of Münster. http://www.geographicknowledge.de/pdf/MyThesis.pdf

Scheider S, Kuhn W (2010) Affordance-based categorization of road network data using a grounded theory of channel networks. Int J Geogr Inf Sci 24(8):1249–1267

Scheider S, Kuhn W (2011) Finite relativist geometry grounded in perceptual operations. In: Egenhofer MJ, Giudice N, Moratz R, Worboys MF (eds) 10th conference on spatial information theory (COSIT). Lecture notes in computer science, vol 6899. Springer, Berlin, pp 304–327

Scheider S, Janowicz K, Kuhn W (2009) Grounding geographic categories in the meaningful environment. In: Hornsby KS, Claramunt C, Ligozat G (eds) 9th International Conference on Spatial Information Theory (COSIT). Lecture notes in computer science, vol 5756. Springer, Berlin, pp 69–87

Schwering A, Kuhn W (2009) A hybrid similarity measure for spatial information retrieval. J Spatial Cogn Comput 9(1):30–63

Sloman A (2008) architectural and representational requirements for seeing processes and affordances. In: Computational modelling workshop, closing the gap between neurophysiology and behaviour: a computational modelling approach. http://www.cs.bham.ac.uk/research/projects/cosy/papers/sloman-newmod.pdf

Warren WH (1984) Perceiving affordances: visual guidance of stair climbing. J Exp Psychol Hum Percept Perform 10(5):683–703

Worboys MF (2005) Event-oriented approaches to geographic phenomena. Int J Geogr Inf Sci 19(1):1–28

Spatial Relation Predicates in Topographic Feature Semantics

Dalia E. Varanka and Holly K. Caro

Abstract Topographic data are designed and widely used for base maps of diverse applications, yet the power of these information sources largely relies on the interpretive skills of map readers and relational database expert users once the data are in map or geographic information system (GIS) form. Advances in geospatial semantic technology offer data model alternatives for explicating concepts and articulating complex data queries and statements. To understand and enrich the vocabulary of topographic feature properties for semantic technology, English language spatial relation predicates were analyzed in three standard topographic feature glossaries. The analytical approach drew from disciplinary concepts in geography, linguistics, and information science. Five major classes of spatial relation predicates were identified from the analysis; representations for most of these are not widely available. The classes are: part-whole (which are commonly modeled throughout semantic and linked-data networks), geometric, processes, human intention, and spatial prepositions. These are commonly found in the 'real world' and support the environmental science basis for digital topographical mapping. The spatial relation concepts are based on sets of relation terms presented in this chapter, though these lists are not prescriptive or exhaustive. The results of this study make explicit the concepts forming a broad set of spatial relation expressions, which in turn form the basis for expanding the range of possible queries for topographical data analysis and mapping.

Keywords Semantic technology · Topographic data · Predicates

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1 Introduction

Geographical analysis is the key objective for methods of geographic information representation, extraction, modeling, and visualization. Spatial relations are a key component of geographical analysis (Foote and Huebner 1996). Many of these relations are difficult to graphically or quantitatively formalize and remain only cognitively or linguistically represented. In most cases, the wider range of spatial relations, beyond those of location, metric distances, and cardinal direction, are cognitively conceptualized by the map or geographic information systems (GIS) user (Clarke 2001; Theobald 2001). Semantics allows data analysts and users to disambiguate and articulate environmental knowledge in specific detail that is otherwise limited in large part within the scope of the cognitive knowledge of the person. Concepts of ontology engineering depict the implementation of users' cognitive environmental models integrated with logical representations of data designs and semantic (Fonseca et al. 2002). Within the scope of such models and in normal geographic information retrieval, vocabulary plays a critical role in the design and use of ontology-driven systems.

The geospatial semantic web allows users to specify and program spatial relations as predicates or properties of semantic web triples, a standard semantic web data model, to be captured and articulated in databases, interfaces, and visualization (Egenhofer 2002; W3C 2010a). Most available spatial relation terms describe taxonomic, topologic, or partonomic relations, but a range of other relations, such as those of processes, scale, or events, may be required for data applications and environmental modeling, but may not be clearly specified for a broad base of system users (Kuhn 2001). By programming these relations, and minimizing the need for manual intervention, the data analysis functions intended for database designs and applied in data queries would be easier to use. One way disambiguation and semantic detail are achieved is by expanding the range of spatial relations to enhance data applications.

Feature type vocabularies, including Wordnet (Princeton University 2010) and Alexandria Digital Library (ADL) Feature Type Thesaurus, based on the National Geospatial Intelligence Agency (NGA) GeoNet and Geographic Names Information System, are easily available (ADL 2002; NGA 2009; U.S. Board on Geographic Names). But these feature term vocabularies, with words such as beach, lagoon, or geyser, do not include the representation of spatial relations that are essential to their meaning, such as, the shore along the water (beach), water between the reef and shore (lagoon), or water ejected with force (geyser). A major source of relations is articulated in natural language statements of geospatial data users, as in spoken words, written text, metadata specifications, or glossaries. This study examines the predicates articulated in topographic knowledge statements to identify semantics of topographic spatial relations. The identification of spatial predicate concepts helps build foundations for their representation as the relation resource of semantic web triples. Because a list of predicates cannot be prescriptive, a set of specific terms is not a practical solution; the list could be incomplete or change over time. Relation types form general classes that can be used as a foundation for predicate identification, analysis, and functioning in further studies. Subsets of terms of these classes are already represented as mereologic and topologic relations, but relations such as force dynamics, for example the control of an object's movement when it is 'in' something, remain a challenge to model.

The objective of this research is to advance a framework of natural language spatial relations terms for topographic data and information retrieval. The motivation for these formalizations is to serve the future development of reasoning algorithms to enhance functions for *The National Map* of the U.S. Geological Survey, but the study was designed for results applicable to any topographical map (National Research Council 2007). The application of natural language labels to specify spatial relations, if effectively chosen and executed, will facilitate communication with broadly diverse users.

The sections of the chapter discuss background concepts of topography, spatial prepositions, and topological relation in GIS; these form a foundation for the spatial relation classes resulting from the analysis. Key terms were extracted definition predicates and categorized on the basis of word types, such as the verb/preposition pair "flowing towards;" a number of prepositions are related to operations in GIS. Each class is presented in the sections that follow and summarized in the conclusions.

2 Background

The analysis of spatial predicates depends on a range of research crossing geographic, linguistic, and geographic information science (GISc). This section focuses on topography, spatial language, and spatial relation formalizations in GISc, and the Semantic Web to support the approach that was implemented in this study to advance new controlled vocabulary development.

2.1 Topography

The topography of a landscape refers to the physical surface and features of an area or local region, limited to a more immediate scale of experience than general geography. A common meaning of the term 'topography' focuses mainly on landform features, but historical and contemporary uses of the term include human experiences and descriptions of places, including local history and biography (Harvey 1980). Topographical experience is the perception and learning of selected features of the environment and their interaction, however the environment may be defined in a cultural context (Curry 2002). Writers often place these concepts of topography in the context of "reading the landscape" (Watts 1975). The elements of landscape and natural history are studied as dialogue, akin to telling a story or narrative.

The communication of topographic knowledge can be called a type of narrative that arises from the environmental bases of experiences and context, and appears in literary sources, way-finding, and other forms of geographical description (Pearce 2008). Spatial language attempts to relate the world as it exists with human perceptions of the world, subject to variations of environmental interaction, the appearance and configurations of an object, and concerns and purposes of a speaker. Topographic narrative draws on the articulation of features and the relations among them expressed primarily through language, but also other forms, such as mapping, tabular data, first-order logic, or as an algorithm. These feature and relation structures result from basic semantic sign selection and the composition of the selections with other basic representational units (Jakobson and Halle 1971). For queries addressing the topographic data to be effective, narratives must be in relative agreement with cognitive experiential thought that map users generate about the topographic landscape.

The relations among feature structures and landscape are essential to the morphology of topography (Leatherbarrow 2004, p. 11). Complex relationships exist in many ways, such as between a feature to its location, a feature to the resource systems supporting it, or relations among elements within the topographic feature itself. The analysis of these relations considers topography to be normally governed by physical laws, such as gravity or changes due to temperature and moisture. Functions of these features are perceived by people based on their knowledge of these physical forces and can be expressed through science and engineering principles, as well as by relatively simple human actions (Buryk 2006). However, many complex topographic relations are formed and governed by social or scientific objectives, such as the component parts of a college campus dedicated to education, or a mine site for mineral extraction.

2.2 Spatial Prepositions

In their most simple and intuitive form, spatial prepositions imply a relation between two entities in space in which the located object is the subject of the sentence and the reference object is the receiver of the action in the predicates. Studies of spatial language in linguistics indicate, through the analysis of pragmatic language and the role of embodied experiences and physical force dynamics in language, that spatial prepositions are closely related to topographic experiences.

Herskovits (1986) designed a framework to relate verb/preposition pairs to spatial concepts. The first part of the three-part framework of semantic analysis consists of the ideal meaning of a term as a geometrical ideal, based on the concept of discrete objects in space. Ideal meanings are inferred from real examples of normal use and can be formalized with such systems as first-order logic or cognitive spatial frameworks, such as an imagined geometry of points, lines, or areas. Deviances from these ideals occur when they fail to explain some uses, such as when reference must be made to the cognitively-viewed description of some aspect of the object, not the object itself. These deviances lead to the second and third parts of the framework; sense shifts, a conceptually close relation to the ideal meaning based on the speakers' pragmatic intentions and context, and tolerance shifts, a gradual range in deviations from ideal meanings. For example, the preposition 'in' means the containment of something within something else, whether it is enclosed by an object, or is part of the structure or composition of an object. But 'in' is also used based on a geometric imagination or projection, such as "the bird in the tree" (sense shift), or within the proximity of an object, as in "the chair in the corner" (tolerance shift) (Herskovits 1986, p. 43). Tolerance limits of deviations are pragmatic principles that prevent the acceptance of variable forms that are obviously untrue or are unacceptable use forms. The discussion of pragmatics was an acknowledgment that the use of spatial prepositions strays beyond the logical limits of perceptions and descriptions of objects in space and often refers to the functions of objects and intention of users. Concepts of idealization and intention are bountiful in topography, as are fuzzy boundary concepts indicating tolerances.

Lakoff's concept of human embodiment in spatial relations explores the key roles that perception, body movement, and experience play (Lakoff 1987). Embodiment is the humanly-centered solution to grounding symbols, such as language, data, or graphics, in reality (the 'real' world). In embodiment, actions in the world have meaning, and symbols emerge from the perception, thought, and concepts based on that meaning. This important concept correlates closely with the traditional meaning of topography based on the experience of the world.

Coventry and Garrod (2004) advanced a concept called the Functional Geometric Framework, in which they argue that geometric spatial relations alone, such as those based on the cognitively-projected visual geometry of Herskovits, have limited influence on prepositional use. Research on force dynamics in language show that physical laws such as gravity are predominant for understanding the meaning of terms such as 'on' (Talmy 1988). The geometric relation of objects located relative to each other varies with different uses of 'on' in language, such as the 'house on the street,' the 'nose on your face,' or the 'box on the floor.' In most cases, the function of objects, afforded by the physical forces involved, predominate as the basis for the selection and use of a spatial preposition. As a result, force dynamics are semantically less ambiguous than geometric spatial relations.

Geometric imagination, pragmatic functions, human embodiment, and force dynamics are important to the analysis of spatial prepositions in topographic data. Defining the subject of topographic data as based on environmental experience and knowledge, feature definitions, and consequently their semantic specifications, reflect a vocabulary based on physical forces on the landscape and human leveraging of those forces. Topographic objects have functions that can be observed by anyone present in the proximity of a place on the land that the topographic data represent. The expression of this shared experience on the landscape through topographic mapping may help to build a common semantic framework for the public, despite the cultural and perceptual differences of a diverse society.

2.3 Mereotopological Relations

Mereotopological relations, representing whether entities are connected as parts of each other or as relations between them, form the basis for many topographical and prepositional spatial relations. These models are important to the deductive reasoning of applied ontologies, but are not widely available (Casati and Varzi 1999). Mereotopologic models could be used for topographic data for features such as engineered systems, in which the parts are critical to the function of the whole, but have topologic relations in the system assembly. Some commonly used models support the representation of topological or mereological relations separately (Rector and Welty 2005).

Mereological relations are part-whole relations that commonly involve physical contact between objects or their integrated processes involving physical matter, but motivated by a unifying function. Part relations are semantically similar to set theory, which is based on aggregation of members of an abstract class that share an identity or activity. For example, settlements may be defined by the presence of a large number of houses. Together, the houses are members of an abstract category called settlement. Topological relations represent properties of objects that do not change with modifications in form.

In GIS, topological spatial relations between objects were formally developed around the 9-intersection model (Egenhofer and Herring 1991). The classification mechanism for the intersection of the interiors, boundaries, and exteriors of two geometric shapes served implementations for operations that support Boolean relations. The concepts were incorporated into standards of the Open Geospatial Consortium (OGC) and International Organization for Standardization (ISO). Specific OGC topological relation (operator) standards are also accepted as ISO 19125—Simple Features Access (ISO 2004). This work adopted eight terms based on the 9-Intersection method using point-set topology. A "Relate" operator returns "true" if the interior, boundary, or exterior of two objects intersect (ISO 2001a, p. 129). The operations that can be implemented are Equals, Disjoint, Intersects, Touches, Crosses, Within, Contains, and Overlaps. The language terms assigned to these relations were selections from sets of synonyms. Relations terms were proposed to be coded as bitmaps, 3×3 matrices, for these relations to lend themselves toward a culturally-neutral notation in a world of linguistic diversity (Mark et al. 1995, p. 691). Other topological relations defined in geographic information science are available, though not as data standards.

Though GIS models topological relations well, mereology is particularly challenging to represent in GIS if different geometries are involved in the complex feature components. Examples of standards for spatial representation, however, reflect many partonymic qualities. Spatial properties of the ISO General Feature Model (ISO 2001b; OGC 2010) include terms that accommodate a range of spatial properties, including location, usually as coordinates; geometric elements such as "surface"; partonomic feature types, such as "memberOf"; and some that could potentially be used to represent geosemantics of scale relations, such as "aggregationType" or "Complex." These relation types capture a diverse range of user experience representations for topographic data.

2.4 Geospatial Semantic Web

The geospatial semantic web refers to conceptual and applied developments that aim to link geospatial data in a manner similar to the Semantic Web (Berners-Lee et al. 2001). Linkages are supported by triples, which refers in computational systems to a type of data representation structured by two nodes related by an edge. The relation is sometimes called a predicate, linking the subject and object; together these resemble simplified linguistic statements. These parts of the triples, or triple resources, indicate the specific meaning of features and properties, such as their spatial relations, feature identities, or object attributes with a universal resource identifier (URI). By linking data by their URI in Resource Description Framework (RDF) and other data formats, predicates support the logical and automated reasoning governing feature type connections and information inference (W3C 2010b). Logical axioms specified in reasoning software form the rules, or the ontology, that controls the automatic extraction of information that was previously unknown. Triples and their inferences can disambiguate the representation of landscape feature contexts by shifting feature semantics between descriptive topographic object labels and complex models. A complex range of feature relations support dynamic topographical processes models reflecting processes on the landscape.

Some spatial relations and their representation as triple resources have been developed for the geospatial semantic web. A number of software packages offer eight spatial relation predicate terms formalized for data reasoning called Geo-SPARQL (Stocker and Sirin 2009; Battle and Kolas 2011; Murray 2011). Parts are represented in semantic technology as, for example, federated graph subclasses or the triple property for part in the W3C standard.. The Ordnance Survey of Great Britain developed 'Rabbit' as a complement to Web Ontology Language (OWL) for spatial reasoning for national topographic modeling (Hart et al. 2007). In addition to spatial relation terms, Rabbit reasons using these prepositions: by, from, for, and of (Dolbear et al. 2007). Seven geospatial relations are available through GeoNames (2010). Of these, most are location-based; for example, ontology:inCountry, ontology:locatedIn, or approximate adjacency, such as, ontology:nearby or ontology:neighbour. Additional spatial relation predicates, found in CYC (OpenCyc 2010) include prepositions, dimension, locality, and other qualities. Most of these relations stress topological or patronymic terms omitting process terms commonly needed in topographic modeling (Brodaric 2008). Options for building those terms include customizing RDF, OWL, and SPARQL with custom or commercial ontology design software (W3C 2010c).

3 Glossary Analysis

An initial list of topographic feature type predicates intended for ontology development were derived by manually analyzing glossaries of topographical terms and relations (Varanka and Mattli 2011; Varanka et al. 2011). A similar manual method was used by others and implemented for this study (Mizen et al. 2005). Fewer constraints and checking steps were involved in the manual analysis compared to similar automated approaches (Navigli and Velardi 2008). Three primary feature type standards were developed based on USGS topographical mapping, beginning with field surveys and later adapted for digital databases. These are the Digital Line Graph (DLG), the Geographical Names Information Systems (GNIS) of the U.S. Board on Geographic Names (USBGN), and the Spatial Data Transfer Standard (SDTS) (USGS 2010; USBGN 2010). These standards or their variations have been previously studied for spatial relation development (Guptill et al. 1990; Mark et al. 1995; USGS 2009). The feature type standards included models for representing feature attributes and their appropriate values.

The definitions were formatted into three main parts to roughly approximate the structure of triples (Table 1) (Caro and Varanka 2011). The analysis was based on approximately 660 predicate phrases of glossary definitions; the variability of number is explained later in this chapter. Some terms appeared in more than one standard with different definitions. Some definitions had no predicates and consisted of a simple phrase. Some consisted of simple sentences, and some were complex sentences involving multiple predicates.

The topographic feature lists were analyzed in tandem with a concordance and spreadsheet. A concordance program lists each word in a text alphabetically along with its frequency of occurrence and a few lines of its immediate placement in the body of a work. The ability of concordance programs to provide a few lines of context clarified meanings of terms as well as the frequency of their usage. For each instance of a verb/preposition pair or other spatial relation term, the

Table 1 Sample glossary data formatted for predicate analysis (USBGN 2010). Verb/preposition pair predicates appear as lower/upper case letters in the central column

Beach: The sloping shore along a body of water that is washed by waves or tides	coveredBY	sand or gravel (coast, shore, strand)
Swamp: Poorly drained wetland, fresh or saltwater, wooded or grassy	coveredWITH	open water (bog, cienega, marais, marsh, pocosin)
Bend: A	curveIN	a linear body of water (bottom, loop, meander)
Gut: Relatively small coastal waterway	connecting	larger bodies of water or other waterways (creek, inlet, slough)
Bay: Indentation of a coastline or shoreline enclosing a part of a body of water; a body of water partly	surroundedBY	land (arm, bight, cove, estuary, gulf, inlet, sound)

concordance was sorted to find all other morphologic forms of the words so they are grouped correctly in the representative analysis. The manual approach was needed because the verbiage throughout the text is inconsistent. Checks for verb/relation consistency in meaning and use were required.

The frequency of occurrence was tabulated to identify the most commonly used terms or type of terms, but most of the desired search terms occur only once, making identification of 'top' terms more complicated. In the three texts that were reviewed for analysis, 75 % or more of specific word instances, called tokens, indicating or inferring a spatial relation occur only once. Combined with the problem of identifying and grouping different forms of the same word, the low number of repeated uses of a word created a challenge in identifying the most frequent spatial relation word occurrences. The verbs or relations and their tokenized forms that occurred more than once in texts were 175 from a total of 641 words. For this reason, the analysis is mainly qualitative and draws trends from repeated instances of similar examples, taking the form of lists of terms in a table. The list of spatial relation verbs that were found may be incomplete and other occurrences of the verb/relation terms may have passed unnoticed because of the omission of verbs in some definitions and morphologic changes of the verbs/relations in the text.

Some definitions were not composed as complete grammatical sentences, and the brevity of feature descriptions often omitted verbs. Where this kind of omission occurred, a verb or preposition or a spatial term other than verbs alone was inferred for inclusion in the data analysis for the purpose of adhering to grammatical predicate rules. An effort was made to keep inferred verbs simple and unassuming in nature while still filling the function of the verb. For example, the verb 'to go' implies a movement from one point to another without adding any other assumptions, such as speed or directionality. This property can be seen in the SDTS definition for "Route": A designated path [to go] *through* a road network. Other common verbs used in these instances include "to be" and "to use".

Definitions used in this study were sometimes composed as a long sentence, but conveyed a relatively simple meaning for its predicate. In such cases, the analysts of this research sometimes chose to focus on the salient part of the phrase. In many cases, the topographical meaning of a term was identified and chosen from among several alternative meanings; for example, some involving the use of cognitive or temporal spatial imagery. For instance, the definition for Overfalls is "Short breaking waves *occurring when* a current passes over a shoal or other submarine obstruction or meets a contrary current or wind" (SDTS). "Caused by" was replaced for "occurring when" to capture the topographic principle of process, rather than time. Risks of modifying the original semantics through generalization are involved in this approach, but the use of this semantic function narrows the potential variability of statements written by multiple authors. Time, or any other principle outside the scope of this study, is equally valid in topographic science, but parameters were set to constrain the criteria of analysis.

The definitions of topographic features often refer to partonomic relations within complex features and systems as well as relations between discrete objects.

The inclusion or exclusion of part relations in topographical feature representation are a function of scale and support feature generalization and multiple representation (Mustière, and van Smaalen 2007). Although many features are differentiated from others on the basis of size, for example a spring from a seep, generalization for many features is a function of the number of parts of the complex that are included in its representation. The geographic scale of feature classes and relations of this study are comparable to the 1:24,000 inch scale of the twentieth-century USGS topographic maps. Other quantitative metrics, such as a minimum representational unit or resolution, were not defined for the analysis.

Temporal shifts were not considered in this study, although time is a factor affecting spatial relation descriptions. For example, the use of the term ‘near’ may indicate that an object of reference may have shifted over time from a place where the subject and object would have been ‘on’ one another, such as the shift of a boundary from an old boundary marker.

4 Topographical Spatial Relation Terms

The glossary entries varied in complexity and content, including modifiers, events, objects, and material composition. Words take various grammatical forms, such as tenses or participles. Many are not defined by spatial relationships, but rather by material composition, intended purpose, or qualitative constraints. Most of the spatial relation terms extracted from the standards were verb/preposition pairs, but are context dependent and are nuanced in meaning within the syntax and semantics of sentences. For these reasons, the following sets of terms form a preliminary list that is expected to be refined after future iterative application and study.

The most frequent prepositions when summed without a paired verb were the topological relations “in” (19 times) and “on” (11 times), and the geometrical relation “between” (9 times). The basic verbs “to be” and “to have,” and simple verbs of space, such as “located,” and time, such as “occurred,” and their synonyms, were frequently assumed or implied in the specialized categories described as follows. Locative terms imply location, such as “located,” “positioned,” or “place” and demand reference objects, as “underground.” The locative term “where” was used 28 times as a conjunction. Many terms have inverse relations. Verbs sometimes appeared in pairs, such as “…disappears underground at…and… reappears at the surface at…” A feature can be assigned a relation to represent the things it generates and an inverse relation representing the forces to which it is subject.

Despite linguistic challenges, terms were categorized into types of roles to help organize their analysis. Active verbs consisting of process terms were most numerous, then descriptive geometric terms. Partonomic and verbs of human intention, such as “designed for,” were fewest, though terms can overlap categories. For example, “roof” is a part, but implies a geometric description (situated on the “top”), a force dynamic (held by gravity), and a function (to shelter).

Examples of triple predicates for modeling topographic data triples for each of the class types appear at the end of the sections. The examples are not in complete RDF format; they pair prepositions together with verbs to illustrate the triple predicate concept.

4.1 Partonomy Terms

Spatial relations were found to closely resemble the logical prime definitions of topographic features themselves. The types of relations between objects often depend on the identity, origins, or meaning of the features themselves. The necessary and sufficient conditions of the feature definition indicate that spatial relations are part of the feature identity (Wierzbicka 1996). Relations are often part of systems that support their formation and existence, and that relate the feature to the surrounding landscape. For example, a “mine” is an excavation of the earth for extracting minerals. Potential predicates that would be logical selections for triple predicates between parts of the mine could include that infrastructure ‘is powered by’ to reflect the definition predicate “excavation” and conveyor belts ‘carry,’ for example, for the “extraction” predicate.

The basic relation “part of” was used only 6 times. Other terms that are classified as “part” relations could include independent features of complexes that imply a part relation, for example a summit is an individual feature although it may be part of a mountain range, or are indicated by terms from a frame of reference, such as “bottom.” Subject phrases can imply part relations, such as “group of islands.” Part relations such as “composed of” (13 times) or “consisting of” (7 times) were considered to be more closely aligned with generative topographic processes that act on feature morphology. Taxomony was used for part relations; for example, the definition for “area” is “any one of several areally extensive natural features not included in other categories.” Anything can be made a part with the use of certain topological prepositions (e.g. within) such as Grave—a place within a cemetery where…

Terms implying part relations appear in Table 2.Examples of the use of such terms include: Island Cluster—A group of islands; Cul-de-sac—The round or circular section of the end of a dead-end street; and Fishladder—A facility consisting of a series of small pools.

The type of “part” terms used most often refer to the material substance of features; these terms are “compose” and “consist,” and “made of, ” a synonym used only once. Groups of things sharing a common concept included “collection,”

Table 2 Part relation terms for topographic data predicates

Collection	Equipped	Made of	Series
Compose	Fitted	Portion	Set
Consist	Group	Section	Subdivide

"group," "set," and "series," the last term slightly more semantically specific than the first three. "Portion," "section," and "subdivide" imply that the entire feature would be significantly altered by additions or removals, unlike sets of object. A more specialized use of "part" relations is indicated by "equipped" and "fitted," referring to parts that are involved in functions. Triple examples are: Water—portionOf—EarthSurface, or Cul-de-sac—section of—Street.

4.2 *Descriptive/Geometric Terms*

The group of active verbs used as predicates in the definitions was organized as two classes of terms, depending on whether they function as descriptors or form cognitive geometric visualizations of forms, to be called here descriptive/geometric terms, or terms referring to a generative process or functional role driven by physical forces, called process/function terms in this study. These are not strictly different categories, but are loose generalizations depending on whether the definition refers to primarily one or the other. Several terms fall in both categories. The action may be expressed in the active or the passive voice relative to the subject. For example, the subject can "bury" something or be "buried." Verbs are listed in the tables as infinitives, except the passive voice is used when the active voice is inappropriate, for example, as where a place is "charted," but does not "chart."

Description/geometry terms use spatial relations to develop an image or appearance, such as "flanked by." Terms are often geometric, including "curve," "depression," "slopes," and "steep," and can be topological, such as "contact," "cross," or "fits." Not all terms are verbs; adjectives, such as "nearly," "characterized by," or "vertical" were included in the list, as the meaning of the word is relative to a reference framework, description, or geometry (Table 3).

Table 3 Descriptive/geometric terms for predicates

Align	Cover	End	Low-point	Roof
Along	Cross	Erect	Lower	Rotate
Angle	Curve	Exit	Measured	Slope
Approach	Descend	Extend	Narrowing	Steep
Attach	Deformation	Fill	Nearly	Strung
Border	Delineated	Flank	Network	Submerge
Broken	Depart	Forming	Open	Surface
Characterized	Depression	Fronted	Overhanging	Surrounds
Confluent	Depth	High, higher	Parallel	Trends
Connect	Devoid	Hold	Pass	Upright
Contain	Distinct	Level	Project	Vertical
Contact	Enclose	Lie	Rise	Visible

The types of terms found in the Descriptors category include closely related concepts in geometry and topology, and relative spatial frames of references. Geometric terms referred to specific shapes involving curves and angles, and terms inferring continuity, such as "confluent" or "strung" indicate topological relationships. In several of the definitions, the descriptive term served visualization. A "crossing" (a feature) serves the role of "forming" an intersection. Two terms, "characterized" and "visible," refer to visualization rather than description itself.

Difference between the description and process/force dynamics may be time. For example, a "descending" slope is descriptive if it is static, but a "waterfall" descends if the process is happening with time. Another example is "divide."

Examples of triples are Lake—contains—Water or Levee—structures—Channel.

4.3 Force Dynamics/Process Terms

Process/function terms of feature generation include active verbs representing causes or processes that directly relate to the formation of the feature or an influence upon the feature. For example, "built," "caused," "constructed," or "formed" all indicate topographical processes of feature formation. Terms caused by gravity, such as "falls" appear in this category. This set of terms applies to a wide range of human activities on the landscape, such as "cultivated" or "developed." Other terms are more general, such as "adapted," "maintained," or "created." Triple examples are quicksand, sand—mixedWith—water, and dunes, sand—blownBy— wind (Table 4).

Table 4 Force dynamics/process terms

Adapted	Convert	Dwell	Generate	Pile	Result
Advance	Course	Eject	Go	Plant	Run
Affected	Descend	Emit	Interrupt	Position	Rush
Block	Deposit	Enter	Inundate	Project	Saturate
Bore	Direct	Exit	Issue	Pump	Send
Break	Disappear	Erode	Join	Purify	Subject
Built	Discharge	Extract	Launch	Raise	Support
Bury	Divide	Fall	Load	Receive	Suspend
Carry	Drain	Float	Made	Remove	Swing
Cause	Draw	Flow	Mix	Render	Transport
Change	Due	Force	Move	Resist	Wash
Control	Dug	Form	Obstruct	Restrict	

4.4 Human Intention Terms

Attributes, such as "known," had a strong relation to human intentionality, meaning the purpose, activity, or the feature importance (Couclelis 2010; Câmara et al. 2000). For example, an airport is "…maintained for the use of aircraft." A list of these verbs appears in Table 5. The verb "used," together with a preposition, such as "used for," occurs with high frequency when inferred (21 times), but only once with the four prepositions as, by, for, and to. Also referring to function are the verb/preposition pairs "functioning as" (5 times) and "set aside for" (8 times). Terms of affordances, such as "affords" or "capable of", relate features to a key concept of topography as experience, events, or action on the landscape (Gibson 1977; Sen 2008). Relations and attributes can combine to form simultaneous complex properties. For example, an area designated for a purpose can have signs explaining that designation. Verb/preposition pairs that indicate purpose, such as "intended for" or "intended to be," indicate the motivation for applied physical forces, true also for power relations, such as ownership, administration, or control. Several verbs are events involving features that are not considered to be topographical, such as "ship." In this example, verbs such as "anchored," "berthed," and "moored" were categorized as events relating to the topographical feature "port," as affordances and not predicates or spatial relations.

Predicates indicating human intentions and their subsequent impact on the landscape are often indicated by the preposition "for." These processes and their impacts are intentional for a purpose and include specific affordances and events (load ships) as well as general, complex purposes (administer park). Human-driven processes, however, may have unintended consequences, and because the study aims to focus on physical reality for semantic disambiguation, terms with a purpose, like "built," would be categorized as a process, unless solely the intention is expressed (managed), or used with non-topographical objects (ships).

Triple examples include BuildingComplex—functionsAs—MilitaryBase and PrincipleMeridian—followsAlong—TrueMeridian.

Table 5 Spatial relation verbs of human intention from feature type definitions

Able	Create	Entry	Intended	Passage	Serve
Access	Cultivate	Established	Kept	Place	Set aside
Administrative	Danger	Form	Known	Prescribe	Store
Afford	Defined	Fortify	Limit	Provide	Subject
Application	Designated	Function	Load	Pump	Submerge
Capable	Designed	Hold	Maintain	Reference	Test
Carry out	Determined	Identified	Obstruct	Require	Jurisdiction
Charted	Develop	Incorporated	Operate	Restrict	Use
Construct	Divide	Indicating	Own	Secure	

4.5 Prepositions

Prepositions take many forms, but prepositions that serve spatial uses are a form of spatial relations. Transitive prepositions are 'pre-positioned' before the complement (or the object) of the spatial relation, but intransitive prepositions do not require a complement. Transitivity of prepositions has implications for their modeling as triples.

Projective prepositions refer to frames of reference where the intrinsic point of observation based on objects, as in the phrase "a series of connected mountain ridges" (they would appear connected regardless of where a viewer would be) or an absolute reference point, referring to a environmental orientation, such as "west of here" (Levinson 2003). Topographic semantics are written as though humanly relative spatial frames of reference, reference systems where a speaker is the reference point, for example, when someone says to the left or to the right of an object, rarely exist, perhaps because they imply a role for the observer as a part of the observation, which reveals the observation subjectivity. Relative frames of reference are used in distinguishing one object (feature) from a context, for example, a salient landmark that seems to stand out. It is expected that few relative frames of reference for spatial prepositions are used in topographical feature class definitions, though perhaps more so in user interfaces (Table 6).

Despite that the meaning of a preposition seems ambiguous when considered a verb or other word of relation or attribute, the meaning of the predicate can vary considerably with the selection of the preposition to use with a term. For example, the term "carry" can work as a force dynamic when used along, as in a bridge "carries" traffic, but "carry out" assumes an entirely different meaning, the execution of work, with the preposition "out."

Table 6 Prepositions (Coventry and Garrod 2004)

Spatial preposition		Intransitive prepositions	
Above	By	Through	Away
Across	Down	To	Back
Along	For	Toward	East
Alongside	From	Under	Landward
Around	In	Up	North
As	Into	Upon	South
At	Near	Where	There
Below	On	With	Together
Between	Out	Within	West
Beyond	Over	Without	

5 Spatial Relation Predicates

The spatial relation terms in the previous tables function in complexes, alone or in phrases, with other nouns, verbs, prepositions, and modifiers. The manual analysis of this study allowed for subtle distinctions of spatial relation semantics that were reflected in the complex assemblages of natural language statements. For example, in all cases in GNIS and SDTS, the use of "surrounded by" is always in reference to land surrounded by water; however, the use of "surrounding" is always in reference to a prominent land feature rising from an area of land. The use of "enclose[d] [by]" usually is reserved for the reverse situation—land situated around water in some way, for example, a bay. Interestingly, the use of "enclose[d]" also extends to the ice around a polyna and the land around a basin; in SDTS, "enclose" also is used for walls. This would imply that there is some semblance of a common semantics that "surround" usually means that the item of prominence occurs in an otherwise level or watery scape, whereas "enclose" usually means the solidity or rigidity of the boundary marker. (i.e., even though it makes sense colloquially, there would never be an instance of "Lake: A body of water surrounded by land" or "Island: An area of land enclosed by water.")

As spatial relation verb/preposition pairs follow semantic patterns, triple predicates require the identification of term usage rules. The Merriam-Webster's Dictionary definitions for "surround" and "enclose", have no connotations in applying to solidity, level, land, or water, yet RDF enables such models (Merriam-Webster 2010). Though W3C standard logical axiom properties are intended to model deductive reasoning about observable spatial patterns, such as the transitive property to organize political boundaries, rules control the linguistic semantics of spatial relations as well. Spatial topographic language patterns, such as the "enclose" and "surround" example, are largely regarded as language rule memorization by natural language speakers, though further study may reveal less ambiguous semantics of their use.

6 Conclusion

Although topological relations are well-recognized in GIS, relations represented by linked-data graphs provide increased clarification of topographic features semantics. Topographic feature vocabularies are readily available, but vocabularies for spatial relations characteristics of topographic features are limited and incomplete. The spatial aspects of topographic feature definitions were analyzed to understand relation concepts for developing a vocabulary for semantic web triples. The semantics of spatial predicates agree with major concepts of environmental experience, language pragmatics, cognitive imagination, embodiment, and force dynamics found in studies of topography, linguistics, and geographic information science. The analysis of predicates found in topographic feature definitions identified spatial relation terms that indicate five major types of natural language spatial relation semantics, including (1) part relations within complex features, (2) active verbs providing descriptive relations, (3) active verbs providing process relations, (4) verbs of human intention, and (5) spatial prepositions for forming verb/preposition pairs. These categories create a framework for building vocabularies for characterizing and organizing topographic relations and for guiding further development and refinement of potential applied solutions to the conversion of natural language spatial relations to predicate operations in RDF triple data.

References

Alexandria Digital Library Project (ADL) (2002) Alexandria digital library feature type Thesaurus. University of California, Santa Barbara. Santa Barbara, CA. http://www.alexandria.ucsb.edu/gazetteer/FeatureTypes/ver070302/index.htm. Accessed 22 Nov 2011

Battle R, Kolas D (2011) Linking geospatial data with GeoSPARQL. Semant Web J Interoperability, Usability, Appl. http://www.semantic-web-journal.net/sites/default/files/swj176_0.pdf. Accessed 24 Oct 2011

Berners-Lee J, Hendler J, Lassila O (2001) The semantic web. Sci Am 184(5):34–43

Brodaric B (2008) A foundational framework for structuring geographical categories. First international workshop on informational semantics and its implications for geographical analysis, geoscience 2008. http://cogsci.uni-osnabrueck.de/~isga08/Brodaric.pdf. Accessed 22 Nov 2010

Burek P (2006) Ontology of functions: a domain-independent framework for modeling functions. PhD dissertation, University of Leipzig. http://www.onto-med.de/publications/2007/burek-p-2007-a.pdf

Câmara G, Vieira-Monteiro AM, Paiva J, deSouza RCM (2000) Action-driven ontologies of the geographical space. In: Egenhofer MJ, Mark DM (eds) GIScience 2000. Association of American Geographers, Savannah

Caro H, Varanka D (2011) Analysis of spatial relation predicates in U.S. Geological Survey feature definitions. U.S. geological survey open-file report 2011-1235. http://pubs.usgs.gov/of/2011/1235/. Accessed 22 Nov 2011

Casati R, Varzi A (1999) Parts and places: the structures of spatial representation. The MIT Press, Cambridge

Clarke KC (2001) Getting started with geographic information systems, 3rd edn. Prentice Hall, Upper Saddle River

Couclelis H (2010) Ontologies of geographic information. Int J Geogr Inf Sci 24:1785–1809

Coventry KR, Garrod SC (2004) Saying, seeing, and acting: the psychological semantics of spatial prepositions. Psychology Press, Hove

Curry MR (2002) Discursive displacement and the seminal ambiguity of space and place. In: Lievrouw L, Livingstone S (eds) The handbook of new media: social shaping and consequences of ICTs. Sage Publications, London

Dolbear C, Hart G, Kovacs K, Goodwin J, Zhou S (2007) The rabbit language: description, syntax and conversion to OWL: ordnance survey research. http://www.ordnancesurvey.co.uk/oswebsite/partnerships/research/publications/docs/2007/Rabbit_Language_v1.pdf. Accessed 19 Mar 2010

Egenhofer MJ (2002) Toward the semantic geospatial web. In: GIS'02: Proceedings of the 10th ACM international symposium on advances in geographic information systems. ACM, New York

Egenhofer MJ, Herring JR (1991) Categorizing binary topological relations between regions, lines, and points in geographic databases. University of Maine. http://www.spatial.maine.edu/~max/9intReport.pdf. Accessed 22 November 2011

Fonseca F, Egenhofer M, Davis C, Câmara G (2002) Semantic granularity in ontology-driven geographic information systems. Ann Math Artif Intell 36(1–2):121–151

Foote K, Huebner D (1996) Representing relationships: the geographer's craft project. University of Texas at Austin. http://www.colorado.edu/geography/gcraft/notes/datacon/datacon_f.html. Accessed 23 Nov 2011

GeoNames (2010) GeoNames. http://www.geonames.org/. Accessed 3 Feb 2010

Gibson JJ (1977) The theory of affordances. In: Shaw R, Bansford J (eds) Perceiving, acting, and knowing. Lawrence Erlbaum, Hillsdale

Guptill SC, Boyko KJ, Domaratz MA, Fegeas RG, Rossmeissl HJ, Usery EL (1990) An enhanced digital line graph design. U.S. geological survey circular 1048. Reston, Virginia

Hart G, Johnson M, Dolbear C (2007) Rabbit: Developing a control natural language for authoring ontologies. Ordnance survey. http://www.ordnancesurvey.co.uk/oswebsite/partnerships/research/publications/docs/2008/5_Rabbit_sem.pdf. Accessed 3 Feb 2010

Harvey PDA (1980) The history of topographical maps: symbols, pictures, and surveys. Thames and Hudson, London

Herskovits A (1986) Language and spatial cognition. University Press, Cambridge

ISO (2001a) ISO/TC 211 Geographic information/geomatics, final text of CD19109, geographic information—rules for application schema. Norwegian Technology Centre, Oslo

ISO (2001b) ISO/TC 211 geographic information/geomatics, final text of CD19107, geographic information—spatial schema. Norwegian Technology Centre, Oslo

ISO (2004) ISO/TC 211 Geographic information/geomatics, Text for IS 19125–1 geographic information—simple feature access—Part1. Norwegian Technology Centre, Oslo

Jakobson R, Halle M (1971) Fundamentals of language. Mouton Publishers, The Hague

Kuhn W (2001) Ontologies in support of activities in geographical space. Int J Geogr Inf Sci 15(7):613–631

Lakoff G (1987) Women, fire, and dangerous things: what categories reveal about the mind. Chicago University Press, Chicago

Leatherbarrow D (2004) Topographical stories: studies in landscape and architecture. University of Pennsylania Press, Philadelphia

Levinson SC (2003) Space in language and cognition: explorations in cognitive diversity. University Press, Cambridge

Mark DM, Egenhofer MJ, Sharif AR (1995) Toward a standard for spatial relations in SDTS and geographic information systems. In: Proceedings, GIS/LIS'95. ACSM/ASPRS, Washington DC

Merriam-Webster (2010) Merriam-Webster online. http://www.merriam-webster.com/dictionary/enclose. Accessed 24 Mar 2010

Mizen H, Dolbear C, Hart G (2005) Ontology ontogeny: understanding how an ontology is created and developed. In: Rodriguez MA, Cruz IF, Egenhofer MJ, Levashkin S (eds) First international conference on GeoSpatial semantics GeoS 2005. Lecture notes in computer science, vol 3799. Springer, Berlin

Murray C (2011) Oracle Database semantic technologies developer's guide, 11 *g* release 2 (11.2). Oracle. http://download.oracle.com/docs/cd/E11882_01/appdev.112/e25609/sdo_rdf_concepts.htm#CIHHAEIH. Accessed 25 Oct 2011

Mustière S, van Smaalen J (2007) Database requirements for generalisation and multiple representations. In: Mackaness WA, Ruas A, Sarjakoski LT (eds) Generalisation of geographic information: cartographic modelling and applications. Elsevier Ltd, Amsterdam

National Geospatial-Intelligence Agency (NGA) (2009) National system for geospatial-intelligence (NSG) Feature data dictionary (NFDD), Version 2.0. http://www.gwg.nga.mil/documents/asfe/NFDD_v2.0.pdf. Accessed 23 Nov 2011

National Research Council (2007) A research agenda for geographic information science at the United States Geological Survey. The National Academies Press, Washington DC

Navigli R, Velardi P (2008) From glossaries to ontologies: extracting semantic structure from textual definitions. In: Buitelaar P, Cimiano P (eds) Ontology learning and population: bridging the gap between text and knowledge. IOS Press, Amsterdam
OGC (2010) Open geospatial consortium, Inc. http://www.opengeospatial.org/. Accessed Mar 25 2010
OpenCyc (2010) OpenCyc.org. http://sw.opencyc.org. Accessed 8 Feb 2010
Pearce MW (2008) Framing the days: place and narrative in cartography. Cartogr Geogr Inf Sci 35:17–32
Princeton University (2010) About WordNet. WordNet. Princeton University. http://wordnet.princeton.edu. Accessed 22 Nov 2011
Rector A, Welty C (2005) Simple part-whole relations in OWL ontologies. W3C editor's draft 24 Mar 2005. W3C. http://www.w3.org/2001/sw/BestPractices/OEP/SimplePartWhole/simple-part-whole-relations-v1.3.html. Accessed 22 Nov 2011
Sen S (2008) Use of affordances in geospatial ontologies. Towards affordance-based robot control. Lecture notes in computer science, vol 4760. Springer, Berlin
Stocker M, Sirin E (2009) PelletSpatial: A hybrid RCC-8 and RDF/OWL reasoning and query engine. The OWL: experiences and direction (OWLED) sixth international workshop. http://ceur-ws.org/Vol-529/owled2009_submission_20.pdf. Accessed 24 Oct 2011
US Geological Survey (2009) National hydrography dataset feature catalog. http://nhd.usgs.gov/NHDFeatureCatalog.pdf. Accessed 27 Oct 2011
US Geological Survey (2010) National geospatial program standards. http://nationalmap.gov/gio/standards/. Accessed 23 Mar 2010
Talmy L (1988) Force dynamics in language and cognition. Cogn Sci 12:49–100
Theobald DM (2001) Topology revisited: representing spatial relations. Int J Geogr Inf Sci 15(8):689–705
US Board on Geographic Names (USBGN) (2010) Geographic names information system. http://geonames.usgs.gov/domestic/index.html. Accessed 25 Mar 2010
Varanka DE, Mattli D (2011) Feature type vocabulary for the national map ontology. http://cegis.usgs.gov/ontology.html. Accessed 25 Nov 2011
Varanka DE, Carter JJ, Usery EL, Shoberg T (2011) Topographic mapping data semantics through data conversion and enhancement. In: Sheth A, Ashish N (eds) Geospatial semantics and the semantic web: foundations, algorithms, and applications. Springer, Berlin
W3C (2010a) Semantic web. World wide web consortium. http://www.w3.org/standards/semanticweb/. Accessed 22 Nov 2011
W3C (2010b) Resource description framework (RDF). http://www.w3.org/RDF/. Accessed 23 Mar 2010
W3C (2010c) SPARQL query language for RDF. http://www.w3.org/2001/sw/wiki/SPARQL. Accessed 23 Mar 2010
Watts MT (1975) Reading the landscape of America. Macmillan, New York
Wierzbicka A (1996) Semantics: primes and universals. Oxford University Press, Oxford

The Egenhofer–Cohn Hypothesis or, Topological Relativity?

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Abstract In this chapter, we provide an overview of research on cognitively validating qualitative calculi, focusing on the region connection calculus (RCC) and Egenhofer's intersection models (IM). These topological theories are often claimed to be foundational to spatial cognition, a concept we term the *Egenhofer–Cohn Hypothesis*. (The authors are aware of the limitations of the chosen title/term. Neither Egenhofer nor Cohn necessarily support this claim in a strong form but they kindly agreed to have their names used here. Additionally, there are other approaches to topology, Cohn is the third author on the classic RCC paper, and Egenhofer published his work with co-authors. However, we feel that these two names best summarize the two most prominent topological theories in the spatial sciences.) We have been particularly interested in extending existing approaches into the realm of spatio-temporal representation and reasoning. We provide an overview on a series of experiments that we conducted to shed light on geographic event conceptualization and topology's role in modeling and explaining cognitive

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behavior. Our framework also incorporates approaches to visually analyze cognitive behavior, allowing for interactive and in-depth analyses of cognitive conceptualizations. We present tangible results that can be distilled from generalizing from several experiments. These results show that the strong version of the Egenhofer–Cohn Hypothesis is not supported by all results; we suggest amendments to topological relationship specifications that are needed to serve as a sufficient basis for bridging formal and observed human spatial cognitive processes. We term this approach *topological relativity*.

Keywords Topology · Spatial knowledge · Qualitative spatial reasoning

1 Introduction

Knowledge, including spatial knowledge, can only be created through abstraction. The myriad individual pieces of information that a cognizing agent, whether artificial or natural, has to process in every second of its interaction with the outside world—be it physical or social—can only be sensibly comprehended on an abstract level: "If every object and event in the world were taken as distinct and unique a thing in itself unrelated to anything else—our perception of the world would disintegrate into complete meaninglessness" (Abler et al. 1971, p. 149). The abstraction mechanisms used by natural cognitive agents are manifold and so are the mechanisms and algorithms implemented for artificial agents: Filtering, aggregation, aspectualization, simplification, and generalization, to name just a few.

Natural cognitive agents (NCAs) have been, for a long time, the inspiration for creating artificial agents.[1] Mimicking natural cognitive agents has provided valuable insights for the design, for example, of robots. Understanding natural cognitive agents on a level of detail where their perceptual, thought, and reasoning processes can be captured formally is also essential for the design of any kind of interface between natural and artificial systems (human—machine or human—computer interaction).

From the perspective of spatial information and knowledge, qualitative spatial reasoning (QSR) has provided many tools for capturing potentially essential information (Cohn and Renz 2008; Freksa 1991). Within QSR, topology and topological calculi are likely the single most often referenced theoretical construct used to provide a more abstract representation of spatial information—often with the goal to be cognitively meaningful. The reason for the prominence of topology is that it allows for abstracting spatial information by specifying classes of equivalence.

[1] For an example how artificial agents provide insights into cognitive agents see, for example, Braitenberg (1984) and the growing body of literature on agent based modeling.

Equivalence classes create categories (or concepts) of spatial information that make its members indistinguishable and that allow all members to be assigned characteristics that are relevant for spatial inferences. By knowing which equivalence class a spatial relation belongs to, we have found a way to powerfully utilize one of the most important cognitive abilities humans possess: categorization and conceptualization.

But how do topology and topological equivalence actually work? From a cognitive perspective, topology is connected to an important theoretical construct, namely that of an *invariant* (see Klein 1872 for one of the first formal treatments). Invariants constitute something similar to equivalence classes by acknowledging that the world that NCAs live in is dynamic and that making sense of this dynamic world requires treating objects and relations between objects as invariant. In other words, NCAs abstract from changes introduced, for example, by changing perspectives, to achieve a consistent representation of their spatial environments. Interestingly, invariants have been approached both from researchers focusing on perception as well as researchers focusing on high-level cognition.

Klix (1971) focused on invariants as a means by which the human mind identifies characteristics in its spatial environment that allow the mind to build a basis for information processing. He explicitly referred to topology as an approach for identifying those invariants. With a particular focus on dynamic characteristics, the construct of invariants has been instrumentally integrated into the work of Shaw and collaborators (1974) and famously Gibson's theory of perception (1979). Shaw is referring to properties of objects and events that do not change, from a group (set) theoretic perceptive, as *transformational invariants*. Gibson, in his seminal publications, calls temporarily constant characteristics of environments *structural invariants*.

Additionally, topology is not only seen as a construct that satisfies the requirements of theories identifying important low-level perceptual characteristics but also the invariants of high-level cognitive processes (Lakoff 1990). Most prominently, topology is featured in the most abstract theories of cognitive information processing such as the work on image schemata (Johnson 1987; Kuhn 2007; Lakoff 1987; Mandler 1992). The most commonly found definition of image schemata is that they are recurring patterns that manifest in our sensory experience. To this end, they are able to bridge very concrete perceptual images on the one hand and abstract propositional structures on the other. As Kuhn points out "Image schemas are often spatial, typically topological […]" (Kuhn 2007, p. 155).

To summarize, spatial knowledge construction depends on abstraction. Qualitative spatial reasoning provides a powerful abstraction mechanism. Prominent QSR theories (e.g., topology) are intimately linked to cognitive theories, for example, through the concept of invariants, which are relevant for both low-level perceptual and high-level conceptual information processing. This, in a nutshell, lays out the foundation for the Egenhofer–Cohn Hypothesis, that is, that topology is foundational to cognitive (spatial) information processing (compare one of the mantras of na geography: topology matters and metric refines—Egenhofer and Mark 1995b).

The remainder of this chapter is structured as follows: We continue reviewing relevant literature from different perspectives. We first briefly introduce the most prominent topological calculi in spatial information science, the region-connection calculus and Egenhofer's intersection models, and we discuss a selection of approaches that have addressed the cognitive adequacy of these calculi. As most of these approaches have targeted static spatial relations, we discuss in more depth our own research that adds several aspects to the body of literature on cognitive adequacy of topological calculi such as dynamics and domain-specificity.

2 Background

2.1 Topological Calculi

Topological information can be captured from spatially different perspectives. The two most important approaches that are addressed in this chapter are the region connection calculus, RCC, which has been proposed by Randell et al. (1992) and intersection models, IM, which have been developed by Egenhofer and Franzosa (1991). We briefly introduce these approaches (for excellent extended overviews and discussion see Galton 2000 or Cohn and Renz 2008).

The region connection calculus, as the name implies, is built around the primitive of a region and a mereotopological connection relation, C, between regions. Galton (2000) points out that an author taking this approach is not obliged to answer the question "what is a region?" in a rigorous way. Regions can simply be acknowledged as being primitive elements in a theory. Given two regions, x and y, C(x, y) means that region x is connected to region y. The connection relation C is both symmetric and reflexive. Using the connection relation, it is possible to define additional relations such as parthood, P. For example, P(x, y), means that x is a part of y as long as anything connected to x is also connected to y. Once P is defined we can build other relations such as what it means to be a proper part, PP, and what it means to overlap, O, respectively. The eight relations in Fig. 1 can be formally characterized using this framework.

In contrast, Egenhofer's intersection models approach topology from an ontologically different perspective. Rather than assigning regions the role of a primitive concept, the intersection models are built around the notion of point set topology (Alexandroff 1961). Points are associated with three locations in relation to a spatial entity: Its interior (which can be region-like/extended, but also linear), its boundary (endpoints in case the spatial entity is linear), and its complement. A 3×3 matrix based on the three locations is established for the spatial relation between two entities by assessing whether the intersection of any of the nine point sets is empty or not. Like RCC, the intersection approach allows for formally characterizing the eight spatial relations in Fig. 1 (details and overviews can be found in Egenhofer and Franzosa 1991; Egenhofer and Mark 1995a).

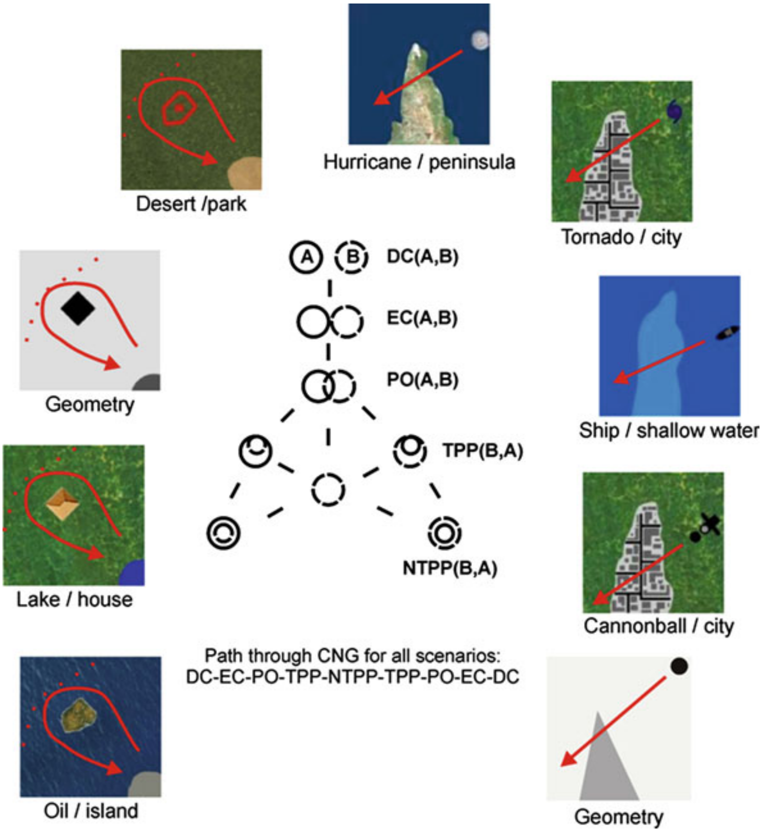

Fig. 1 Conceptual neighborhood graph (CNG) with topological relations DC (disconnected), EC (externally connected), PO (partial overlap), TPP (tangential proper part), NTPP (nontangential proper part). Patterns of the dynamic entities in the nine scenarios (referred to as semantic domains) are identical from the perspective of topology: they can be characterized by the same path through the conceptual neighborhood graph (DC-EC-PO-TPP-NTPP-TPP-POEC-DC). Hence, topology identifies a universal (i.e., invariant) aspect in humans' dynamic environments (adapted from Klippel 2012)

Topologically characterized spatial (and temporal) relations unfold their full potential when they are organized as conceptual neighborhood graphs (Cui et al. 1992; Egenhofer and Al-Taha 1992; Freksa 1992). This approach was publicized by Freksa (1992) for Allen's (1983) temporal intervals but the concept was quickly applied to corresponding spatial (topological) relations (Cui et al. 1992; Egenhofer and Al-Taha 1992). In the original work by Freksa, two temporal relations (e.g., meet and overlap) are considered being conceptual neighbors if a continuous transformation such as shortening, lengthening, or moving (translation) allows for directly transforming one relation into the other with no other (third) relation holding in between. For the spatial domain Egenhofer and Al-Taha (1992) have shown that this principle can be applied to topological relations between two spatially extended entities, that is, certain relations can be transformed directly into one another by translation, rotation, or scaling. Later on, the concept of conceptual neighborhood graphs has been shown to be universal for qualitative calculi (Egenhofer 2010; Egenhofer and Mark 1995a; Kurata 2008a). In fact, for virtually every qualitative calculus with jointly exhaustive and pairwise disjoint (JEPD) relations, a conceptual neighborhood graph can be formed (Cohn and Renz 2008).

Conceptual neighborhood graphs are essential, because they broaden the spectrum of applications of topological calculi in essential ways: They allow for measuring the similarity between topological relations. As such, they can be applied to assessing the similarities of scenes (Bruns and Egenhofer 1996), allow for relaxing queries of spatial databases in case an exact match cannot be found (Egenhofer 2010), they enable qualitative simulation (Cui et al. 1992), or allow for converting noisy quantitative video data into qualitative characterizations (Sridhar et al. 2011). Conceptual neighborhood graphs have been essential as a tool for assessing and formalizing cognitive assessments of similarity between spatial relations and are also used as a formal foundation for natural language expressions (see next section).

2.2 Behaviorally Researching Topology

Topology has been central to bridging the gap between a formal characterization of relations between spatial entities on the one side and the cognitive processing of spatial information on the other. While the number of behavioral validations of spatial calculi is small compared to the number of proposed formalisms, there is an active community that performs research on refining and tailoring formalisms through validating their cognitive adequacy.

First and foremost, there is the extensive research by Mark and Egenhofer (1995a, 1994a, b). Naturally, they focused on IMs such that their research is only partially comparable to RCC. They employed a number of different methods to evaluate whether or not the 9-IM (focusing largely on line-region relations, specifically a road in relation to a park) is indeed capturing both cognitive as well as linguistic spatial categories. They used a grouping task to assess people's conceptual knowledge (Mark and Egenhofer 1994b) and they used agreement tasks in which they created an assessment of spatial expressions in relation to formal topological descriptions (Mark and Egenhofer 1994a). Interestingly, they also reversed their approach: participants were provided with linguistic expressions and were asked to draw sketch maps. Their conclusions converge on the famous sentence that *topology matters and metric refines* (Egenhofer and Mark 1995b). There are some aspects of their research that are not as prominently discussed in the literature such as the finding that topological relations form groups, that is, not every topological equivalence class has a unique cognitive counterpart (at least not on the same categorical level). Given that their research addressed primarily line-region relations this finding may not be surprising as

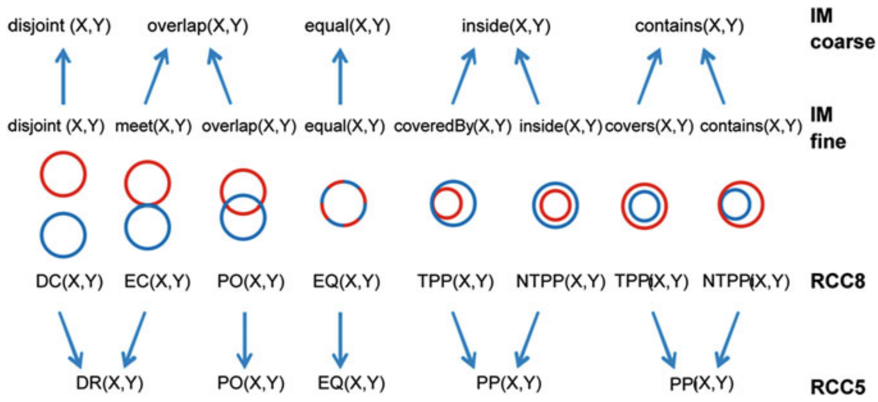

Fig. 2 Spatial relations distinguished by RCC-8 and RCC-5 and corresponding coarse and fine distinction explicated in IMs (adapted from Knauff et al. 1997)

the 9-intersection model distinguishes 19 equivalence classes (for line-region relations).

A study, or actually a set of studies that allow for a direct comparison between IMs and RCC was published by Knauff, Renz and collaborators (Knauff et al. 1997; Renz 2002); their research focused on extended spatial entities. For both approaches (IMs and RCC) two different levels of granularity can be defined and, interestingly, there is no direct mapping at the coarser level (although both distinguish five relations, see Fig. 2). Hence, it could be that either model would deserve the label "cognitively (more) adequate". Their results, however, show that actually the eight relations specified by both RCC-8 and IM are the ones that are deemed cognitively adequate and that coarsening the eight relations to five may be cognitively irrelevant (Knauff et al. 1997). Figure 2 shows the two approaches and their two levels of granularity. It has to be noted though, that the stimuli used in their experiments were geometric figures, very much like the ones used in Fig. 2. This design strongly emphasizes boundaries (although this concept does not exist in RCC) and also does not account for any influence that the semantics of a specific domain might have (as compared to the research of Mark and Egenhofer, see preceding paragraph).

There are additional studies that show that matching, for example, linguistic description and topological operators, such as those used in various GIS products, is still not a straight forward task. Riedemann (2005) asked participants in a simple agreement task whether a term used to describe an operation in a GIS corresponds to a specification of this operation as derived from the 9-IM. While she did find that terms can be matched to operations, she also showed that (a) these terms are not necessarily the ones used in GIS products and (b) that there is more flexibility with respect to the interpretation and applicability of a linguistic term as formally specified.

Other studies assessing the cognitive adequacy of topological calculi are only briefly mentioned here (without claiming that this is an exhaustive overview). Shariff and collaborators (Egenhofer and Shariff 1998; Shariff et al. 1998) did extensive work to calibrate natural language expressions (see also Schwering 2007). In addition to topological distinctions they introduced metric details that they organized into three categories: splitting, closeness, and approximate alongness. From a behavioral perspective, they largely relied on their previous work; however, they developed a formal model that allows for capturing the semantics of over 60 natural language expression such as *goes across*.

Zhan (2002) addressed the question of modeling quantifying linguistic expressions such as *a little bit*, *somewhat*, and *nearly completely*. Topology alone is not sufficient to create such a model. He performed a user study in which participants rated the appropriateness of sentences describing a spatial scene showing two spatially extended entities. To integrate the data he obtained into a model of the meaning of spatial language expressions he used fuzzy set theory.

Xu (2007) focused on the relation between two linear entities. Like Zhan and, to some extent, Mark and Egenhofer, she found that topology alone is not sufficient to capture the semantics of spatial expressions describing the relation between two linear entities. She used an agreement task and modeled the results for particular spatial expressions and whether or not they match a graphic depiction of two linear entities as input for a rule-based approach. Through this approach she was able to define, formally, the spatial semantics of terms such as *crosses* or *is parallel to*.

To summarize, topology is likely the single most often used formalism (ignoring the different perspectives on it) that is applied to bridge the gap between requirements of formal systems and spatial cognition. From this perspective, the Egenhofer–Cohn Hypothesis is an inspiring, valid, and testable assumption that has stimulated a plethora of research papers. However the cognitive validation of qualitative formalisms is still underdeveloped. We have discussed several of them that led to varying results, often finding that topological information is a start but not sufficient to model spatial cognition.

One aspect that has not received sufficient attention is the combination of space and time (although the classic *road crossing a park* and the two linear objects in Xu's work 2007 could be interpreted as spatio-temporal trajectories, see also Gottfried, van de Weghe et al. 2009). Spatio-temporal, or, from a cognitively inspired perspective, event-based approaches to spatial information systems and science are important. Cognitively inspired frameworks were proposed in the 1980s (Peuquet 1988); however, only the availability of ubiquitous computing facilities in the form of, for example, sensor networks (Worboys and Duckham 2006) has spurred the necessity to integrate both time and space into information science and systems.

In the following sections we introduce a framework that we have established to allow for evaluating topological calculi and their role in bridging the cognition of events and their formal characterization.

3 A Framework for Assessing the Cognitive Adequacy of Topological Calculi for Modeling Geographic Events

We have extended research on assessing topological relations (primarily between spatially extended entities) from a cognitive perspective. We will summarize here the main findings and provide an overview of our contributions that primarily address the role of topology in geographic event conceptualization. Table 1 provides an overview and accompanies the discussion.

One important aspect to keep in mind (which we will also come back to in the outlook) is that we addressed movement patterns from the perspective that a spatially extended entity (figure) is changing its spatial relation with a reference entity which is also spatially extended (ground). One of the reasons for this approach is that only on this level of spatial information are RCC and IM directly comparable. Additionally, regions have long been central to qualitative theories of motion (Muller 2002). It should be noted that an alternative approach is to treat the figure and its path as a point objects that leave a trail (or line) and use the flexibility of the intersection models to model the relation between a region and a line (Egenhofer and Mark, 1995a; Kurata 2008b; Kurata and Egenhofer 2009). While we have conducted experiments with DLine-Regions, too, they are less advanced and will only be mentioned briefly.

3.1 Methodology

From the various methodological possibilities we selected the grouping paradigm as one of the most central methods for assessing conceptual knowledge (and cognitive adequacy). The set-up of our experiments follows work by Mark and Egenhofer (1994b) and Knauff et al. (1997) as well as established practice in psychology experiments (Pothos and Close 2008): A set of stimuli is created, in our case animations of movement patterns (see, e.g., Fig. 1), and participants are asked to create groups (categories) in which they sort the icons. Because we are genuinely interested in the (natural/commonsense) conceptualizations of movement patterns we followed an approach that is called *category construction* (Medin et al. 1987), *free classification* or *unsupervised learning* (Pothos and Chater 2002). The main characteristic of this approach is that participants do not receive a predefined number of groups/categories but that they are free to create any number of categories that they deem appropriate for the given stimuli. The opposite of this approach is called non-free classification or supervised learning, in which participants are given a set of categories and are evaluated whether they are able to categorize a set of stimuli correctly.

Besides collecting grouping data it is also common practice to collect linguistic data, often in the form of labels that are given to the groups after they have been created. We follow this approach, too, as the linguistic data offers valuable insights

Table 1 Overview of behavioral experiments

	Publication	Topological aspect	Additional spatial information	Stimulus	Result
1	Klippel et al. (2008)	Paths through a topological neighborhood graph. Same starting relations (DC) and three ending relations that also constrain aspects such as size differences (NTPP, NTPPi, EQ)	Size differences, whether one or both entities in a scene are moving	Animated geometric figures, translation movement	Size and whether one or both entities were moving were singled out as main criteria to conceptualize movement patterns
2	Klippel (2009)	Paths through a topological neighborhood graph. Same starting relation (DC), different ending relations (DC, EC, PO, TPP, NTPP, TPP, PO, EC, DC)	Size differences, whether one or both entities in a scene are moving	Animated geometric figures, translation movement	Size was the primary grouping criterion
3	Klippel and Li (2009)	Paths through the conceptual neighborhood graph with a static ground (peninsula) and moving figure (hurricane). Same starting relation (DC), different ending relations (DC, EC, PO, TPP, NTPP, TPP, PO, EC, DC)	Randomized start and end coordinates	Animated hurricanes in relation to peninsula, translation movement	Topology was used as the main criterion. However, not all topologically defined ending relations were equally salient, that is, they formed groups
4	Klippel et al. (2010)	Same as 3	Randomized start and end coordinates plus hurricanes had different sizes	Animated hurricanes in relation to peninsula, translation movement	Participants had a clear focus on the size differences, then topology
5	Li et al. (2011)	Same as 3	Randomized start and end coordinates plus the paths of the hurricanes were either animated or represented as a static line	Animated or static paths of hurricanes in relation to peninsula, translation movement	Participants paid statistically significantly more attention to ending relations in case the trajectory is represented statically

(continued)

Table 1 (continued)

	Publication	Topological aspect	Additional spatial information	Stimulus	Result
6	Klippel (2012)	Same as 3	Randomized start and end coordinates plus five different semantic contexts/domains. Within each domain the topological information is identical. Scenarios: Hurricane/peninsula, tornado/city, ship/shallow water, cannonball/city, geometric figures	Five different translation scenarios (see Fig. 1)	Topological relations are not equally salient across different semantic domains
7	Yang et al. (in revision)	Similar to 3 in that the topological information is identical. However, instead of using translational movement patterns, scaling movement was employed	Randomized start and end coordinates plus four different semantic contexts/domains. Within each domain the topological information is identical (also to 6). Scenarios: Oil/island, desert/park, lake/house, geometric figures	Four different scaling scenarios (see Fig. 1)	Topological relations are not equally salient across different semantic domains
8	Klippel et al. (2011)	Meta-analysis of previous results/experiments focusing on individual differences	div.	div.	The tools and approaches we developed allow for an in depth analysis of categorization/conceptualization behavior

into cognitive processes as well as input to computational/formal models of natural language. The latter aspect is possible because our experiments are grounded in a formal (topological) framework. However, the primary use of the linguistic data in our experiment has been on providing additional insights into cognitive conceptualizations.

One important development that reflects the symbiotic and mutually beneficial influence of the spatial and cognitive sciences is the development of tools to analyze behavioral data. Especially in the area of visual analysis, promising results have been obtained (Fabrikant et al. 2010). We have invested in this line of research as well and have created a number of tools that allow for overview or in-depth analysis of participants' behavior. *CatScan*, the tool that administers the experiment collects data such as the time spent on the grouping task, the order in which icons are selected, and the linguistic descriptions; *KlipArt*, is a visual analytics tool based on Weaver's *improvise* programming environment (Weaver 2004). This tool allows for an in-depth analysis of grouping behavior and for the identification of individual differences in conceptualizing the stimuli; *MatrixViewer*, is again realized within *improvise* and allows for an overview of similarities between stimuli (within one experiment) and for comparing the grouping behavior between participants (again within one experiment) both visually as well as using similarity measures such as the Levenshtein distance (Levenshtein 1966). We have written about these tools extensively and will not provide a detailed discussion here (see Klippel et al. 2011).

3.2 Tangible Results

We call this section 'tangible results' as we are summarizing some of our and other researchers' results on cognitively validating and evaluating topological calculi that may prove useful to researchers interested in the relation between qualitative formalisms and cognition. Our results show that purely topological approaches, as the strong version of the Egenhofer–Cohn Hypothesis, are difficult to defend. In a comprehensive model other aspects (the unequal salience of topological relations, competing spatial information, the semantics of a domain, and the way information is presented) need to be integrated.

Topological relations (as identified by RCC-8 and IMs) are not equally salient from a cognitive perspective. Despite the results of Knauff and collaborators (1997) which assert that the eight relations—identified in RCC-8 and IM—are cognitively adequate, we claim, with some certainty, that this is not the case. Earlier research by Mark and Egenhofer (1994b) already showed that several topological relations form groups (superordinate categories). While Mark and Egenhofer's experiments used 19 topological equivalence classes and creating superordinate categories therefore may be a more natural cognitive behavior, we did not find in any of our experiments that topological relations (which used RCC/IM relations as ending relations of movement patterns) were treated as being equally salient; not in purely geometric scenarios, not in scenarios with domain semantic, neither in translation nor in scaling experiments, and not in static or dynamic representations of trajectories.

Our experiments thereby confirm assumptions (and render them precise) that have been made by several researchers, that is, that in order for topology to be cognitively adequate we need to reduce the number of relations to less than eight. We find this approach in Clementini's work (Clementini et al. 1993), who proposed a maximum of five relations as being a cognitively adequate number, in Li and Fonseca's (2006) approach to build a comprehensive model for the assessment of similarity based on qualitative spatial calculi, and, last but not least, we also find this aspect surfacing in research on Allen's temporal calculus (Allen 1983) conducted by Lu and colleagues (Lu and Harter 2006; Lu et al. 2009).

Topology, while certainly of great importance, is not always the (spatial) aspect that is selected as the main criterion for conceptualizing spatial information. This has been shown in several results we presented and casts some doubts on the unequivocal truth of the statement that *topology matters and metric refines*. It is important though to make a distinction between experiments (scenarios) in which geometric figures are used and those that use examples from the real world. The difference is that geometric figures do not inherit constraints from the domain that they represent. Therefore, it is, for example possible to create scenarios in which one out of two spatial entities or both spatial entities are moving. While there are scenarios in the real world that would allow for such a distinction (two medieval armies conceptualized as extended spatial entities running into each other), it is definitely the case that geometric figures have more degrees of freedom (would those armies also run unaffectedly through one another). Hence, it may be easier for non-topological information to dominate as a category construction criterion in cases in which no real world constraints apply. However, in scenarios which reflect real world movement patterns we find that aspects other than topology may be responsible for guiding human conceptualizations prior to topology, too. One such aspect is direction information. Figure 3 shows an analysis that we performed using KlipArt for the hurricane scenario (see Fig. 1 and Table 1). The majority of participants used topology (which surfaced as the main distinguishing criterion); however, several participants, in addition to making a topological distinction created subgroups based on the direction of the hurricane (relative to the peninsula). A second aspect, which actually dominated topology, is size. For example, employing differently sized hurricanes leads participants to clearly separate animations by the size of the hurricanes (Klippel et al. 2010). In case of a hurricane this would make perfect sense as small hurricanes often injure no-one while the big ones pose a considerable threat. Additionally, this aspect is also prominent in experiments which use geometric figures (Klippel 2009; Klippel et al. 2008) and should therefore be regarded as a serious competitor to topology. If we look into the literature on size we find a couple interesting correspondences:

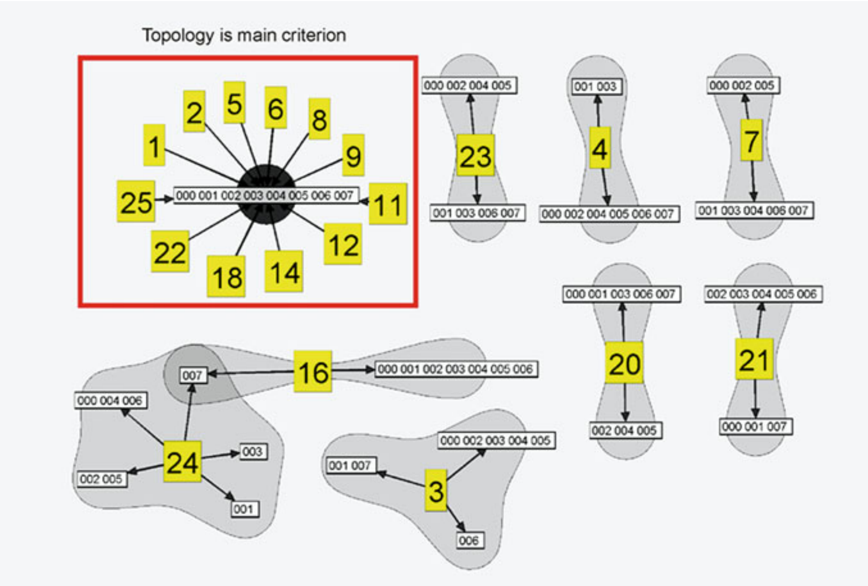

Fig. 3 Depicted is the grouping behavior of participants for the topological relation DC, disconnected. This relation has eight topologically equivalent instances numbered from 000 to 007. Most participants (*red box*) used topology as their criterion for conceptualizing hurricane movement patterns, that is, they placed all icons into the same group. The remaining participants used primarily direction concepts (exception: participant 4 distinguished the length of paths)

- Size (scale) is an important aspect in many geographic theories (Freundschuh and Egenhofer 1997; Montello 1993).
- Size is an important criterion for selecting reference entities (Gapp 1995).
- Size differences, in contrast to changing spatial relations, are continuously present. As such they are potentially easier to conceptualize as movement patterns. This perspective would correspond to research on categorization by Chater and Pothos and colleagues (Chater 1999; Pothos and Close 2008) on the principle of simplicity that they propose as a means to explain perceptual organization as well as conceptual aspects of categorization. In a similar vein research by Gentner and Boroditsky (2001) can be interpreted. They found that children have more difficulties naming events compared to naming objects. It may be the case that topologically characterized changing relations are more difficult to conceptualize as continuously present object characteristics. While an argument could be made that this may only be the case for dynamic presentations, recent research on static spatial relations argues in a similar direction (Schwering 2011).

The cognitive salience of topological relations varies across semantic domains. In several experiments we have compared topologically identical movement patterns across different domains (see Fig. 1). We were able to show

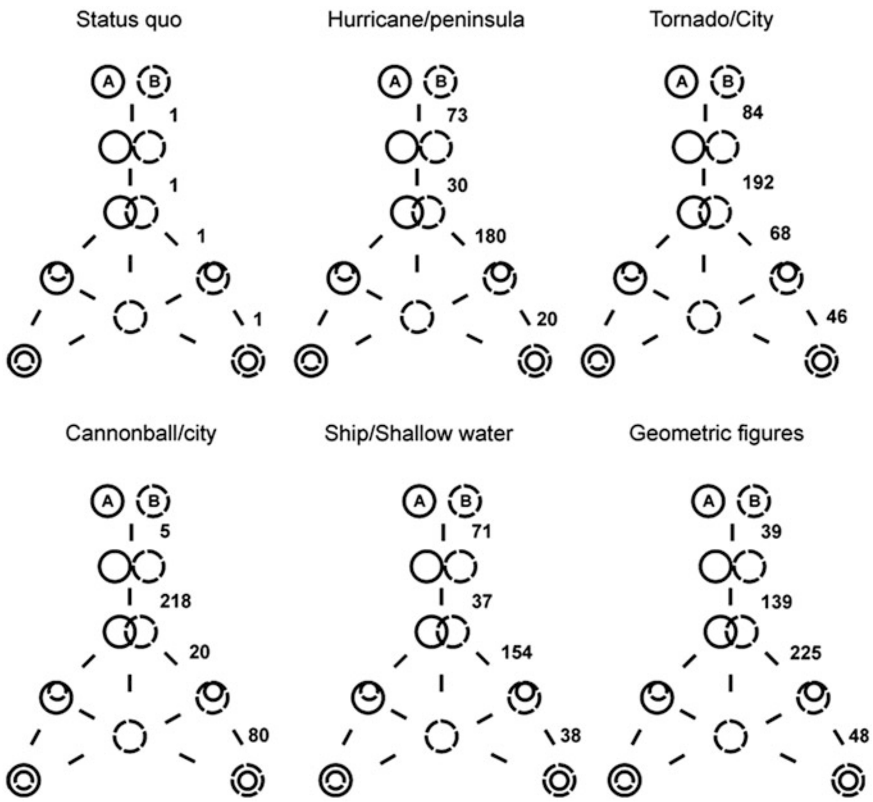

Fig. 4 Conceptual neighborhood graphs with weighted edges. Weights are derived from cluster analysis using fusion coefficients (Ward's method; see also Fig. 1)

that topologically equivalent paths through the conceptual neighborhood graph are not equally salient across different domains. Topologically defined ending relations are meaningfully (from the perspective of the domain semantics) grouped together resulting in different category structures across domains. To illustrate, Fig. 4 shows a first approach towards deriving weights for edges in the conceptual neighborhood graph based on the grouping behavior of participants (see also Fig. 1). It is clear that (a) semantics (and associated background knowledge) has an influence on which topological relations are perceived as being more similar to each other, and (b) that the similarities vary across domains. We performed studies with translation movement patterns (Klippel 2012) and recently also scaling (Yang et al., in revision). In both cases the results show influences of domain semantics.

To some extent these results are not surprising. The cognitive literature is discussing domain specific factors in several ways (e.g., Hirschfeld and Gelman 1994), however, in the light of manifold proposals suggesting to assess similarities between spatial relations on a purely spatial basis, our findings suggest some caution.

The mode of presentation, static or dynamic, of geographic events has a statistically significant influence on how topological information is used to create a conceptualization. In the age of unprecedented digital opportunities this is an important finding that goes, however, beyond our immediate work. In our experiments representing trajectories statically—in contrast to showing an actual animation—had an effect on how the ending relation of a trajectory was used resulting in more participants placing icons of the same topological equivalence class into the same category. It is, of course, easier to attend to endpoints in case a trajectory is statically presented and further research is necessary; however, in recent experiments by Maguire and collaborators (2011) on the segmentation of trajectories that were presented either statically (objects) or dynamically (events) differences were found, too. This research allows for some basic understanding of the effects of animation that has long been a topic of intensive discussions (Tversky et al. 2002).

4 Conclusions and Future Work

We have presented and summarized work on cognitively evaluating topological calculi. Topology, as a way to qualitatively characterize static and dynamically changing spatial relations, has long been recognized as an important construct in both spatial and cognitive sciences. We termed the claim that topology lays (always) the foundation for modeling and explaining cognitive behavior the Egenhofer–Cohn Hypothesis. While research exists that requests a modification of this hypothesis, we found some experiments in which not even the naïve geography mantra that *topology matters and metric refines* (Egenhofer and Mark 1995b) holds and that other spatial aspects such as size may have primacy over topological information. Hence, just like the approach of linguistic relativity (Gumperz and Levinson 1996) seeks to draw a more concise picture of the relation between language and thought we need *topological relativity* as a theoretical construct to provide better models of human spatial reasoning.

To this end, spatial and cognitive sciences have a potential that seems to be not fully explored yet, that is, spatial science provides tools such as RCC and IMs that allow for rendering spatial information precise. This precisely defined information can then be scrutinized in behavioral experiments. We have discussed a number of experiments addressing QSR approaches that primarily originated in spatial sciences and associated fields. Exceptions from a more cognitive science side are the experiments by Knauff et al. (1997) and more recently research by Lu and collaborators (Lu and Harter 2006; Lu et al. 2009). This distinction is based on the home disciplines of the authors but it shows that only a few truly interdisciplinary approaches have been established.

Such a development would be important as topology is not only a potential bridge between formal and cognitive perspectives on space and spatial relations, but it is also a bridge between perceptual and cognitive aspects of space. This insight is manifesting itself in manifold theories that center on invariants that we briefly discussed in the introduction. To this end, topology might also play a central part in theories on concepts and conceptualization. Work by Barsalou, Goldstone, and colleagues (Barsalou 2008; Goldstone and Barsalou 1998), who address the relation between perception and perceptual aspects of environments and its relation to categorization, assign directly perceivable characteristics of environments an important role in theories on categorization. Again, the spatial sciences potentially allow for rendering the notion of environmental characteristics precise and can help design targeted investigations.

With a large group of researchers working on new and/or refined spatial calculi it is not possible to put all of them under the scrutiny of behavioral validation (and many of them are not claiming cognitive adequacy but are important from other, such as computational perspectives—Renz 2002). However, we have clearly seen that the strong version of the Egenhofer–Cohn Hypothesis is addressing cognition too narrowly and that *topological relativity* is the more fruitful approach. To this end, some future behavioral research directions that we consider important should be briefly discussed.

One of the most important research directions is the combination of both spatial and semantic information to fully understand (or model) cognitive behavior. The majority of research in the spatial sciences that develops spatial formalisms is, for obvious reasons, addressing the spatial component of spatial information rather than the semantic aspect. However, several approaches exist which aim for a more comprehensive framework such as early work by Gapp (1995) on selecting cognitively salient reference objects. In line with a tremendous amount of research on ontological characterizations of spatial information (e.g., Kuhn 2001), a cognitively inspired ontological characterization is necessary to structure domains into categories. This view, of course, is not new. Hirschfeld and Gelman (1994) edited a book that addresses the topic of domain-specificity of the mind (although domain in their case is not restricted to semantic domain). From the perspective of concept theories the still somewhat elusive *theory* (Laurence and Margolis 1999) has developed; and, from the perspective of event segmentation Zacks' (2004) model explicitly incorporates knowledge structures (background knowledge) as a factor that identifies meaningful (event) units. These are but a few examples. However, we are still not at a stage where results from spatial and cognitive sciences are intimately intertwined to be applicable to cognitive models and geospatial tools (see also Stock and Cialone 2011).

So far, research on cognitively validating topological calculi has addressed changing spatial relations between spatial entities. However, there are also topological transformations that an individual entity can undergo. Medak (1999) refers to these as lifelines; in a recent article Jiang and Worboys (2009) laid the formal foundation for identifying primitive states of an evolving spatial entity (see also Galton 1997; Renolen 2000). The application areas for these formalisms are substantial and reach from oil spills to heat islands. However, to the best of our knowledge, there is no behavioral research on this aspect of topology and its role in modeling cognitively changing spatial relations. We have started to make plans for assessing continuous change of individual spatial entities to extend our work on assessing the adequacy of current topological formalisms to continuous topological change.

References

Abler R, Adams JS, Gould P (1971) Spatial organization: the geographer's view of the world. Prentice-Hall, Englewood Cliffs

Alexandroff P (1961) Elementary concepts of topology. Dover Publications, New York

Allen JF (1983) Maintaining knowledge about temporal intervals. Commun ACM 26(11):832–843

Barsalou LW (2008) Grounded cognition. Annu Rev Psychol 59:617–645

Braitenberg V (1984) Vehicles. Experiments in synthetic psychology. MIT Press, Cambridge

Bruns HT, Egenhofer MJ (1996) Similarity of spatial scenes. In: Kraak MJ, Molenaar M (eds) Seventh international symposium on spatial data handling (SDH'96), Delft, The Netherland. Taylor & Francis, London and NewYork pp 173–184

Chater N (1999) The search for simplicity: a fundamental cognitive principle. Q J Exp Psychol 52A(2):273–302

Clementini E, Di Felice P, van Oosterom P (1993) A small set of formal topological relationships suitable for end-user interaction. In: Abel D, Ooi BC (eds) Advances in spatial databases. Proceedings of the third international symposium, SSD '93 Singapore, 23–25 June 1993. Springer, Berlin, pp 277–295

Cohn AG, Renz J (2008) Qualitative spatial representation and reasoning. In: van Harmelen F, Lifschitz V, Porter B (eds) Foundations of artificial intelligence. Handbook of knowledge representation, 1st edn. Elsevier, Amsterdam, pp 551–596

Cui Z, Cohn AG, Randell DA (1992) Qualitative simulation based on a logical formalism of space and time. In: Proceedings AAAI-92. AAAI Press, Menlo Park, pp 679–684

Egenhofer MJ (2010) The family of conceptual neighborhood graphs for region–region relations. In: Fabrikant SI, Reichenbacher T, van Krefeld M, Schlieder C (eds) Proceedings of sixth international conference, GIScience 2010 Zürich, Switzerland, 14–17 Sep 2010. Springer, Berlin, pp 42–55

Egenhofer MJ, Al-Taha KK (1992) Reasoning about gradual changes of topological relationships. In: Frank AU, Campari I, Formentini U (eds) Theories and methods of spatio-temporal reasoning in geographic space. Springer, Berlin, pp 196–219

Egenhofer MJ, Franzosa RD (1991) Point-set topological spatial relations. Int J Geogr Inf Syst 5(2):161–174

Egenhofer MJ, Mark DM (1995a) Modeling conceptual neighborhoods of topological relations. Int J Geogr Inf Syst 9(5):555–565

Egenhofer MJ, Mark DM (1995b) Naive geography. In: Frank AU, Kuhn W (eds) Spatial information theory. A theoretical basis for GIS. Proceedings of international conference, COSIT 95, Semmering, Austria, 21–23 Sept 1995. Springer, Berlin, pp 1–15

Egenhofer MJ, Shariff AR (1998) Metric details for natural-language spatial relations. ACM Trans Inf Syst 16(4):295–321

Fabrikant SI, Hespanha SR, Hegarty M (2010) Cognitively inspired and perceptually salient graphic displays for efficient spatial inference making. Ann Assoc Am Geogr 100(1):13–29

Freksa C (1991) Qualitative spatial reasoning. In: Mark DM, Frank AU (eds) Cognitive and linguistic aspects of geographic space. Kluwer, Dordrecht, pp 361–372

Freksa C (1992) Temporal reasoning based on semi-intervals. Artif Intell 54(1):199–227

Freundschuh SM, Egenhofer MJ (1997) Human conceptions of spaces: implications for geographic information systems. Trans GIS 2(4):361–375

Galton A (1997) Continuous change in spatial regions. In: Hirtle SC, Frank AU (eds) Spatial information theory: a theoretical basis for GIS. Springer, Berlin, pp 1–14
Galton A (2000) Qualitative spatial change. Spatial information systems. Oxford University Press, Oxford
Gapp K-P (1995) Object localization: selection of optimal reference objects. In: Frank AU, Kuhn W (eds) Spatial information theory. A theoretical basis for GIS. Proceedings of international conference, COSIT 95, Semmering, Austria, 21–23 Sept 1995. Springer, Berlin
Gentner D, Boroditsky L (2001) Individuation, relativity, and early word learning. In: Bowerman M, Levinson SC (eds) Language, culture and cognition, vol 3., Language acquisition and conceptual developmentCambridge University Press, Cambridge, pp 215–256
Gibson J (1979) The ecological approach to visual perception. Houghton Mifflin, Boston
Goldstone RL, Barsalou LW (1998) Reuniting perception and conception. Cognition 65:231–262
Gottfried B, van de Weghe N, Billen R, de Maeyer P (eds) (2009) Behaviour monitoring and interpretation—BMI'09 studying moving objects in a three-dimensional world: Proceedings of the 3rd workshop on behaviour monitoring and interpretation (BMI'09) Ghent, Belgium, Novemb 3, 2009. CEUR-WS.org, Aachen
Gumperz JJ, Levinson SC (eds) (1996) Rethinking linguistic relativity. Cambridge University Press, Cambridge
Hirschfeld LA, Gelman SA (eds) (1994) Mapping the mind: domain specificity in cognition and culture. Cambridge University Press, New York
Jiang J, Worboys M (2009) Event-based topology for dynamic planar areal objects. Int J Geogr Inf Sci 23(1):33–60
Johnson M (1987) The body in the mind: the bodily basis of meaning, imagination, and reasoning. University of Chicago Press, Chicago
Klein F (1872) Vergleichende Betrachtungen über neuere geometrische Forschungen ("A comparative review of recent researches in geometry"). Math Ann 43:63–100
Klippel A (2012) Spatial information theory meets spatial thinking—is topology the Rosetta Stone of spatio-temporal cognition? Ann Assoc Am Geogr. doi:10.1080/00045608.2012.702481
Klippel A (2009) Topologically characterized movement patterns: a cognitive assessment. Spatial Cogn Comput 9(4):233–261
Klippel A, Li R (2009) The endpoint hypothesis: a topological-cognitive assessment of geographic scale movement patterns. In: Stewart Hornsby K, Claramunt C, Denis M, Ligozat G (eds) Spatial information theory. Proceedings of 9th international conference, COSIT 2009, Aber Wrac'h, France, 21–25 Sept 2009. Springer, Berlin, pp 177–194
Klippel A, Li R, Hardisty F, Weaver C (2010) Cognitive invariants of geographic event conceptualization: what matters and what refines. In: Fabrikant SI, Reichenbacher T, van Krefeld M, Schlieder C (eds) Proceedings of sixth international conference, GIScience 2010 Zürich, Switzerland, 14–17 Sept 2010. Springer, Berlin, pp 130–144
Klippel A, Weaver C, Robinson AC (2011) Analyzing cognitive conceptualizations using interactive visual environments. Cartogr Geogr Inf Sci 38(1):52–68
Klippel A, Worboys M, Duckham M (2008) Identifying factors of geographic event conceptualisation. Int J Geogr Inf Sci 22(2):183–204
Klix F (1971) Information und Verhalten: Kybernetische Aspekte der organismischen Informationsverarbeitung; Einführung in naturwissenschaftliche Grundlagen der allgemeinen Psychologie. Huber, Bern
Knauff M, Rauh R, Renz J (1997) A cognitive assessment of topological spatial relations: results from an empirical investigation. In: Hirtle SC, Frank AU (eds) Spatial information theory: a theoretical basis for GIS. Springer, Berlin, pp 193–206
Kuhn W (2001) Ontologies in support of activities in geographic space. Int J Geogr Inf Sci 15(7):612–632
Kuhn W (2007) An image-schematic account of spatial categories. In: Winter S, Kuipers B, Duckham M, Kulik L (eds) Spatial information theory. Proceedings of 9th international conference, COSIT 2007, Melbourne, Australia, 19–23 Sept 2007. Springer, Berlin, pp 152–168

Kurata Y (2008a) A strategy for drawing a conceptual neighborhood diagram. In: Stapleton G, Howse J, Lee J (eds) Lecture notes in computer science. Lecture notes in artificial intelligence, vol 5223. Diagrammatic representation and inference. Proceedings of 5th international conference, Diagrams 2008, Herrsching, Germany, 19–21 Sept 2008. Springer, Berlin, pp 388–390

Kurata Y (2008b) The 9+-intersection: a universal framework for modeling topological relations. In: Cova TJ, Miller HJ, Beard K, Frank AU, Goodchild MF (eds) Geographic information science. Proceedings of 5th international conference, GIScience 2008, Park City, UT, USA, 23–26 Sept 2008. Springer, Berlin, pp 181–198

Kurata Y, Egenhofer MJ (2009) Interpretation of behaviors from a viewpoint of topology. In: Gottfried B, Aghajan H (eds) Behaviour monitoring and interpretation. Ambient intelligence and smart environments. IOS Press, Amsterdam, pp 75–97

Lakoff G (1987) Women, fire and dangerous things. Chicago University Press, Chicago

Lakoff G (1990) The invariance hypothesis: is abstract reason based on image schemata? Cogn Linguist 1(1):39–74

Laurence S, Margolis E (1999) Concepts and cognitive science. In: Margolis E, Laurence S (eds) Concepts. Core readings. MIT Press, Cambridge, pp 3–81

Levenshtein V (1966) Binary codes capable of correcting deletions, insertions, and reversals. Sov Phys Doklady 10(8):707–710

Li B, Fonseca F (2006) TDD: a comprehensive model for qualitative spatial similarity assessment. Spatial Cogn Comput 6(1):31–62

Li R, Klippel A, Yang J (2011) Geographic event conceptualization: where spatial and cognitive sciences meet. In: Carlson LA, Hölscher C, Shipley TF (eds) Proceedings of the 33rd annual conference of the cognitive science society. Cognitive Science Society, Austin, pp 3168–3173

Lu S, Harter D (2006) The role of overlap and end state in perceiving and remembering events. In: Sun R (ed) The 28th annual conference of the cognitive science society, Vancouver, British Columbia, Canada, 26–29 July 2006. Lawrence Erlbaum, Mahwah, pp 1729–1734

Lu S, Harter D, Graesser AC (2009) An empirical and computational investigation of perceiving and remembering event temporal relations. Cogn Sci 33:345–373

Maguire MJ, Brumberg J, Ennis M, Shipley TF (2011) Similarities in object and event segmentation: a geometric approach to event path segmentation. Spatial Cogn Comput 3:254–279

Mandler JM (1992) How to build a baby II. Conceptual primitives. Psychol Rev 99(4):587–604

Mark DM, Egenhofer MJ (1994a) Calibrating the meanings of spatial predicates from natural language: line-region relations. In: Waugh TC, Healey RG (eds) Advances in GIS research, 6th international symposium on spatial data handling, Edinburgh, Scotland, UK, pp 538–553

Mark DM, Egenhofer MJ (1994b) Modeling spatial relations between lines and regions: Combining formal mathematical models and human subject testing. Cartogr Geogr Inf Syst 21(3):195–212

Mark DM, Egenhofer MJ (1995) Topology of prototypical spatial relations between lines and regions in English and Spanish. In: Proceedings, Auto Carto 12, Charlotte, North Carolina, March 1995, pp 245–254

Medak D (1999) Lifestyles—an algebraic approach to change in identity. In: Böhlen M, Jensen C, Scholl M (eds) Lecture notes in computer science. Spatio-Temporal Database Management. Springer, Berlin, pp 19–39

Medin DL, Wattenmaker WD, Hampson SE (1987) Family resemblance, conceptual cohesiveness, and category construction. Cogn Psychol 19(2):242–279

Montello DR (1993) Scale and multiple psychologies of space. In: Frank AU, Campari I (eds) Spatial information theory: a theoretical basis for GIS. Springer, Berlin, pp 312–321

Muller P (2002) Topological spatio-temporal reasoning and representation. Comput Intell 18(3):420–450

Peuquet DJ (1988) Representations of geographic space: toward a conceptual synthesis. Ann Assoc Am Geogr 78(3):375–394

Pothos EM, Chater N (2002) A simplicity principle in unsupervised human categorization. Cogn Sci 26(3):303–343

Pothos EM, Close J (2008) One or two dimensions in spontaneous classification: a simplicity approach. Cognition 2:581–602

Randell DA, Cui Z, Cohn AG (1992) A spatial logic based on regions and connections. In: Nebel B, Rich C, Swartout WR (eds) Proceedings of the 3rd international conference on knowledge representation and reasoning. Morgan Kaufmann, San Francisco, pp 165–176

Renolen A (2000) Modelling the real world: conceptual modelling in spatiotemporal information system design. Trans GIS 4(1):23–42

Renz J (2002) Qualitative spatial reasoning with topological information. Springer, Berlin

Riedemann C (2005) Matching names and definitions of topological operators. In: Cohn AG, Mark DM (eds) Spatial information theory. Proceedings of international conference, COSIT 2005, Elliottville, NY, USA, 14–18 Sept 2005. Springer, Berlin, pp 165–181

Schwering A (2007) Evaluation of a semantic similarity measure for natural language spatial relations. In: Winter S, Kuipers B, Duckham M, Kulik L (eds) Spatial information theory. Proceedings of 9th international conference, COSIT 2007, Melbourne, Australia, 19–23 Sept 2007. Springer, Berlin

Schwering A (2011) Does metric really define topology, 20 May 2011 (personal communication)

Shariff AR, Egenhofer MJ, Mark DM (1998) Natural-language spatial relations between linear and areal objects: the topology and metric of English-language terms. Int J Geogr Inf Sci 12(3):215–246

Shaw R, McIntyre M, Mace W (1974) The role of symmetry in event perception. In: MacLeod RB, Pick HL (eds) Perception. Essays in honour of James J. Gibson. Cornell University Press, Ithaca, pp 276–310

Sridhar M, Cohn A, Hogg D (2011) From video to RCC8: exploiting a distance based semantics to stabilise the interpretation of mereotopological relations: spatial information theory. In: Egenhofer M, Giudice N, Moratz R, Worboys M (eds) Spatial information theory. Proceedings of 10th international conference, COSIT 2011, Belfast, ME, USA, 12–16 Sept 2011. Springer, Berlin, pp 110–125

Stock K, Cialone C (2011) Universality, Language-variability and individuality: defining linguistic building blocks for spatial relations. In: Egenhofer M, Giudice N, Moratz R, Worboys M (eds) Lecture notes in computer science. Spatial information theory. Proceedings of 10th international conference, COSIT 2011, Belfast, ME, USA, 12–16 Sept 2011. Springer, Berlin, pp 391–412

Tversky B, Morrison JB, Betrancourt M (2002) Animation: does it facilitate? Int J Hum Comput Stud 57:247–262

Weaver C (2004) Building highly-coordinated visualizations in improvise. In: Proceedings of the IEEE symposium on information visualization 2004, Austin, TX, Oct 2004

Worboys M, Duckham M (2006) Monitoring qualitative spatiotemporal change for geosensor networks. Int J Geogr Inf Sci 20(10):1087–1108

Xu J (2007) Formalizing natural-language spatial relations between linear objects with topological and metric properties. Int J Geogr Inf Sci 21(4):377–395

Yang J, Klippel A, Li R (in revision) Cognitive saliency of topological change under expansion and contraction. Int J Geogr Inf Sci

Zacks JM (2004) Using movement and intentions to understand simple events. Cogn Sci 28:979–1008

Zhan FB (2002) A fuzzy set model of approximate linguistic terms in descriptions of binary topological relations between simple regions. In: Matsakis P, Sztandera LM (eds) Applying soft computing in defining spatial relations. Physica-Verlag, Heidelberg, pp 179–202

Twenty Years of Topological Logic

Ian Pratt-Hartmann

Abstract Topological logics are formal systems for representing and manipulating information about the topological relationships between objects in space. Over the past two decades, these logics have been the subject of intensive research in Artificial Intelligence, under the general rubric of *Qualitative Spatial Reasoning*. This chapter sets out the mathematical foundations of topological logics, and surveys some of their many surprising properties.

Keywords Spatial logic · Qualitative spatial reasoning · Artificial Intelligence

1 Introduction

At about the time of Las Navas 1990, the first steps were being taken in a discipline that has since come to be called *Qualitative Spatial Reasoning*. The driving force behind these developments was the conviction that effective, commonsense, spatial reasoning requires representation languages with two related features: first, their variables should range over spatial *regions*; second, their non-logical—i.e. geometrical—primitives should express *qualitative* relations between those regions. In particular, the traditional conceptual scheme of coordinate geometry, where the only first-class geometrical objects are points, and where all geometrical relations are defined with reference to the coordinate positions of points, appeared unsuited to the rough-and-ready knowledge we have of spatial arrangements in our everyday surroundings. Such point-based, metrical representations—so it seemed—would

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require either excessive amounts of geometrical data, or else infeasibly powerful logical syntax to abstract away from those data. Various qualitative geometrical primitives were considered; but the most natural and appealing were, broadly speaking, *topological* in character. Thus, the suggestion arose to represent spatial arrangements using a language with variables ranging over spatial regions, and predicates representing topological properties and relations. This suggestion brought with it a collection of natural mathematical questions. What can we say with such languages? Which ones are best: are some more expressive, or perhaps more succinct, than others? What kinds of reasoning can we carry out using them? And what computational resources does such reasoning consume? *Topological logic* came into being.

Since then, considerable strides have been made towards answering these questions. From faltering, axiomatic beginnings, the appropriate semantic framework within which to analyse topological logics was, by the turn of the millennium, firmly established; and technical results quickly followed. The aim of this chapter is to outline that semantic framework, and to summarize the technical results it has made possible. The former task is undertaken in Sect. 2, which provides the basic definitions and notation to be used in the sequel. Section 3 surveys results on propositional—that is to say, quantifier-free—topological logics. Section 4 then does the same for first-order topological logics. Our account is, of necessity, mathematical; however it is intended for non-specialists. We assume only a general grasp of standard topological and logical notation, and provide glosses of definitions and theorems in English wherever possible. There are no proofs.

Notwithstanding their relatively recent provenance, both qualitative spatial reasoning more generally, and topological logic in particular, have obvious precursors in both the philosophical and mathematical literature. For example, many of the earliest topological logics considered in Artificial Intelligence trace their ancestry to Whitehead's theory of "Extensive Connection" (Whitehead 1929), and its subsequent re-working in (Clarke 1981, 1985). Or again, the celebrated (McKinsey and Tarski 1944) defines, in our sense, a topological logic—albeit one of limited expressive power—just as the less well-known (Tarski 1956) defines a very expressive one. But it is not the aim of the present chapter to describe these early antecedents of topological logic. That subject arose, in its present form, in the last decade of the second millennium; and it is there that we begin.

2 The Conceptual Framework

By a *topological language*, we understand any formalism for describing topological properties of arrangements of regions in some space of interest, such as, for example, the Euclidean plane or three-dimensional Euclidean space. From a mathematical point of view, we can identify regions with subsets of the space in question, it being understood that we may want only certain subsets to qualify as regions. We proceed as follows. If T is a topological space, and S a non-empty collection of subsets of T, then we call the pair (T, S) a *frame*. Frames are to be thought of as mathematical models of the space to be represented: the space T specifies the underlying geometry, and the collection of subsets S, the geometrical objects about which we can speak. When T is clear from context, we often suppress reference to it, and denote the frame (T, S) simply by S. When S is clear from context, we refer to its elements as *regions*. Although any non-empty collection of subsets of a topological space qualifies as a frame, one particular class of frames has, historically, played a dominant role. Let T be a topological space. If $X \subseteq T$, we denote by X^- the topological closure of X (i.e. the smallest closed set including X), and by X^0, the topological interior of X (i.e. the largest open set included in X). We call a set *regular closed* (*in* T) if it is of the form $(X^0)^-$—that is to say, if it is the closure of the interior of some set. Figure 1 illustrates the case where the space T is the Euclidean plane, $\mathbb{R}^2$. Very roughly: in the context of $\mathbb{R}^2$, the regular closed sets are those closed sets with no isolated points or 1-dimensional 'filaments'. We denote the set of regular closed sets in T by $\mathrm{RC}(T)$. Note that regular closed sets need not be connected (i.e. may consist of more than one 'piece'), and need not have connected complements (i.e. may contain 'holes').

Regular closed sets are appealing from the point of view of qualitative spatial reasoning, because on the one hand, no two such sets differ only with respect to boundary points, and, on the other, they admit natural and intuitive notions of aggregation, complementation and taking common parts. Technically, $\mathrm{RC}(T)$ forms a Boolean algebra under the operations $+$ (aggregation), $\cdot$ (common part) and $-$ (complement). The Boolean ordering, $\leq$, then coincides with the subset-ordering, $\subseteq$; the smallest element is $0 = \emptyset$; and the largest element is $1 = T$. Note that the aggregation operation, $+$, coincides with set-theoretic union; however, its dual, namely $\cdot$, does not in general coincide with set-theoretic intersection. Usually, therefore, we shall be concerned with frames of the form $\mathrm{RC}(T)$, where T is a topological space. We denote this class of frames by RegC.

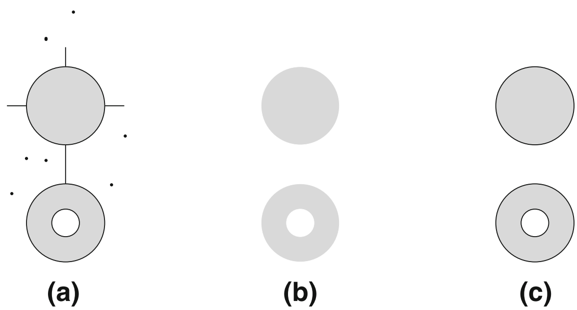

Fig. 1 (**a**) A closed set (**b**) its interior and (**c**) the closure of its interior

It is important to realize that, in topological logics, the focus of attention is not on frames themselves, but rather, on frames *as they are described in some language*. Consider, for example, the language known as *Region Connection Calculus* (RCC8). This language features six binary predicates: disconnection (DC), external contact (EC), partial overlap (PO), equality (EQ), tangential proper part (TPP) and non-tangential proper part (NTPP). Satisfying instances of these relations are shown, for discs in the plane, in Fig. 2. The proposal to use these topological primitives in the context of qualitative spatial reasoning is due to (Randell et al. 1992); an essentially equivalent formalism appeared in (Egenhofer and Franzosa 1991). We remark that the "8" in RCC8 derives from the fact that the last two of the six relations depicted in Fig. 2 are asymmetric.

Formally, the language RCC8 is defined as follows. Fix a countably infinite collection of variables. An *atomic formula* is an expression of the form $R(x_1, x_2)$, where x_1, x_2 are variables, and R is one of the six predicates just listed; and a *formula* is any expression formed in the normal way from atomic formulas by means of the usual propositional connectives $\wedge, \vee, \rightarrow, \neg$. Thus, for example,

$$\text{PO}(x_1, x_2) \wedge \text{TPP}(x_2, x_3) \rightarrow (\text{PO}(x_1, x_3) \vee \text{TPP}(x_1, x_3) \vee \text{NTPP}(x_1, x_3)) \qquad (1)$$

is an RCC8-formula. Informally, it says: "If x_1, x_2 and x_3 are regions such that x_1 partially overlaps x_2 and x_2 is a tangential proper part of x_3, then x_1 either partially overlaps x_3 or is a tangential or non-tangential proper part of x_3." Under natural interpretations of the operative notions, this seems to be a piece of folk-topology we can all agree on.

Informal glosses and folk-topology, however, are not fruitful objects of mathematical study. Rather, we give the non-logical primitives precise interpretations, proceeding as follows. Fix a frame (T, S) in RegC. An *interpretation* $\Im$ over (T, S) is a function mapping each variable x to an element $x^{\Im}$ of S. The idea is that an interpretation determines the truth or falsity of any formula by means of a fixed set of semantic rules. Writing $\Im \models \varphi$ to indicate that φ is true under the interpretation $\Im$, we may specify the precise meanings of the RCC8-primitives as follows:

$$\Im \models \text{DC}(x_1, x_2) \text{ iff } x_1^{\Im} \cap x_2^{\Im} = \emptyset$$

$$\Im \models \text{EC}(x_1, x_2) \text{ iff } x_1^{\Im} \cap x_2^{\Im} \neq \emptyset \text{ and } (x_1^{\Im})^0 \cap (x_2^{\Im})^0 = \emptyset$$

$$\Im \models \text{PO}(x_1, x_2) \text{ iff } x_1^{\Im} \setminus x_2^{\Im} \neq \emptyset, x_2^{\Im} \setminus x_1^{\Im} \neq \emptyset \text{ and } (x_1^{\Im})^0 \cap (x_2^{\Im})^0 \neq \emptyset$$

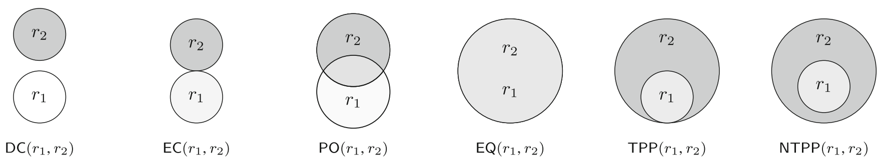

Fig. 2 RCC8-relations over discs in the Euclidean plane

and similarly for EQ, TPP and NTPP. Thus: two regions are in the relation DC if they have no points in common; they are in the relation EC if they have points in common, but their interiors do not; they are in the relation PO if each has points not contained in the other, and in addition their interiors have points in common; and so on. This truth-definition is extended to all RCC8-formulas by means of the usual truth tables for $\wedge$, $\vee$, $\rightarrow$, and $\neg$. These semantics seem rather arbitrary at first sight: however, it turns out that for regular closed sets, they naturally partition the space of possibilities: any two non-empty regular closed sets satisfy (in some order) exactly one of the RCC8-predicates. An RCC8-formula φ is *satisfiable* over a frame (T, S) if there is an interpretation $\Im$ over (T, S) such that $\Im \models \varphi$; and φ is *satisfiable* over a class of frames K if φ is satisfiable over some frame in K. Dually, we say that φ is *valid* over (T, S) if $\neg\varphi$ is not satisfiable over (T, S); and φ is *valid* over a class of frames K if it is valid over every frame in K. These notions are directly motivated by considerations in qualitative spatial reasoning: if we think of K as our mathematical model of some class of spaces an RCC8-equipped agent might conceivably inhabit, then the set of formulas valid over K constitutes that agent's (potential) geometrical understanding of his environment. It is easy to verify that the formula (1) is valid over the frame class RegC (and hence over any smaller frame class). Thus, the above semantic framework transforms the statement in question from an intuitive hunch into a mathematical fact.

A second example will illustrate the flexibility of this framework. In RCC8, it is impossible to *combine* regions to form larger (or smaller) ones; and it is natural to wonder what happens when this facility is provided. Since the variables of RCC8 are assumed to range over regular closed sets, and since these form a Boolean algebra, a particularly obvious set of region-combinators presents itself. Let the language BRCC8 (for *Boolean* RCC8) be defined as follows. As before, we take a countably infinite set of variables. A *term* of BRCC8 is any expression formed from the variables, the constants 0 and 1, the unary function $-$ and the binary functions $+$ and $\cdot$. An *atomic formula* is an expression of the form $R(\tau_1, \tau_2)$, where R is one of the six RCC8-predicates and τ_1, τ_2 are BRCC8-terms; and the *formulas* are again combinations of atomic BRCC8-formulas in propositional logic. Thus, for example,

$$\mathrm{EC}(x_1 + x_2, x_3) \rightarrow \mathrm{EC}(x_1, x_3) \vee \mathrm{EC}(x_2, x_3) \tag{2}$$

is a BRCC8-formula. Informally, it says: "If x_1, x_2 and x_3 are regions such that the region formed by aggregating x_1 and x_2 externally contacts x_3, then at least one of x_1 and x_2 externally contacts x_3." As with RCC8, so with BRCC8, we give a formal semantics to justify such glosses. Specifically, we extend any interpretation $\Im$ (over a space T) from variables to terms in the standard way, thus:

$$1^{\Im} = T \qquad (\tau_1 + \tau_2)^{\Im} = \tau_1^{\Im} + \tau_2^{\Im} \qquad (-\tau)^{\Im} = -(\tau^{\Im}).$$

$$0^{\Im} = \varnothing \qquad (\tau_1 \cdot \tau_2)^{\Im} = \tau_1^{\Im} \cdot \tau_2^{\Im}$$

In words: "0" denotes the empty region; "1" denotes the entire space; "$\tau_1 + \tau_2$" denotes the region formed by aggregating the regions denoted by τ_1 and τ_2; and so on. And we assign truth-values to atomic (hence, to all) formulas exactly as for RCC8. The notions of satisfiability and validity of BRCC8-formulas are again defined as before. Under these semantics, the formula (2) is valid over the frame class RegC.

The languages RCC8 and BRCC8 feature only the logical syntax of propositional logic. But, of course, there is no reason why we should not also consider languages with an expanded—or indeed contracted—logical syntax. For example, the atomic formulas of RCC8 can be combined with the syntax of first-order logic (thus allowing formulas to *quantify* over regions) to yield a more expressive language, which we can sensibly interpret over any class of frames included in RegC. More generally, let L be any language with a signature of primitives interpreted, in a standard way, as topological operations and relations on regions. Let K be a class of frames. The pair (L, K) is a *topological logic*. Given any topological logic, (L, K), we denote by $\mathrm{Sat}(L, K)$ the set of L-formulas that are satisfiable over K. Perhaps the most salient problem arising in connection with any topological logic is the problem of determining its satisfiable (dually: its valid) formulas. However, there are many other intriguing problems to settle, as we shall see in particular in Sect. 4.

The above conceptual scheme—with its strongly semantic flavour—emerged only gradually in the study of qualitative spatial reasoning, and supersedes the earliest approaches to the subject, which relied heavily on axiom systems and logical calculi; for an early example of this new, semantic approach, see (Nutt 1999). The reader may be surprised by the degree of generality involved. After all, from the point of view of Artificial Intelligence, the spaces we are principally interested in are $\mathbb{R}^2$ and $\mathbb{R}^3$: why, therefore, the talk of general topological spaces and satisfiability over frame classes? This point is well-taken: in the sequel we shall indeed be very much concerned with the regular closed sets in the Euclidean plane and in three-dimensional Euclidean space, because these frames represent obvious models of space for an agent operating in a two-dimensional (respectively, three-dimensional) environment. Nevertheless, as we shall see, from a mathematical point of view, the satisfiability problem for topological languages over more general frame classes repays careful study—particularly when the language in question is very inexpressive.

3 Topological Constraint Languages

By a *topological constraint language*, we mean a topological language featuring no quantifiers: that is, one whose syntax is confined to that of propositional logic. Thus, RCC8 and BRCC8 are both topological constraint languages. In this section, we consider various *satisfiability problems*, $\mathrm{Sat}(L, K)$, were L is a topological constraint language, and K some class of frames. The following (standard) terminology will be useful. If φ is a formula with (free) variables $x_1, x_2, \ldots, x_k$, in some order, and $\Im$ is an interpretation over some frame (T, S) such that $\Im \models \varphi$, we say that the tuple of regions $r_i = x_i^{\mathfrak{I}}$ $(1 \leq i \leq k)$ *satisfies* $\varphi(x_1, x_2, \ldots, x_k)$. We typically use letters r_1, r_2, r_3 … to range over regions in some frame.

We begin with $L =$RCC8. This case is straightforward, not least because, as was quickly realized, RCC8 is almost completely *in*sensitive to the frame class over which it is interpreted (Renz 1998). Thus, for example, if an RCC8-formula is satisfiable over the class RegC, then it is easily seen to be satisfiable over the regular closed sets in Euclidean space of any dimension. In symbols, $\text{Sat}(\text{RCC8}, \text{RegC}) = \text{Sat}(\text{RCC8}, \text{RC}(\mathbb{R}^n))$ for all $n \geq 1$. (Note that, to reduce notational clutter, we here identify singleton frame classes with their members: thus, for example, we write $\text{Sat}(\text{RCC8}, \text{RC}(\mathbb{R}^n))$ rather than the technically more correct $\text{Sat}(\text{RCC8}, \{\text{RC}(\mathbb{R}^n)\})$.) The reason for this insensitivity is simply that, given a tuple satisfying an RCC8-formula φ over an arbitrary topological space, we can embed that tuple into $\text{RC}(\mathbb{R}^n)$ in such a way as to preserve all RCC8-predicates. Indeed, we can insist that the embedded sets satisfy additional properties which make them mathematically well-behaved (more on this below); however, in dimensions 1 and 2, we cannot insist that the embedding preserves connectedness of sets. There is a particularly straightforward algorithm for determining satisfiability of a conjunction of RCC8-atoms, based on saturation under a finite collection of rules of the form

$$R(x_1, x_2) \wedge S(x_2, x_3) \rightarrow (T_1(x_1, x_3) \vee \cdots \vee T_k(x_1, x_3))$$

as outlined in (Bennett 1997). (For constraint-satisfaction experts: this method is tantamount to determining 'path-consistency' using a rectangular table of 'products' of relations.) We remark in passing that the valid formula (1) is an example of such a rule. Analysis of this algorithm shows that the problem of determining satisfiability for conjunctions of RCC8-atoms is NLogSpace-complete (Griffiths 2008); hence, $\text{Sat}(\text{RCC8}, \text{RegC})$ is NP-complete, though various tractable fragments have been investigated (Renz 1999; Renz and Nebel 1999, 2001, 2007).

The more expressive BRCC8 has somewhat greater discriminative capacity. For example, the BRCC8-formula

$$\neg\text{DC}(x_1, x_1) \wedge \neg\text{DC}(-x_1, -x_1) \wedge \text{DC}(x_1, -x_1) \tag{3}$$

is satisfiable over certain frames of the form $\text{RC}(T)$ where T is a topological space, but *only* if T is not connected: for example, if T consists of two separated spheres. In particular (3) is not satisfiable over $\text{RC}(\mathbb{R}^n)$ for any $n \geq 1$; and of course these are the spaces that we are most interested in. However, this is essentially the *only* respect in which BRCC8 is sensitive to the domain of interpretation: denoting by ConRegC the class of frames of the form $\text{RC}(T)$ where T is a *connected* topological space, the problems $\text{Sat}(\text{BRCC8}, \text{ConRegC})$ and $\text{Sat}(\text{BRCC8}, \text{RC}(\mathbb{R}^n))$ coincide, for all $n \geq 1$. It is shown in (Wolter and Zakharyaschev 2000) that $\text{Sat}(\text{BRCC8}, \text{RegC})$ is NP-complete, and that $\text{Sat}(\text{BRCC8}, \text{ConRegC})$ is PSpace-complete.

Before proceeding, we take this opportunity to reformulate BRCC8 in a more elegant way. Let us take the binary predicate C to denote the *contact* relation—holding between regular closed sets r_1 and r_2 just in case $r_1 \cap r_2 \neq \emptyset$. Formally, we specify its semantics as follows:

$$\Im \models C(\tau_1, \tau_2) \text{ iff } \tau_1^{\Im} \cap \tau_2^{\Im} \neq \emptyset,$$

where τ_1 and τ_2 range over BRCC8-terms. Thus: $C(\tau_1, \tau_2)$ is nothing more than a re-writing of $\neg\text{DC}(\tau_1, \tau_2)$. In addition, let us re-write $\text{EQ}(\tau_1, \tau_2)$ using the more conventional notation $\tau_1 = \tau_2$. Then it is easy to check that all RCC8-predicates can be defined in terms of C, = and the usual Boolean operations on regions:

$$\text{DC}(\tau_1, \tau_2) \equiv \neg C(\tau_1, \tau_2)$$

$$\text{EC}(\tau_1, \tau_2) \equiv C(\tau_1, \tau_2) \wedge (\tau_1 \cdot \tau_2 = 0)$$

$$\text{PO}(\tau_1, \tau_2) \equiv (\tau_1 \cdot \tau_2 \neq 0) \wedge (-\tau_1 \cdot \tau_2 \neq 0) \wedge (\tau_1 \cdot -\tau_2 \neq 0)$$

and similarly for EQ, TPP and NTPP. Denoting the topological constraint language with primitives C, $=$, $+$, $\cdot$, $-$, 0 and 1 by C, we see that C is expressively equivalent to BRCC8. Henceforth, then, we shall speak of C rather than the more cumbersome BRCC8. Further, by dropping the predicate C, we obtain the language with primitives $=$, $+$, $\cdot$, $-$, 0 and 1, here denoted by B. This language is too weak to be of any topological interest; however, some of its extensions, which we shall encounter below, are not; and so it will be useful to retain it in our inventory of topological constraint languages. Observe that C is strictly more expressive than both RCC8 and B, but that B and RCC8 are expressively incomparable.

We have seen that the languages RCC8, B and C (alias BRCC8) are relatively insensitive to the class of spaces over which they are interpreted: the set of satisfiable formulas is the same for (virtually) any interesting frame. For more expressive languages, however, matters change dramatically. Let c and c^0 be unary predicates. We read $c(\tau)$, where τ is any term, as "τ is connected", and $c^0(\tau)$ as "τ has a connected interior". It will be convenient in the sequel to call a region *interior-connected* if it has a connected interior. Let RCC8c, Bc and Cc be the languages obtained by adding c to the languages RCC8, B and C, respectively; and similarly for RCC8c^0, Bc^0 and Cc^0. The formal syntax is defined in the obvious way; the semantics are given using rules similar to those for the RCC8-predicates:

$$\Im \models c(\tau) \text{ iff } \tau^{\Im} \text{ is connected}$$

$$\Im \models c^0(\tau) \text{ iff } \tau^{\Im} \text{ is interior-connected}$$

These new languages discriminate very easily between different frames. Consider, for example, the language Bc^0. The formula

$$\bigwedge_{1 \leq i \leq 3} (x_i \neq 0 \wedge c^0(x_i)) \wedge \bigwedge_{1 \leq i < j \leq 3} (x_i \cdot x_j = 0 \wedge c^0(x_i + x_j))$$

is satisfiable over $\mathrm{RC}(\mathbb{R}^n)$ for $n \geq 2$, but not over $\mathrm{RC}(\mathbb{R})$, since no three intervals on the line can form pairwise connected sums without overlapping. Likewise, the formula

$$\bigwedge_{1 \leq i \leq 5} (x_i \neq 0 \wedge c^0(x_i)) \wedge \bigwedge_{1 \leq i < j \leq 5} (x_i \cdot x_j = 0 \wedge c^0(x_i + x_j))$$

is satisfiable over $\mathrm{RC}(\mathbb{R}^n)$ for $n \geq 3$, but not over $\mathrm{RC}(\mathbb{R}^2)$, since any satisfying assignment over $\mathrm{RC}(\mathbb{R}^2)$ would permit a planar embedding of the pentagram. Thus, the problems $\mathrm{Sat}(\mathrm{Bc}^0, \mathrm{RC}(\mathbb{R}^n))$ are different for $n = 1, 2, 3$. This ability to differentiate between dimensions illustrates the greater expressive power provided by c and c^0.

Even when we limit attention to two- and three-dimensional Euclidean space, the languages Bc and Bc^0 bring into focus a subtle issue concerning the most appropriate choice of frames over those spaces. To understand this issue, we begin by observing that among the regular closed sets in $\mathbb{R}^2$ and $\mathbb{R}^3$ are regions that could not possibly correspond to the space occupied by ordinary objects. In particular, it is obvious that regular closed sets may have infinitely many components, and only slightly less obvious that they may lack well-behaved boundaries, as illustrated by the regions r_2 and r_3 depicted in Fig. 3. Thus, it is reasonable to seek a class of regions immune to these pathologies. Here is one solution. Any $(n-1)$-dimensional hyperplane in $\mathbb{R}^n$ divides the space into two regular closed sets, which we call *half-spaces*. We take the *regular closed polyhedra* in $\mathbb{R}^n$, denoted $\mathrm{RCP}(\mathbb{R}^n)$, to be the Boolean subalgebra of $\mathrm{RC}(\mathbb{R}^n)$ finitely generated by the half-spaces. When $n = 2$, we speak of *regular closed polygons*. Every regular closed polyhedron has finitely many components and a well-behaved boundary (in a sense we discuss in detail below). The frame $\mathrm{RCP}(\mathbb{R}^n)$ thus provides an alternative to $\mathrm{RC}(\mathbb{R}^n)$ when interpreting topological languages.

It is easy to see that the language C is insensitive to the distinction between arbitrary regular closed sets and regular closed polyhedra: that is, $\mathrm{Sat}(\mathrm{C}, \mathrm{RC}(\mathbb{R}^n)) = \mathrm{Sat}(\mathrm{C}, \mathrm{RCP}(\mathbb{R}^n))$ for all $n \geq 1$. However, matters change when the predicates c and c^0 become available. Consider, for example, the Bc^0-formula:

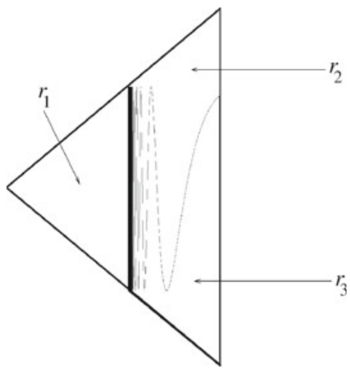

Fig. 3 A triple of regions r_1, r_2, r_3 in $\mathrm{RC}(\mathbb{R}^2)$satisfying (4)

$$\bigwedge_{i=1}^{3} c^0(x_i) \wedge c^0\left(\sum_{i=1}^{3} x_i\right) \wedge \neg c^0(x_1 + x_2) \wedge \neg c^0(x_1 + x_3). \tag{4}$$

The arrangement of Fig. 3, where r_2 and r_3 are separated by the graph of the function $\sin(1/x)$ on the interval (0,1], shows that this formula is satisfiable over $\mathrm{RC}(\mathbb{R}^2)$, and hence—by cylindrification—over $\mathrm{RC}(\mathbb{R}^n)$ for all $n \geq 2$. However, it can also be shown that (4) is unsatisfiable over $\mathrm{RCP}(\mathbb{R}^n)$ for all $n \geq 1$. Hence, for all $n \geq 2$, $\mathrm{Sat}(\mathrm{Bc}^0, \mathrm{RC}(\mathbb{R}^n))$ and $\mathrm{Sat}(\mathrm{Bc}^0, \mathrm{RCP}(\mathbb{R}^n))$ are distinct. To summarize: the language Bc^0 is sufficiently expressive that it can distinguish between dimensions 1, 2 and 3, and can distinguish between the regular closed sets and the regular closed polyhedra in all dimensions above 1. We remark in passing that Bc^0 cannot distinguish between $\mathrm{RC}(\mathbb{R})$ and $\mathrm{RCP}(\mathbb{R})$, though the more expressive language Cc^0 can.

Turning our attention from c^0 to c, it can be shown that the problems $\mathrm{Sat}(\mathrm{Bc}, \mathrm{RC}(\mathbb{R}^n))$ are again different for $n = 1, 2, 3$. (The arguments are similar to those required for Bc^0.) Less obviously, for all $n \geq 2$, $\mathrm{Sat}(\mathrm{Bc}, \mathrm{RC}(\mathbb{R}^n))$ and $\mathrm{Sat}(\mathrm{Bc}, \mathrm{RCP}(\mathbb{R}^n))$ are also distinct. More precisely: it is shown in (Kontchakov et al. 2011) that there is a Bc-formula φ_∞ with variables $x_1, \ldots, x_k$ having the following properties for all $n \geq 2$: (*i*) it is satisfiable over $\mathrm{RC}(\mathbb{R}^n)$; (*ii*) if $r_1, \ldots, r_k$ is any tuple from $\mathrm{RC}(\mathbb{R}^n)$ satisfying φ_∞, then the first element, r_1, has infinitely many components. That $\mathrm{Sat}(\mathrm{Bc}, \mathrm{RC}(\mathbb{R}^n)) \neq \mathrm{Sat}(\mathrm{Bc}, \mathrm{RCP}(\mathbb{R}^n))$ for $n \geq 2$ then follows from the fact that polyhedra all have finitely many components. Summarizing again: the language Bc—hence also Cc—is sufficiently expressive that it can distinguish between dimensions 1, 2 and 3, and can distinguish between the regular closed sets and the regular closed polyhedra in all dimensions above 1. We remark in passing that forcing regions to have infinitely many components using the language Bc^0 is trickier. For $n = 1$ or $n \geq 3$ there is no satisfiable Bc^0-formula which forces infinitely many components, in the sense of φ_∞; but for $n = 2$, such a formula does exist (Kontchakov et al. 2011). However, as noted above, we already know from the formula (4) that $\mathrm{Sat}(\mathrm{Bc}^0, \mathrm{RC}(\mathbb{R}^n)) \neq \mathrm{Sat}(\mathrm{Bc}^0, \mathrm{RCP}(\mathbb{R}^n))$ for all $n \geq 2$.

What of RCC8c and $\mathrm{RCC8c}^0$? Using similar techniques to those described above, it is routine to show that the problems $\mathrm{Sat}(\mathrm{RCC8c}, \mathrm{RC}(\mathbb{R}^n))$ are distinct for $n = 1, 2, 3$: and likewise for $\mathrm{Sat}(\mathrm{RCC8c}^0, \mathrm{RC}(\mathbb{R}^n))$. Further, it is shown in (Kontchakov et al. 2010b) that $\mathrm{Sat}(\mathrm{RCC8c}, \mathrm{RC}(\mathbb{R}))$ and $\mathrm{Sat}(\mathrm{RCC8c}, \mathrm{RCP}(\mathbb{R}))$ are distinct, but that $\mathrm{Sat}(\mathrm{RCC8c}, \mathrm{RC}(\mathbb{R}^n)) = \mathrm{Sat}(\mathrm{RCC8c}, \mathrm{RCP}(\mathbb{R}^n))$ for all $n \geq 2$. (The equation is non-trivial only in the case $n = 2$.) For $\mathrm{RCC8c}^0$, the picture is incomplete. It is trivial to show that the problems $\mathrm{Sat}(\mathrm{RCC8c}^0, \mathrm{RC}(\mathbb{R}^n))$ and $\mathrm{Sat}(\mathrm{RCC8c}^0, \mathrm{RCP}(\mathbb{R}^n))$ are identical for all $n \geq 3$. However, at the time of writing, it is not known whether $\mathrm{Sat}(\mathrm{RCC8c}^0, \mathrm{RC}(\mathbb{R}^2)) = \mathrm{Sat}(\mathrm{RCC8c}^0, \mathrm{RCP}(\mathbb{R}^2))$.

In the wake of this increased discriminative power comes, as so often, increased complexity of satisfiability for most domains of interest. We consider general topolgical spaces first. It is trivial to show that the problems $\mathrm{Sat}(\mathrm{RCC8c}, \mathrm{RegC})$,

$\text{Sat}(\text{RCC8c}^0, \text{RegC})$ and $\text{Sat}(\text{Bc}^0, \text{RegC})$ are all NP-complete. On the other hand, if L is any of the languages Bc, Cc or Cc^0, then $\text{Sat}(L, \text{RegC})$ is ExpTime-complete (Kontchakov et al. 2010a). Over this class of domains, these languages all have an exponential-sized model property: if a formula φ is satisfiable in $(T, \text{RC}(T))$ for some topological space T, then φ is satisfiable in $(T, \text{RC}(T))$ for some topological space T of size bounded by an exponential function of the number of symbols in φ. (It is known that this is the best bound possible.)

We turn our attention now to the complexity of satisfiability over frames on the Euclidean spaces $\mathbb{R}^n$ $(n \geq 1)$. The case $n = 1$ is easy to analyse. It is shown in (Kontchakov et al. 2010b) that $\text{Sat}(\text{Bc}, \text{RC}(\mathbb{R}))$ (= $\text{Sat}(\text{Bc}, \text{RCP}(\mathbb{R}))$ is NP-complete; likewise, the (distinct) problems $\text{Sat}(\text{RCC8c}, \text{RC}(\mathbb{R}))$ and $\text{Sat}(\text{RCC8c}, \text{RCP}(\mathbb{R}))$ are NP-complete; on the other hand, $\text{Sat}(\text{Cc}, \text{RC}(\mathbb{R}))$ and $\text{Sat}(\text{Cc}, \text{RCP}(\mathbb{R}))$ are PSpace-complete. The case $n = 2$ is much more challenging, and the picture here not quite complete. We consider first the languages RCC8c and RCC8c^0. Very surprisingly (Schaefer et al. 2003) showed that the satisfiability problem for RCC8, interpreted over *disc-homeomorphs* in the plane, is NP-complete. Using this result (Kontchakov et al. 2010b) showed that $\text{Sat}(\text{RCC8c}, \text{RC}(\mathbb{R}^2))= \text{Sat}(\text{RCC8c}, \text{RCP}(\mathbb{R}^2))$ is NP-complete. It is also shown in (Griffiths 2008), again by reduction to the result in (Schaefer et al. 2003), that $\text{Sat}(\text{RCC8c}^0, \text{RCP}(\mathbb{R}^2))$ is NP-complete. Intriguingly, it is not known whether $\text{Sat}(\text{RCC8c}^0, \text{RC}(\mathbb{R}^2))$ is decidable. By contrast, if L is any of the languages Bc, Bc^0, Cc or Cc^0, then it is known that $\text{Sat}(L, \text{RC}(\mathbb{R}^2))$ is r.e.-hard, and that $\text{Sat}(L, \text{RCP}(\mathbb{R}^2))$ is r.e.-complete (Kontchakov et al. 2011). That is: all these satisfiability problems are undecidable. It is worth dwelling briefly on these last results. The language Bc involves apparently very modest expressive resources—just the ability to say that a region is connected or that two regions are equal, and to combine regions in the regular closed algebra; similarly with Bc^0. It is difficult to imagine, *pace* the enthusiasts for RCC8, a useful topological representation language of more slender means. Yet, remarkably, even these expressive resources suffice for undecidability in the Euclidean plane.

Finally, we consider Euclidean spaces of dimension 3 or more. Trivially, for $n \geq 3$, $\text{Sat}(\text{RCC8c}, \text{RC}(\mathbb{R}^n)) = \text{Sat}(\text{RCC8c}, \text{RCP}(\mathbb{R}^n))$ is NP-complete; similarly with RCC8c^0. Of the remaining languages, the picture is complete only in regard of Bc^0: for $n \geq 3$, the problems $\text{Sat}(\text{Bc}^0, \text{RCP}(\mathbb{R}^n))$ all coincide, and are ExpTime-complete; further, for $n \geq 3$, the problems$\text{Sat}(\text{Bc}^0, \text{RC}(\mathbb{R}^n))$ all coincide, and are NP-complete (Kontchakov et al. 2011). It goes without saying that these decidability results are not a cause for jubilation: they just reflect the expressive poverty of these languages over space of dimension 3 or more. At the time of writing, it is not known whether any of the problems $\text{Sat}(L, \text{RC}(\mathbb{R}^n))$ or $\text{Sat}(L, \text{RCP}(\mathbb{R}^n))$ for L one of Bc, Cc or Cc^0, and $n \geq 3$, is decidable; though they are certainly ExpTime-hard. The results of this section are summarized in Table 1. All complexity bounds are tight, except for lower bounds, which are indicated with $\geq$.

Table 1 Complexity of satisfiability for topological constraint languages

	$\mathbb{R}$		$\mathbb{R}^2$		$\mathbb{R}^3$	
	RCP	RC	RCP	RC	RCP	RC
RCC8c	NP	NP	NP		NP	
RCC8c^0			NP	$\geq$ NP		
Bc	NP		Undec	Undec	$\geq$ Exp	$\geq$ Exp
Bc^0			Undec	Undec	Exp	NP
Cc	PSpace	PSpace	Undec	Undec	$\geq$ Exp	$\geq$ Exp
Cc^0			Undec	Undec	$\geq$ Exp	$\geq$ Exp

4 First-Order Topological Languages

The topological languages we considered in the previous section were all limited to straightforward Boolean combinations of assertions about spatial regions. In this section, we turn to topological languages in which formulas can *quantify* over regions. The logical characteristics of such languages are well-understood; and we survey what is known about them here.

We denote by L_{c^0} the first-order language over the signature $\{c^0, +, \cdot, -, 0, 1\}$, and by L_C the first-order language over the signature $\{C, +, \cdot, -, 0, 1\}$. (It is understood that these languages include the equality predicate.) Thus, L_{c^0} is the first-order extension of Bc^0, and L_C is the first-order extension of C, with the standard quantifiers $\forall$ and $\exists$ available. There is little point in considering first-order topological languages with the other signatures considered in Sect. 3, since, over the domains of greatest interest, it principally matters only whether that signature contains the predicate c^0 or the predicate C. The satisfiability problems for these languages, over a wide range of frame classes, are undecidable—as shown by (Grzegorczyk 1951); but see also (Dornheim 1998). Of course, for the frames RC($\mathbb{R}^2$) and RCP($\mathbb{R}^2$), this also follows from the much stronger undecidability results reported in Sect. 3. Therefore, it is on matters other than the complexity of satisfiability that we must concentrate our attention. The following (standard) terminology and notation will be useful. Suppose L is a first-order topological language, and S a frame. A *sentence* of L is a formula with no free variables; the notions of *satisfaction* of L-formulas by tuples of regions from S, and of *truth* of L-sentences in S are understood via the standard semantics of first-order logic. As usual, we write $S \models \varphi[\bar{r}]$ if the tuple $\bar{r} = r_1, \ldots, r_k$ satisfies $\varphi(x_1, \ldots, x_k)$ in S; and when φ has no free variables, we write $S \models \varphi$ if φ is true in S. The *L-theory* of S is the set of L-sentences true in S; the *L-theory* of a frame class K is the set of L-sentences true in every frame of K.

One of the most natural questions regarding first-order topological languages is whether the theories of various frames (or classes of frames) can be axiomatically characterized. That is, we would like a system of axioms and rules of inference whose theorems are exactly the valid formulas of the frame. (In the context of Qualitative Spatial Reasoning, one imagines an intelligent agent whose geometrical knowledge is obtained by means of a theorem-prover operating on these axioms and rules of inference.) We begin by defining a very general frame class (essentially of purely mathematical interest) for which we will be able to provide an axiomatization for the language L_C. To motivate our definition, recall that the frame $\mathrm{RCP}(\mathbb{R}^n)$ contains only a selection of the elements of $\mathrm{RC}(\mathbb{R}^n)$. However, this selection is not arbitrary: first, $\mathrm{RCP}(\mathbb{R}^n)$ forms a Boolean algebra; second, it represents all parts of the space, in the sense that, for any point p and any open set o containing p, there exists $r \in \mathrm{RCP}(\mathbb{R}^n)$ such that $p \in r \subseteq o$. (In technical parlance, we say that the sets $\{r^0 \mid r \in \mathrm{RCP}(\mathbb{R}^n)\}$ *form a basis for the topology on* $\mathbb{R}^n$.) Generalizing, if T is any topological space, we say that a *mereotopology* (*on* T) is a Boolean subalgebra M of $\mathrm{RC}(T)$ such that the sets $\{r^0 \mid r \in M\}$ form a basis for T. Thus, $\mathrm{RC}(\mathbb{R}^n)$ and $\mathrm{RCP}(\mathbb{R}^n)$ are mereotopologies on $\mathbb{R}^n$, for all $n \geq 1$. It turns out that the class of *all* mereotopologies constitutes an interesting class of frames from the point of view of axiomatization.

A *Boolean connection algebra* (hereinafter: *BCA*) is any structure interpreting the signature $\{C, +, \cdot, -, 0, 1\}$ and satisfying:

$$\text{The usual axioms of Boolean algebra} \tag{5}$$

$$\forall x_1 \neg C(x_1, 0) \tag{6}$$

$$\forall x_1 (x_1 \neq 0 \rightarrow C(x_1, x_1)) \tag{7}$$

$$\forall x_1 \forall x_2 (C(x_1, x_2) \rightarrow C(x_2, x_1)) \tag{8}$$

$$\forall x_1 \forall x_2 \forall x_3 (C(x_1, x_2) \wedge x_2 \leq x_3 \rightarrow C(x_1, x_3)) \tag{9}$$

$$\forall x_1 \forall x_2 \forall x_3 (C(x_1, x_2 + x_3) \rightarrow C(x_1, x_2) \vee C(x_1, x_3)). \tag{10}$$

It is routine to check that all mereotopologies are BCAs; conversely, it was shown in (Dimov and Vakarelov 2006) that any BCA is isomorphic to a mereotopology on some topological space or other. Thus (5)–(10) completely axiomatize the first-order L_C-theory of the class of mereotopologies. Indeed, the relationship between BCAs and mereotopologies goes deeper than we can usefully discuss here (de Vries 1962; Roeper 1997; Düntsch and Winter 2005).

However, it is not very general, abstract, frame classes that most interest us, but rather, very specific, concrete ones—in particular, singleton frame classes over low-dimensional Euclidean spaces. Are there any mereotopologies over $\mathbb{R}^2$ or $\mathbb{R}^3$ whose first-order theories can be axiomatized? Results are available here too: in particular, the L_{c^0}-theory of the mereotopology $\mathrm{RCP}(\mathbb{R}^2)$ is axiomatized in (Pratt-Hartmann 2007). The axiomatization in question features various axioms and rules of inference: for example, one of the axioms is

$$\forall x_1 \forall x_2 \forall x_3 \left(\bigwedge\nolimits_{i=1}^{3} c^0(x_i) \wedge c^0\left(\sum_{i=1}^{3} x_i\right) \rightarrow (c^0(x_1 + x_2) \vee c^0(x_1 + x_3)) \right), \tag{11}$$

stating that the configuration described in the formula (4) cannot occur. (This axiom is a true statement in the frame $\mathrm{RCP}(\mathbb{R}^2)$, though it is false in $\mathrm{RC}(\mathbb{R}^2)$.) In addition to these axioms, the underlying proof-system incorporates a special rule of inference in which a formula is inferred from an *infinite* collection of antecedents. Specifically, the rule in question states that if, for all m, it can be proved that every element which is the sum of m interior-connected regions has some property φ, then any element whatsoever has that property. In symbols:

$$\frac{\left\{\forall x(\exists x_1 \ldots \exists x_m (x = \sum_{i=1}^{m} x_i \wedge \bigwedge_{i=1}^{m} c^0(x_i)) \rightarrow \varphi) \geq 1\right\}}{\forall x \varphi}. \tag{12}$$

This rule is clearly valid in $\mathrm{RCP}(\mathbb{R}^2)$, because every polygon is the sum of finitely many interior-connected polygons. A similar axiomatization of the L_C-theory of the mereotopology $\mathrm{RCP}(\mathbb{R}^2)$ is given in (Schoop 1999). However, there is so far no comparable account of the first-order theory of $\mathrm{RC}(\mathbb{R}^2)$, in any interesting topological signature.

Why might we be interested in such axiomatizations? Here is one reason. We have observed that the Bc^0-formula (11) belongs to the first-order L_{c^0}-theory of $\mathrm{RCP}(\mathbb{R}^2)$, but not to the first-order L_{c^0}-theory of $\mathrm{RC}(\mathbb{R}^2)$. That is: restricting attention to the regular closed polygons changes the theory of space as described by the language L_{c^0}. How general is this phenomenon? Do other reasonable restrictions produce yet more theories? Is there any end to the theories that we can obtain by being suitably selective in the regions we are prepared to quantify over? Axiomatizations of the kind just discussed can help us answer such questions.

Specifically, it transpires that, notwithstanding the fact that $\mathrm{RCP}(\mathbb{R}^2)$ and $\mathrm{RC}(\mathbb{R}^2)$ have different L_{c^0}-theories, the possibilities for generating new theories by varying the set of subsets of $\mathbb{R}^2$ we are prepared to count as regions are very limited. This can be shown very simply using the complete axiomatization of the L_{c^0}-theory of $\mathrm{RCP}(\mathbb{R}^2)$ mentioned above: we examine the conditions under which its axioms are true and its special rule of inference is valid, and conclude that *any* frame over $\mathbb{R}^2$ conforming to these conditions must have the same L_{c^0}-theory. Consider, for example, the formula (11), which, as we observed, holds for $\mathrm{RCP}(\mathbb{R}^2)$ but not for $\mathrm{RC}(\mathbb{R}^2)$. Let us say that a regular closed set r *has the curve-selection property* if, for any point q in that set, there exists a point p in the interior of r and a continuous arc α from p to q such that α is contained entirely in the interior of r, except possibly for the end-point q; and let us say that a mereotopology M *has the curve-selection property* if every $r \in M$ has. The mereotopology $\mathrm{RC}(\mathbb{R}^2)$ lacks this property (the regions r_2 and r_3 in Fig. 3 are counterexamples); however, it is routine to show that $\mathrm{RCP}(\mathbb{R}^2)$ does have curve-selection for all $n \geq 1$, and that, moreover, curve-selection is precisely the property of mereotopologies over $\mathbb{R}^2$ required for the truth of the axiom (11). Or consider again the infinitary rule of inference (12), which is valid for $\mathrm{RCP}(\mathbb{R}^2)$, but not for $\mathrm{RC}(\mathbb{R}^2)$.

Let us call a mereotopology M *finitely decomposable* if every region of M is the sum of finitely many interior-connected regions in M. The mereotopology $\mathrm{RC}(\mathbb{R}^2)$ is not finitely decomposable; however $\mathrm{RCP}(\mathbb{R}^2)$ is, and, moreover (12) is always valid for finitely decomposable mereotopologies. Curve selection and finite decomposability are reasonable properties to expect of a mereotopology over $\mathbb{R}^2$. It can be shown that any finitely decomposable mereotopology with curve-selection over $\mathbb{R}^2$ (and fulfilling some simple additional technical conditions) must have the same L_{c^0}-theory as $\mathrm{RCP}(\mathbb{R}^2)$. Indeed, this result can be generalized: for any first-order topological language L with at least the expressive power of L_{c^0}, any reasonable mereotopology on $\mathbb{R}^2$ having curve selection and finite decomposability must have the same L-theory as $\mathrm{RCP}(\mathbb{R}^2)$ (Pratt-Hartmann 2007). That is, that set of L-sentences may be regarded as the *standard* L-theory of well-behaved regions in the plane.

Let us turn now to the issue of expressive power. Let T be a topological space, and X, Y subsets of T. We say that X and Y are *similarly situated*, and write $X \sim Y$, if there is a homeomorphism of T onto itself which maps X to Y; this terminology and notation is extended to tuples of sets in the obvious way. Intuitively, similarly situated arrangements of sets may be regarded as topologically fully equivalent. It can be shown that, if M is a mereotopology satisfying certain (unobjectionable) technical properties, and $\varphi(\bar{x})$ a formula in some topological language, then for all similarly situated pairs of tuples $\bar{r}$ and $\bar{s}$ (of the appropriate arity), $M \models \varphi[\bar{r}]$ if and only if $M \models \varphi[\bar{s}]$. That is: over reasonable mereotopologies, topological languages can express only properties that are preserved under homeomorphic images. We regard this observation as providing an upper bound on the expressive power of topological logics.

This leads us to consider lower bounds on expressive power. We concentrate on the domains $\mathrm{RCP}(\mathbb{R}^2)$ and $\mathrm{RCP}(\mathbb{R}^3)$, for which interesting results have been obtained. A straightforward counting argument shows that no converse of the result of the previous paragraph can hold: there are uncountably many topological properties and relations over $\mathrm{RCP}(\mathbb{R}^n)$, and only countably many formulas in the languages under consideration; hence some topological properties and relations must be inexpressible. But we can have the next best thing. Let M be a mereotopology on some space T, and L a topological language. We say that an L-formula $\varphi(\bar{x})$ is *topologically complete* in M if, for all tuples $\bar{r}$ and $\bar{s}$ of the appropriate arity, $M \models \varphi[\bar{r}]$ and $M \models \varphi[\bar{s}]$ implies $\bar{r} \sim \bar{s}$. That is, a topologically complete formula is one that is satisfied by at most one tuple, up to the relation of similar situation. It was shown in (Kuijpers et al. 1995) that, for any tuple $\bar{r}$ in $\mathrm{RCP}(\mathbb{R}^2)$, there exists a topologically complete L_C-formula satisfied by $\bar{r}$ (see also Papadimitriou et al. 1999, Pratt and Schoop 2000). An analogous result was shown for $\mathrm{RCP}(\mathbb{R}^3)$ in (Pratt and Schoop 2002). In other words, the language L_C is sufficiently expressive that any tuple of regular closed polygons can be characterized up to topological equivalence by one of its formulas; similarly for regular closed polyhedra in $\mathbb{R}^3$. The language L_{c^0}, by contrast, lacks this degree of expressiveness. It is possible to show that there exist elements of $\mathrm{RCP}(\mathbb{R}^2)$ which satisfy no topologically complete $\mathcal{L}_{c^0}$-formula. As a corollary, we see that $\mathcal{L}_{c^0}$ lacks the expressive power to define the contact-relation, C, over $\mathbb{R}^2$. By contrast, it is easy to define the property of interior-connectedness over $\mathbb{R}^2$ by means of an $\mathcal{L}_C$-formula. Thus, over $\mathrm{RCP}(\mathbb{R}^2)$, $\mathcal{L}_C$ is strictly more expressive than $\mathcal{L}_{c^0}$. Results of this kind illustrate the possibility of determining the relative expressive power of topological languages interpreted over frames on Euclidean spaces.

Finally, we consider the question of alternative models of first-order theories of plane mereotopology. Consider, for definiteness, the $\mathcal{L}_{c^0}$-theory of $\mathrm{RCP}(\mathbb{R}^2)$, and recall that we are invited to think of this theory as the geometrical knowledge of an idealized agent who employs $\mathrm{RCP}(\mathbb{R}^2)$ to represent the space he inhabits. The models of this theory constitute the possible views of space the agent is committed to. What models are these; and how do they relate to the familiar model based on regular closed polygons in the Euclidean plane, with which we began?

The answers are again surprising for the severe limits they place on the models in question. We know that $\mathrm{RCP}(\mathbb{R}^2)$ is not the smallest model of its theory, for the simple reason that it is uncountable. However, we can easily obtain a countable model by considering only those polygons in $\mathbb{R}^2$ whose bounding line-segments are those defined by linear equations with *rational* coefficients. Denote the resulting Boolean subalgebra of $\mathrm{RCP}(\mathbb{R}^2)$ by $\mathrm{RCQ}(\mathbb{R}^2)$. As one might put it, $\mathrm{RCQ}(\mathbb{R}^2)$ is the *next* mereotopology of well-behaved regions, after $\mathrm{RCP}(\mathbb{R}^2)$, that one is likely to think of. It is easy to show that $\mathrm{RCQ}(\mathbb{R}^2)$ and $\mathrm{RCP}(\mathbb{R}^2)$ have the same first-order theories for all topological signatures; and, of course, $\mathrm{RCQ}(\mathbb{R}^2)$ is countable. Less obviously, $\mathrm{RCQ}(\mathbb{R}^2)$ is a *prime* model of its $\mathcal{L}_{c^0}$-theory (Pratt and Lemon 1997): that is, it is elementarily embeddable in any elementarily equivalent model. Intuitively, this means the following: suppose we take an arbitrary model $\mathfrak{A}$ of the $\mathcal{L}_{c^0}$-theory of $\mathrm{RCP}(\mathbb{R}^2)$. (Note that the elements of $\mathfrak{A}$ need not be sets of points in any topological space: they are just objects in some structure.) Contained within $\mathfrak{A}$ is an isomorphic copy $\mathfrak{Q}$ of $\mathrm{RCQ}(\mathbb{R}^2)$, with the property that, if $\bar{r}$ is any tuple of regions from the domain of $\mathfrak{Q}$, then $\bar{r}$ satisfies the same $\mathcal{L}_{c^0}$-formulas in $\mathfrak{A}$ as it does in the smaller model $\mathfrak{Q}$. In other words, the elements outside $\mathfrak{Q}$ are invisible to those inside! Even more follows. Suppose $\mathfrak{A}$ is countable and, in addition, finitely decomposable, in the sense that every element is the sum in $\mathfrak{A}$ of finitely many regions satisfying the predicate c^0 in $\mathfrak{A}$. Then it can be shown that $\mathfrak{A}$ is isomorphic to $\mathrm{RCQ}(\mathbb{R}^2)$. Thus, $\mathrm{RCQ}(\mathbb{R}^2)$ is the unique countable, finitely decomposable structure validating the standard $\mathcal{L}_{c^0}$-theory of well-behaved regions in the plane. Similar results can again be obtained for other topological signatures in (Pratt-Hartmann 2007). Evidently, the class of models of space allowed by the standard theories of well-behaved regions in $\mathbb{R}^2$ is more constrained than one might at first have imagined.

5 Conclusion and Outlook

Topological logic began with the initially enticing idea of describing spatial arrangements by taking the objects of reference (or quantification) to be *regions* (rather than points), and by employing geometrical primitives denoting *qualitative* (rather than quantitative) properties and relations. Hopes were high for, at the very least, a computationally effective medium in which to represent and manipulate spatial knowledge in everyday situations, and perhaps even for a new and conceptually more satisfying spatial ontology than the familiar Cartesian construction of space as the set of triples of real numbers. The pursuit of these ideas led to the semantic framework outlined in Sect. 2, to the complexity-theoretic problems for topological constraint languages discussed in Sect. 3, and to the model-theoretic problems for first-order topological languages discussed in Sect. 4.

Many of these problems have now been solved; and the solutions together paint a mathematical landscape which few could initially have foreseen. Consider, for example, topological constraint languages equipped with a connectedness predicate. All the languages we considered in this category are highly sensitive to the domain of interpretation, and have undecidable satisfiability problems when interpreted over most frames based on the Euclidean plane. Decidability is possible (in some cases) for Euclidean spaces of other dimensions, and (in all cases) for very general frame classes. But, as we saw, these are the cases where the languages in question are too weak to encode any really characteristic features of the space we inhabit. Or consider first-order topological languages over almost any signature. Here, we have expressive power in abundance. Thus, for example, the language L_C is topologically 'lossless' over frames of mathematically well-behaved regions in low-dimensional Euclidean spaces, in the sense that it is able to characterize any tuple of regions up to topological equivalence. Furthermore, the first-order L_{c^0}-theory of $\mathrm{RCP}(\mathbb{R}^2)$ —we called it the *standard* theory—comes so close to determining its models that no interestingly different spatial ontologies to those based on the familiar Euclidean model of space could result.

One lesson to be drawn from this picture is that the original goals of qualitative spatial reasoning were further off than they at first appeared. Those goals will not be achieved simply by switching to an ontology of regions, adopting a vocabulary of topological primitives, and writing down a few likely-looking axioms. This of course, does not mean that the goals were illusory, or unattainable. Rather, it means that we must approach them with a more realistic understanding of what is required—and of what is possible. That the mathematical foundations of qualitative spatial reasoning are now well-understood should stimulate, not inhibit, further development. And while it would be useless to predict the course of that development here, we can be confident that, in the next two decades of research, as in the first two, the finest gems will be discovered in the most unexpected places.

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References

Bennett B (1997) Determining consistency of topological relations. Constraints 3:1–13

Clarke BL (1981) A calculus of individuals based on ‘connection’. Notre Dame J Formal Logic 23:204–218

Clarke BL (1985) Individuals and points. Notre Dame J Formal Logic 26:061–75

de Vries H (1962) Compact spaces and compactifications, an algebraic approach. Van Gorcum & Co. N.V., Assen, Netherlands

Dimov G, Vakarelov D (2006) Contact algebras and region-based theory of space: a proximity approach. Fund. Informaticae 740(2–3):0 209–249

Dornheim C (1998) Undecidability of plane polygonal mereotopology. In: Proceedings of KR’98, Morgan Kaufmann, San Francisco, pp 342–353

Düntsch I, Winter M (2005) A representation theorem for Boolean contact algebras. Theor Comput Sci 347:498–512

Egenhofer M, Franzosa R (1991) Point-set topological spatial relations. Int J Geogr Info Syst 5:161–174

Griffiths A (2008) Computational properties of spatial logics in the real plane. PhD thesis, School of Computer Science, U. Manchester

Grzegorczyk A (1951) Undecidability of some topological theories. Fundamenta Mathematicae 38:137–152

Kontchakov R, Pratt-Hartmann I, Wolter F, Zakharyaschev M (2010a) The complexity of spatial logics with connectedness predicates. Logical Methods Comp Sci 60 (3:7)

Kontchakov R, Pratt-Hartmann I, Zakharyaschev M (2010b) Interpreting topological logics over Euclidean spaces. In Proceedings of KR, AAAI Press, California, pp 534–544

Kontchakov R, Nenov Y, Pratt-Hartmann I, Zakharyaschev M (2011) On the decidability of connectedness constraints in 2D and 3D Euclidean spaces. In Proceedings IJCAI, AAAI Press, California, pp 957–962

Kuijpers B, Paredaens J, van den Bussche J (1995) Lossless representation of topological spatial data. In Advances in spatial databases, vol 951, LNCS, Springer, Berlin, pp 1–13

McKinsey JCC, Tarski A (1944) The algebra of topology. Ann Math 45:141–191

Nutt W (1999) On the translation of qualitative spatial reasoning problems into modal logics. In Proceedings of KI, vol 1701, LNCS, Springer, Berlin, pp 113–124

Papadimitriou CH, Suciu D, Vianu V (1999) Topological queries in spatial databases. J Comp Syst Sci 580(1):29–53

Pratt I, Lemon O (1997) Ontologies for plane, polygonal mereotopology. Notre Dame J Formal Logic 380(2):225–245

Pratt I, Schoop D (2002) Elementary polyhedral mereotopology. J Phil Logic 31:461–498

Pratt I, Schoop D (2000) Expressivity in polygonal, plane mereotopology. J Symb Logic 650(2):822–838

Pratt-Hartmann I (2007) First-order mereotopology. In: Aiello M, Pratt-Hartmann I, van Benthem J (eds) Handbook of spatial logics. Springer, Berlin, pp 13–97

Randell D, Cui Z, Cohn A (1992) A spatial logic based on regions and connection. In: Proceedings of KR, Morgan Kaufmann, San Mateo, pp 165–176

Renz J (1998) A canonical model of the region connection calculus. In: Cohn A (ed) Proceedings of KR, Morgan Kaufmann, pp 330–341

Renz J (1999) Maximal tractable fragments of the region connection calculus: a complete analysis. In: Proceedings of IJCAI, Morgan Kaufmann, pp 448–454

Renz J, Nebel B (1999) On the complexity of qualitative spatial reasoning. Artif Intell 108:69–123

Renz J, Nebel B (2001) Efficient methods for qualitative spatial reasoning. J Artif Intell Res 15:289–318

Renz J, Nebel B (2007) Qualitative spatial reasoning using constraint calculi. In: Aiello M et al Handbook of spatial logics, Springer, pp 161–216

Roeper P (1997) Region-based topology. J Phil Logic 26:251–309

Schaefer M, Sedgwick E, Štefankovič D (2003) Recognizing string graphs in NP. J Comp Syst Sci 67:365–380

Schoop D (1999) A model-theoretic approach to mereotopology. PhD thesis, School of Computer Science, U. Manchester, 1999

Tarski A (1956) Foundations of the geometry of solids. In: Logic, semantics, metamathematics, Clarendon Press, Oxford, pp 24–29

Whitehead AN (1929) Process and reality. MacMillan, New York

Wolter F, Zakharyaschev M (2000) Spatial reasoning in RCC-8 with boolean region terms. In: Proceedings of ECAI, IOS, pp 244–248

Reasoning on Class Relations: An Overview

Stephan Mäs

Abstract Class relations are used whenever the semantics of entire classes are described, independently of single entities. This chapter focuses on class relations that define cardinality restrictions for a certain instance relation (e.g., a topological relation) between all entities of the involved classes. Typical examples are spatial semantic integrity constraints or ontologies of geospatial entity classes. Reasoning on such class relations allows for the detection of inconsistencies and redundancies in sets of class relations. Therefore the logical properties of the applied instance relations and those of the cardinality restrictions have to be considered, in particular symmetry and compositions, but also other inferences. The chapter provides a summary of research and a discussion of open issues for future work on class relation reasoning.

Keywords Class relations · Spatial reasoning · Composition · Inheritance · Semantic integrity constraints

1 Introduction

The inclusion of spatial and temporal concepts, rules and relations should be a main consideration when designing geographic ontologies (Agarwal 2005). The corresponding formalization of spatial and temporal relations and hierarchies to enable a consistent representation of real world phenomena is still one of the major research

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themes in GI Science. While research on spatio-temporal relations and their logical properties has been relatively intense in the last two decades (Cohn and Hazarika 2001), the definition of corresponding class relations and their logical properties is a relatively new field. Nevertheless, it is of particular interest for geographical information, since the concepts of such data often refer to spatial relationships which can be represented by class relations (e.g. "*alluvial forests are surrounded by a floodplain*"). As already argued by Donnelly and Bittner (2005) the facilitation of interoperability requires a clear distinction if a relation holds among classes of entities (i.e., universals, feature classes or types) or among concrete entities (i.e., instances, objects or individuals), in particular when the logical properties of the relations are analyzed. Typical class relations are inheritance/generalization relations (Brachman 1983; Baumeister and Seipel 2006). This chapter focuses on class relations that define cardinality restrictions for a certain relation between all entities of the involved classes. Thereby the class relations neither specify the exact number of instances of the classes nor the particular relations between single entities. The constrained instance relation can be of any kind; for geographical information typical examples are the topological (Egenhofer and Herring 1991) or metric relations (Frank 1992) between spatial entities.

The following example shall illustrate the definition of such class relations and the feasibility to infer implicit knowledge with them. The entity relationship diagram in Fig. 1a contains the three classes A*irport*, *Forest* and *Airport Tower.* Among the classes three class relations are defined:

- *airports* and *forests* are either disjoint or meet.
- every *airport* contains at least one *airport tower* and every *airport tower* is contained by an *airport*.
- *forests* and *airport towers* are disjoint.

Such relations are commonly defined in an ontology or as semantic integrity constraints as part of a data model (Tarquini and Clementini 2008; Mäs et al. 2005; Mäs and Reinhardt 2009). In Fig. 1b the last of the three class relations is left out. Considering that the applied instance relations are the topological relations between areal entities defined in Egenhofer and Herring (1991), it is relatively obvious that the two diagrams have the same restriction on the relation between

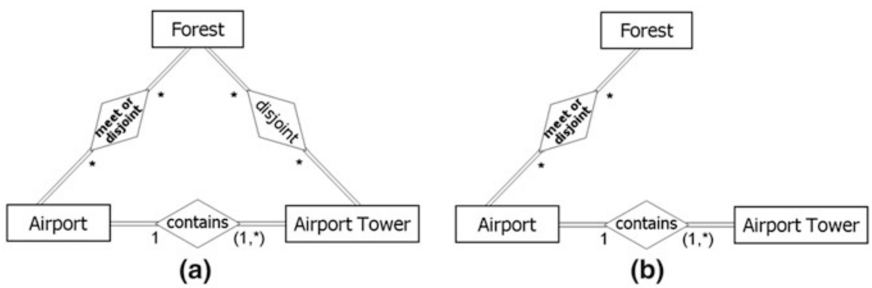


Fig. 1 Entity-Relationship Diagram of the three entity classes and their class relations

the classes *Forests* and *Airport Towers.* Since every *forest* meets or is disjoint from every *airport* the entities of these classes can have intersecting boundaries, but their interiors are disjoint. Since every *airport tower* is contained by an *airport* an *airport tower* has an intersecting interior with this *airport*, but no intersecting boundary. Therewith is no intersection between any *airport tower* and any *forest* possible, even if the third class relation is not explicitly defined. For quality assurance this means that the third class relation (i.e., semantic integrity constraint) does not need to be proven if a data set is conform to the first two. This shows that such a detection and removal of redundant constraints enables the reduction of the calculation costs of a quality check. In practice, this can be of great value, since the constraint sets used, for example, by utility companies or public agencies can easily contain hundreds of constraints.

Similar examples can be found in many disciplines, also in "non-spatial" ontologies such as in biomedicine (Donnelly et al. 2006): from "every *vertebra* has some *cartilage* as a proper part" and "every *vertebra* is a proper part of some *vertebral column* and every *vertebral column* has some *vertebra* as a proper part", it follows that "every *vertebral column* has some *cartilage* as a proper part". For a triple of class relations, like those in the two examples, it is easy to imagine that the third relation could also be in contradiction to the restrictions implied by the other two. Also two relations that apply to the same classes can specify contradicting restrictions. Therefore, the internal consistency of such sets of class relations must be assured.

Most ontologies deal with the description of classes and therefore with the formal description of relations among those classes. Nevertheless, class relations other than inheritance/generalization relations are hardly used for the inference of implicit knowledge or analyzed for conflicting assertions. The examples illustrate the need of methodologies to compare, manage and consistently integrate class relations. A consistency check of class relations must include implicitly defined constraints, because the constraints do not necessarily directly contradict. Conflicts might, for example, result from other constraints defined within a triple of classes. The objective of this chapter is to summarize available approaches for the detection of explicit and implicit redundancies and contradictions and inequalities in sets of class relations.

A class relation can be defined in terms of an instance relation (e.g., the topological relation "*disjoint"*) or a disjunction of instance relations (e.g., "*meet or disjoint"*). It is obvious that the reasoning properties of such class relation are influenced by those of the applied instance relation. Therefore it is reasonable to use and extend the reasoning properties and methods of instance relations for reasoning based on class relations. The formal theory of relations of individuals is the necessary foundation for the formal theory of class relations (Donnelly et al. 2006). Nevertheless, a relation among classes is not necessarily subject to the same logical properties as a relation between instances. The cardinality restrictions must also be considered for reasoning.

Spatial reasoning approaches often refer to qualitative descriptions of spatial entities and their relations. Qualitative representations are characterized by making only as many distinctions in the domain as necessary in a given context (Hernández 1994). Typical examples are spatial relations such as "*a is inside b*", "*c is north of d*" and "*e is longer than f*". The different aspects of space, like topology, orientation, distance and shape, are usually represented by different spatial relations (Cohn and Hazarika 2001). To solve reasoning problems based on such knowledge representations, special purpose inference mechanisms have been developed. An advantage of such approach is that certain constraints which always hold in the spatial domain do not have to be modeled and verified in each situation anew (Freksa 1991). For example, once the composition of a set of topological relations has been calculated and verified, the corresponding composition table (Egenhofer 1994; Grigni et al. 1995) can be used whenever a set of these relations is analyzed. Such compact representation of knowledge should be an integral part of a spatial reasoning system. The class relation reasoning approaches discussed in this chapter also refer to qualitative descriptions and make use of the knowledge about the logical properties of the spatial relations.

In the following section a set class relations is defined, that allows for a qualitative representation of cardinality restrictions. This set is then exemplarily used to explain the reasoning properties of class relations like their symmetry, composition and conceptual neighborhood, and to demonstrate how these inference methods link to the logical properties of the instance relations. After that some open issues for class relation reasoning are discussed.

2 Cardinality Properties and Class Relation Definition

Class relations are used whenever the semantics of entire classes are described, independently of any knowledge about specific single entities. A class relation is defined in terms of an instance relation or a disjunction of instance relations in combination with a cardinality restriction. Cardinalities express the number of elements of a set. Class relations define a cardinality restriction for a certain relation between the individuals of one or more classes (Mäs 2009a).

For the definition of class relations some basic assumptions have to be fulfilled. First, every instance has to be a member of some class. Second, the involved classes must have at least one instance, that is, empty classes are not feasible. Since class relations are linked to individual relations, the third condition specifies that if a class relation is defined, there exists at least one corresponding individual relation among the instances of the classes involved. This chapter is restricted to binary relations defined between entity classes. Relations between three or more classes are not considered.

In the following definitions the lowercase letters *('a', 'b'* and *'c')* denote variables for instances or individuals. Every instance must belong to an entity class. For entity classes the capital letters *('A', 'B'* and *'C')* are used as variables. '*Inst(a, A)*' is the instantiation relation, meaning that individual *'a'* is an instance of class *'A'*. The claim *'r(a, b)'* means instance *'a'* has the relation *'r'* to instance *'b'*; *'a'* and 'b' are said to participate in the relationship instance *'r'*. The meta-variable *'r'* can stand for any binary relation between instances (e.g., a spatial or temporal relation) or for a disjunction of such relations. The validity of the binary relation depends on the properties of the instances (e.g., for spatial relations on the geometries of the instances). Instance relationships can be associated with a class relation *'R'*. For class relation definitions '$R_{<cp>}(A, B)$' denotes that *'R'* relates the classes *'A'* and *'B'*. The meta-variable *'R'* can stand for any class relationship. Every *'R'* is defined in terms of an instance relation *'r'* (same letter(s) in lower case). In formulas this is made explicit by the claim '*InstR(r, R)*'. If a class relation is defined by an '$R_{<cp>}(A, B)$', at least one *'r'* must exist between the instances of *'A'* and *'B'*, independently of the cardinality restriction. For example, if '$MEET_{<cp>}(A, B)$' is defined, at least one *'meet(a, b)'* must exist. The placeholder '*<cp>*' stands for the cardinality properties of the class relation. In the following, class relations that are not linked to a particular instance relation are referred to as **abstract class relations** (e.g., '$R_{LD\ RD\ LT}(A, B)$'). These are only used to define generic reasoning rules. Only relations that incorporate a concrete instance relation are called class relations (e.g. '$DISJOINT_{LT}(A, B)$').

A first approach for the formal definition of such class relations has been made by Donnelly and Bittner (2005). It was based on totality cardinality restrictions of the involved classes:

$$LT(A,B,r) := \forall a(Inst(a,A) \rightarrow \exists b(Inst(b,B) \cap r(a,b))). \tag{1}$$

$$RT(A,B,r) := \forall b(Inst(b,B) \rightarrow \exists a(Inst(a,A) \cap r(a,b))). \tag{2}$$

The cardinality restrictions Eqs. (1) and (2) define a totality for the class *'A'* and *'B'* respectively. Equation (1) holds if every instance of *'A'* has the relation *'r'* to some instance of *'B'*. In set theory such relations are called **left-total**.

Equation (2) holds if for each instance of *'B'* there is some instance of *'A'* which stands in relation *'r'* to it. This means that every instance of *'B'* has the converse relation of *'r'* to some instance of *'A'*. In this case the relation is **right-total**.

In order to improve expressiveness this approach has been extended by unambiguousness cardinality restrictions in Mäs (2007):

$$LD(A,B,r) := \forall a,b,c\begin{pmatrix} Inst(a,A) \cap Inst(b,B) \cap Inst(c,A) \\ \cap\ r(a,b) \cap r(c,b) \rightarrow a = c \end{pmatrix} \cap Ex(A,B,r). \tag{3}$$

$$RD(A,B,r) := \forall a,b,c\begin{pmatrix} Inst(a,A) \cap Inst(b,B) \cap Inst(c,B) \\ \cap\ r(a,b) \cap r(a,c) \rightarrow b = c \end{pmatrix} \cap Ex(A,B,r). \tag{4}$$

$$Ex(A,B,r) := \exists a \exists b(Inst(a,A) \cap Inst(b,B) \cap r(a,b)).$$

Class relations which hold Eq. (3) are **left-definite** and specify that for no instance of *'B'* there is more than one instance of *'A'* which stands in relation *'r'* to it. This property restricts the number of *'r'* relations an instance of *'B'* can participate in; the instances of *'A'* are not restricted. The last term *'Ex(A, B, r)'* ensures that at least one instance relation *'r'* does exist between the instances of *'A'* and *'B'*.

Equation (4) specifies that no instance of *'A'* participates in a relationship *'r'* to more than one instance of *'B'*. When this cardinality property is defined in a class relation all instances of *'A'* are restricted while the instances of *'B'* are not affected. The corresponding class relations are **right-definite**.

Such cardinality restrictions are well established in data modeling and ontology engineering (Tarquini and Clementini 2008; Donnelly et al. 2006). Since the four cardinality properties are independent of each other they can be combined for the definition of a class relation. For example, a class relation which defines that "every country contains exactly one capital and every capital is contained by exactly one country" requires all four cardinality properties Eq. (5). The class relation "every building is contained by exactly one parcel" would be based on *'LT(Building, Parcel, contains)'* and '*RD(Building, Parcel, contains)'* (Mäs 2007). The other two cardinality properties are invalid Eq. (6).

$$R_{LD\,RD\,LT\,RT}(A,B) := \forall r \begin{pmatrix} InstR(r,R) \rightarrow LD(A,B,r) \cap RD(A,B,r) \cap \\ LT(A,B,r) \cap RT(A,B,r) \end{pmatrix}. \quad (5)$$

$$R_{RD\,LT}(A,B) := \forall r \begin{pmatrix} InstR(r,R) \rightarrow \neg LD(A,B,r) \cap RD(A,B,r) \cap \\ LT(A,B,r) \cap \neg RT(A,B,r) \end{pmatrix}. \quad (6)$$

Therewith a formal definition of a class relation is based on cardinality definitions as well as their negations. An investigation of all possible combinations of the four cardinality properties leads to the following categorization of abstract class relations:

- one abstract class relation where all four properties are valid (5);
- four abstract class relations that combine three of the four defined cardinality properties respectively and exclude the corresponding fourth;
- six abstract class relations where two properties are valid and the other two are excluded (e.g. 6); and
- four abstract class relations where one property is valid and the corresponding other three are excluded.

In addition to these 15 abstract class relations two special cases have been considered in Mäs (2007). The first is a strict case of a *left-total* and *right-total* relation that specifies that all instances of '*A*' must have a relationship instance of '*R*' to all instances of '*B*' (7). For class relations it is frequently occurring, for example if the instances of two classes are allowed to intersect: *'DISJOINT$_{LT\,RT\text{-}all}$(Streets, Lakes)'* (Mäs 2008).

The abstract class relation '*R_{some}(A, B)'* is defined for the situation that none of the four cardinality properties is valid, but nevertheless some instances of '*A*' stand in relation '*r*' to some instances of '*B*' (8). '$R_{some}(A, B)$' is defined as *not left-total* and *not right-total*, which implies that some instances of '*A*' and '*B*' participate in a relation '*r*' to an instance of '*B*' and '*A*' and some do not. Furthermore the exclusions of '*LD(A, B, r)*' and '*RD(A, B, r)*' specify that some '*A*' and some '*B*' participate in a relation r to at least two instances of '*B*' and '*A*'. All cardinalities from "2" till "all-1" are valid for both classes. Therefore, it is a relatively imprecise representation of all cardinalities that the other 16 abstract class relations do not cover.

$$R_{LT\,RT-all}(A,B) := \forall r \forall a \forall b \begin{pmatrix} InstR(r,R) \,\cap\, Inst(a,A) \,\cap\, Inst(b,B) \\ \rightarrow r(a,b) \end{pmatrix}. \quad (7)$$

$$R_{some}(A,B) := \forall r \begin{pmatrix} InstR(r,R) \rightarrow \neg LD(A,B,r) \,\cap\, \neg RD(A,B,r) \,\cap \\ \neg LT(A,B,r) \,\cap\, \neg RT(A,B,r) \,\cap\, Ex(A,B,r) \end{pmatrix}. \quad (8)$$

All together the 17 abstract class relations are a jointly exhaustive set of relations. They enable the definition of class relations based on any binary instance relation. The set of 17 abstract class relations allows for a qualitative description of all possible (indefinitely many) cardinality properties. Only class relations, that base on the four cardinality properties Eqs. (1–4) or $R_{LT\ RT\text{-}all}(A, B)$ (7) can precisely be defined. Further details on the definition of the abstract class relations can be found in Mäs (2007 and 2009a). Other notations, like for example Entity-Relationship Diagrams, are more expressive with regard to the possible cardinality constraints. However, some of the reasoning concepts investigated in the following sections, require a discrete set of abstract class relations. Also, it is assumed that the introduced set of abstract class relations can precisely represent a majority of the class relations used in practice. Nevertheless, this set of abstract class relations is only exemplarily used here and the reasoning approaches can also be transferred to other sets of relations.

3 Transferring Logical Properties of Instance Relations to Class Relations

In general, the logical properties of class relations, such as their symmetry, transitivity and reflexivity, depend not only on the properties of the applied instance relation, but also on the cardinality restrictions. Donnelly and Bittner (2005) have studied the transfer of logical properties of instance relations to class relations. It has been shown that some, but not all, logical properties of the instance relations transfer to the class relations.

For the set of class relations defined in the previous section only the symmetry/ converseness has been sufficiently researched yet. In Mäs (2007) it has been shown, how the converse of a class relation can be defined, if the converse relation of the corresponding instance relation is known. The converse of a class relation bases on the converse of the applied instance relation. If an abstract class relation is *left-total/left-definite* the converse relation is *right-total/right-definite*, and vice versa. The relations 'R_{some}' and '$R_{LT\ RT\text{-}all}$' are symmetric. Table 1 summarizes this correlation between symmetry/converseness of instance relations and those of the corresponding class relations.

The following examples demonstrate the derivation of converse class relations. The class relations base on the symmetric instance relation '*overlap*' and the converse relations '*contains*' and '*inside*':

$$OVERLAP_{RD\,LT}(Watermill,\ Stream)^i := OVERLAP_{LD\,RT}(Stream,\ Watermill).$$

$$CONTAINS_{LD\,RD\,LT\,RT}(Country,\ Capital)^i := INSIDE_{LD\,RD\,LT\,RT}(Capital,\ Country).$$

The examples show that not all class relations are symmetric, even if they are based on symmetric instance relations.

In a recent paper Egenhofer (2011) researched the inference of complements of class relations. Therefore, the applied instance relations must be part of a jointly exhaustive and pair wise disjoint (JEPD) set of relations. The complement of a class relation captures the relations that must hold between all instances of the related classes other than the instance relations covered by the original class relation. For example, the complement of the class relation "*every building is inside or covered by a land parcel*" captures the relations between all buildings and land parcels other than the hosts of the buildings: "*every building meets or is disjoint from land parcels (it is not hosted by)*".

For other logical properties of the class relations, such as antisymmetry, transitivity and reflexiveness a detailed analysis is still missing.

4 Composition of Class Relations

The composition of binary relations enables the derivation of implicit knowledge about a triple of entities. If two binary relations are known, the corresponding third

Table 1 Symmetry/converseness of the class relations (Mäs 2007)

Individual relation '*r*' is…	Class relation '*R*' is…					
	Left-definite	Right-definite	Left-total	Right-total	R_{some}	$R_{LTRT-all}$
	Converse class relation 'R^i' is…					
Symmetric	*R* right-definite	*R* left-definite	*R* right-total	*R* left-total	R_{some}	$R_{LTRT-all}$
Not symmetric	R^i right-definite	R^i left-definite	R^i right-total	R^i left-total	R^i_{some}	$R^i_{LTRT-all}$

r^i converse instance relation
R^i converse class relation (defined in terms of 'r': '*InstR*(r^i ,R^i)')

one can potentially be inferred, or at least some of the possible relations can be excluded. Examples of composition tables of instance relations can be found in Egenhofer (1994) and Grigni et al. (1995) for topological relations between areal entities and in Hernández (1994) and Freksa (1992a) for directional/orientation relations. Many other sets of binary spatial relations also allow for such derivations. As the examples in the introduction of this chapter illustrate, a transfer of this reasoning formalism to the class level is very useful for work with geographical data, but also for many other application domains. In the example two class relations have been defined:

- *airports* and *forests* are either disjoint or meet.
- every *airport* contains at least one *airport tower* and every *airport tower* is contained by an *airport*.

The composition of these two class relations leads to:

- *forests* and *airport towers* are disjoint.

It is obvious that the composition depends on the composition of the applied instance relations, but the cardinality restrictions also have an influence. In Mäs (2008) a two level reasoning formalism has been proposed, which separates the compositions of the abstract class relations from those of the instance relations. Therewith the composition of the abstract class relations can be defined independently of a concrete set of instance relations. The composition table of the 17 abstract class relations is shown in Fig. 2.

To illustrate the two levels reasoning formalism and the use of the composition table the introductory example of Fig. 1 is used. The composition of the instance relations of the three entities forest *f1*, airport *a*1 and airport tower *t1* is in this case (Egenhofer 1994):

$$meet \cup disjoint(f1, a1);\ contains(a1, t1) \rightarrow disjoint(f1, t1).$$

The composition of the abstract class relations is provided by the composition table in Fig. 2 (row 17, column 14):

$$R1_{LT\,RT-all}(Forest, Airport);\ R2_{LD\,LT\,RT}(Airport, Airport\,Tower) \\ \rightarrow R3_{LT\,RT-all}(Forest, Airport\,Tower).$$

The combination of the compositions of the two levels results in:

$$[MEET \cup DISJOINT]_{LT\,RT-all}(Forest, Airport); \\ CONTAINS_{LD\,LT\,RT}(Airport, Airport\,Tower) \rightarrow \\ DISJOINT_{LT\,RT-all}(Forest, Airport\,Tower)$$

Since the compositions of both levels have a unique result the combined composition is also unique. For a more detailed explanation and further examples of the composition see Mäs (2007 and 2008).

1. Relation \ 2. Relation		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	LD.RD	$\mathcal{U}$	$\mathcal{U}$	$\mathcal{U}$	$\mathcal{U}$	1	$\mathcal{U}$	$\mathcal{U}$	1,3	1,2	$\mathcal{U}$	1,2, 3,4	$\mathcal{U}$	1	1,2	1,3, 6,10	1,2,3, 4,6,7, 10,12	6, 7, 10,12
2	LD	$\mathcal{U}$	$\mathcal{U}$	$\mathcal{U}$	$\mathcal{U}$	2	$\mathcal{U}$	$\mathcal{U}$	1,2, 3,4	2	$\mathcal{U}$	1,2, 3,4	$\mathcal{U}$	2	2	1,2,3,4, 6,7,10, 12	1,2,3, 4,6,7, 10,12	6, 7, 10,12
3	RD	$\mathcal{U}$	$\mathcal{U}$	$\mathcal{U}$	$\mathcal{U}$	3	$\mathcal{U}$	$\mathcal{U}$	3	3,4	$\mathcal{U}$	3,4	$\mathcal{U}$	3	3,4	3,10	3,4, 10,12	10,12
4	some	$\mathcal{U}$	$\mathcal{U}$	$\mathcal{U}$	$\mathcal{U}$	4	$\mathcal{U}$	$\mathcal{U}$	3,4	4	$\mathcal{U}$	3,4	$\mathcal{U}$	4	4	3,4, 10,12	3,4, 10,12	10,12
5	LD.RD.LT	$\mathcal{U}$	$\mathcal{U}$	$\mathcal{U}$	$\mathcal{U}$	5	$\mathcal{U}$	$\mathcal{U}$	5,8	5,9	$\mathcal{U}$	5,8, 9,11	$\mathcal{U}$	5	5,9	5,8, 13,15	5,8,9, 11,13,14, 15,16,17	17
6	LD.RD.RT	1	2	3	4	1	6	7	3	2	10	4	12	6	7	10	12	6, 7, 10,12
7	LD.RT	1,2	2	1,2, 3,4	2,4	2	6,7	7	1,2, 3,4	2	6,7, 10,12	2,4	7,12	7	7	6,7, 10,12	7,12	6, 7, 10,12
8	RD.LT	$\mathcal{U}$	$\mathcal{U}$	$\mathcal{U}$	$\mathcal{U}$	8	$\mathcal{U}$	$\mathcal{U}$	8	8,11	$\mathcal{U}$	8,11	$\mathcal{U}$	8	8,11	8,15	8,11,15, 16,17	17
9	LD.LT	$\mathcal{U}$	$\mathcal{U}$	$\mathcal{U}$	$\mathcal{U}$	9	$\mathcal{U}$	$\mathcal{U}$	5,8, 9,11	9	$\mathcal{U}$	5,8, 9,11	$\mathcal{U}$	9	9	5,8,9,11, 13,14,15 16,17	5,8,9,11, 13,14,15, 16,17	17
10	RD.RT	1,3	2,4	3	4	3	6,10	7,12	3	4	10	4	12	10	12	10	12	10,12
11	LT	$\mathcal{U}$	$\mathcal{U}$	$\mathcal{U}$	$\mathcal{U}$	11	$\mathcal{U}$	$\mathcal{U}$	8,11	11	$\mathcal{U}$	8,11	$\mathcal{U}$	11	11	8,11, 15,16, 17	8,11, 15,16, 17	17
12	RT	1,2 3,4	2,4	1,2, 3,4	2,4	4	6,7, 10,12	7,12	3,4	4	6,7, 10,12	4	7,12	12	12	10,12	12	10,12
13	LD.RD.LT.RT	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
14	LD.LT.RT	1,2, 5,9	2,9	1,2,3, 4,5,8, 9,11	2,4, 9,11	9	6,7, 13,14	7,14	5,8, 9,11	9	6,7,10, 12,13,14, 15,16,17	9,11	7,12, 14,16, 17	14	14	13,14, 15,16, 17	14,16, 17	17
15	RD.LT.RT	1,3	2,4	3	4	8	6,10	7,12	8	11	10	11	12	15	16	15	16	17
16	LT.RT	1,2,3, 4,5,8, 9,11	2,4, 9,11	1,2,3, 4,5,8, 9,11	2,4, 9,11	11	6,7,10, 12,13,14, 15,16,17	7,12, 14,16, 17	8,11	11	6,7,10, 12,13,14, 15,16,17	11	7,12, 14,16, 17	16	16	15,16, 17	16,17	17
17	LT.RT-all	5,8, 9,11	9,11	5,8, 9,11	9,11	5,8, 9,11	17	17	5,8, 9,11	9,11	17	9,11	17	17	17	17	17	17

Fig. 2 Composition table of the 17 abstract class relations (Mäs 2008), the *numbers* are defined in the *left column*

To allow for a more convenient use of the compositions of the abstract class relation some of them can be summarized by general rules, which deduce the composition results directly from cardinality properties. In Mäs (2008) some obvious rules were defined. The corresponding compositions are highlighted in grey in Fig. 2. Examples of these rules are:

- If the first abstract class relation is not right-total and the second relation is not left-total the composition is always a universal disjunction $\mathcal{U}$.
- If the first relation holds '$R1_{LT\ RT\text{-}all}(A, B)$' and the second is right-total the composition is always '$R3_{LT\ RT\text{-}all}(A, C)$'.
- If the first relation is left-total and the second holds '$R2_{LT\ RT\text{-}all}(B, C)$' the composition is always '$R3_{LT\ RT\text{-}all}(A, C)$'.

A set of rules that completely represents the composition table is subject to further research. Such rule set could enhance the understanding of the class relation compositions and would prove the correctness and completeness of the contents of the composition table. Furthermore, it would make the compositions transferable to other sets of abstract class relations and the composition tables of different sets comparable, respectively.

5 Conceptual Neighborhood of Class Relations

The notion of conceptual neighborhood has been introduced by Freksa (1992b). It represents continuous transformations between relations by linking relations that are connected by an atomic change. Examples of conceptual neighborhood networks of spatio-temporal relations can be found for temporal interval relations (Freksa 1992b; Hornsby et al. 1999), for topological relations between regions (Egenhofer and Al-Taha 1992), between regions and lines (Egenhofer and Mark 1995), and between directed lines (Kurata and Egenhofer 2006). The conceptual neighborhood of class relations has been introduced by Mäs (2008). In this approach, two class relations are considered as conceptually neighbored if they are linked to the same instance relation and they differ only in a single instance relation between two entities. The number of instances of the classes is considered fixed.

In Fig. 3 the conceptual neighborhood of '$R_{LD\ RD}(A, B)$' and '$R_{RD}(A, B)$' is exemplarily illustrated. All arrows symbolize one instance relation of the same kind '*r*' (again: '*InstR(r, R)*'). In the example, the addition of a further instance relation between the instances '*a2*' and '*b*1' in the right box leads to a transition from '$R_{LD\ RD}$' to 'R_{RD}' (row 1, column 3 in Table 2). An addition of an instance relation between other instances can lead to other transitions. The 17 class relations have 45 conceptual neighborhoods. Additionally nine class relations are conceptual neighbors of themselves (Table 2).

Since the conceptual neighborhood is defined through the addition or removal of a single instance relation, all neighborhoods are directed. Table 2 represents the

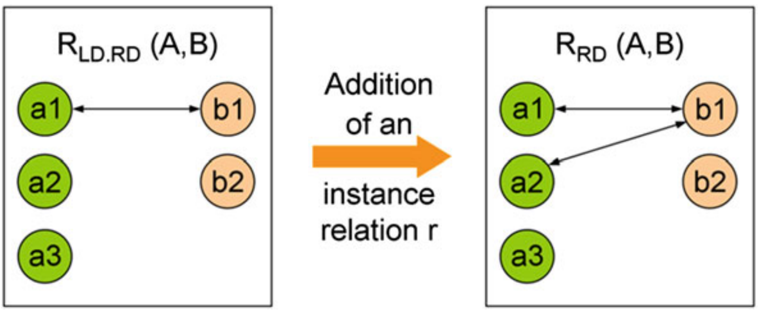


Fig. 3 Conceptual neighborhood between '$R_{LD\ RD}(A, B)$' and '$R_{RD}(A, B)$' (Mäs 2009a)

Table 2 Conceptual neighborhood between the class relations

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1 LD.RD	±	+	+	+	+	+	+	+					+				
2 LD	−	±		+			+		+		+			+			
3 RD	−		±	+				+		+		+			+		
4 some	−	−	−	±							+	+				+	
5 LD.RD.LT	−								+		+			+			+
6 LD.RD.RT	−									+		+			+		+
7 LD.RT	−	−										+				+	
8 RD.LT	−		−								+					+	
9 LD.RT		−			−				±		+			+			+
10 RD.RT			−			−				±		+			+		+
11 LT		−		−	−			−	−		±					+	
12 RT			−	−		−	−			−		±				+	
13 LD RD LT RT	−															+	
14 LD.LT.RT		−			−				−							+	
15 RD.LT.RT			−			−				−						+	
16 LT.RT				−			−	−			−	−	−	−	−	±	+
17 LT.RT-all					−	−			−	−						−	

± corresponds to neighborhood through addition/removal of an instance (Mäs 2009a), numbers are defined in the left column

neighborhoods, which result from an addition ('+') and those which result from a removal ('−'). The symbol '±' marks class relations that are conceptual neighbors of themselves. If an addition or removal of an instance relation has changed a class relation it is impossible to get the same class relation again by further adding/removing of instance relations. The addition of instance relations ultimately leads to a '$R_{LT\ RT\text{-}all}$' class relation. A removal leads to '$R_{LD\ RD}$'.

In Mäs (2008 and 2009a) some practical examples of the conceptual neighborhood of class relations and its relevance for the reasoning on class relation compositions have been discussed. For example, if three class relations hold for the classes '*A*', '*B*' and '*C*': '$MEET_{some}(A, B)$', '$CONTAINS_{LD\ RD\ LT\ RT}(B, C)$' and '$DISJOINT_{LT\ RT}(A, C)$'. These relations are analyzed for conflicts through the comparison of the class relation composition '*R(A,B);R(B,C)*' with the given '*R(A, C)*'. The compositions of the corresponding instance and abstract class relations are:

$$meet(a1, b1);\ contains(b1, c1) \rightarrow disjoint(a1, c1).$$

$$R1_{some}(A, B);\ R2_{LD\,RD\,LT\,RT}(B, C) \rightarrow R3_{some}(A, C).$$

The combination of the compositions of the two levels results in: '$DISJOINT_{some}(A, C)$' (row 4, column 13 in Fig. 2), which seems to be in conflict with the given third relation '$DISJOINT_{LT\ RT}(A, C)$'. Figure 4 exemplarily illustrates this situation. Figure 4a shows a possible setting of instance relations between the classes '*A*' to '*B*' and '*B*' to '*C*', and Fig. 4b the inferred relations between '*A*' and '*C*'. Thereby

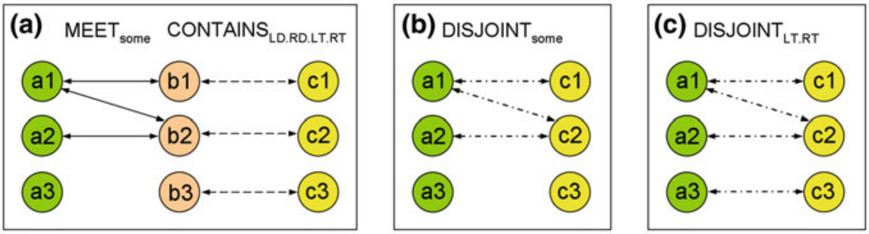


Fig. 4 Use of the conceptual neighborhood for the composition of class relations (Mäs 2009a)

only those instances of '*A*' and '*C*' are related in Fig. 4b, which are connected via an instance of '*B*' in Fig. 4a. In comparison to this, the Fig. 4c shows that the given relation '*DISJOINT*$_{LT\ RT}$*(A, C)*' possibly differs from '*DISJOINT*$_{some}$*(A, C)*' by only one '*disjoint*' instance relation (in this case '*a3*' to '*c3*'). Thus '*DISJOINT*$_{some}$' and '*DISJOINT*$_{LT\ RT}$' are conceptual neighbors (row 4, column 16 in Table 2).

The three instance relations in Fig. 4b are implied by the relations shown in Fig. 4a. The composition does not allow for any conclusion about further relations between the instances of '*A*' and '*C*'. Also, it cannot be excluded that further pairs of '*A*' and '*C*' instances are '*disjoint*'. Hence the composition of '*MEET*$_{some}$*(A,B)*' and '*CONTAINS*$_{LD\ RD\ LT\ RT}$*(B, C)*' does not contradict '*DISJOINT*$_{LT\ RT}$*(A,C)*' and the given triple of class relations is consistent. Beside '*DISJOINT*$_{LT\ RT}$', also the other direct conceptual neighbors of '*DISJOINT*$_{some}$' '*DISJOINT*$_{LT}$' and '*DISJOINT*$_{RT}$' (row 4, columns 11 and 12 in Table 2), as well as '*DISJOINT*$_{LT\ RT\text{-}all}$' as a conceptual neighbor of '*DISJOINT*$_{LT\ RT}$*(A,C)*' (row 16, columns 17 in Table 2) have no conflict.

Mäs (2008) correspondingly concluded with the generic rule: a class relation '*R3*' is not in conflict with a composition '*R1; R2* → *R3**' if '*R3**' and '*R3*' base on the same instance relation '*r3*' ('*InstR(r3, R3)*' and '*InstR(r3, R3*)*') and the addition of further '*r3*' instance relations to '*R3**' can lead to a transition to class relation '*R3*'. For this the result of the composition '*R3**' and '*R3*' do not need to be direct conceptual neighbors. There can also be further class relation transitions between the two class relations. Nevertheless the conceptual neighborhood points out which '*R3*' class relations are valid, since it shows which transitions are possible for a certain class relation '*R3**'.

6 Constraint Satisfaction Problems in Class Relation Networks

The previous sections discussed the reasoning properties of class relations. The application of these reasoning techniques for checking consistency in networks of class relations is a constraint satisfaction problem (CSP). Such detection of conflicts and redundancies in sets of class relations requires a network graph, in which the nodes represent the entity classes and the edges represent the class relations. In a consistent network of jointly exhaustive and pair wise disjoint (JEPD) relations, the following three requirements are fulfilled (Rodriguez et al. 2004). Proofs of these requirements for class relation networks have been discussed in Mäs (2007 and 2009a):

- Node consistency is ensured if every node has a self-loop arc, which corresponds to the identity relation (i.e., relation of an entity/entity class to itself). If a corresponding identity instance relation is available the identity class relation is in general '$R_{LD\ RD\ LT\ RT}(A, A)$'; for example '$EQUAL_{LD\ RD\ LT\ RT}(A, A)$' when using the topological relations areal entities.
- Arc consistency is ensured if every edge of the network has an edge in the reverse direction, that is, every relation has a converse relation that is consistent with the network. As shown in Sect. 3, the converse of a class relation can be defined, if the converse relation of the corresponding instance relation is known.
- Path consistency is ensured if all relations are consistent with their induced relations, determined by the corresponding intersection of all possible composition paths of length two (n = number of nodes):

$$\forall_{i,j} r_{i,j} = \bigcap_{k=1}^{n} r_{i,k};\ r_{k,j}.$$

In general, the algorithm for checking path consistency of a class relation network is similar to algorithms used for the instance relations (e.g. Allen 1983; Hernández 1994). However, due to the higher complexity of the relations, the detection whether two relations between the same classes are in conflict is more extensive (Mäs 2009a).

7 Reasoning on Class Relations in Class Hierarchies

So far, the existing reasoning approaches only consider classes without a hierarchical structure. For a class relation network this means that all nodes in the graph are considered at the same level and all edges are treated equally. For a practical application this is insufficient, since most data models and ontologies are hierarchically structured. The hierarchical organization makes it easy to distribute properties, since the properties and methods of a class depend on the properties of its superclass(es). The properties that are shared by a superclass and all its subclasses are defined only once with the superclass. The subclasses inherit all properties of their parent-/superclasses in the hierarchy (Brachman 1983; Egenhofer and Frank 1992). Such properties can be spatio-temporal or thematic attributes or explicitly defined relations between classes. If a class relation is defined in a class hierarchy it has an influence on the classes at the lower levels. It also results in additional logical rules and consistency requirements between the class relations of the different hierarchy levels. For example from: "*Watercourse* is a subclass of *Waterbody*" and

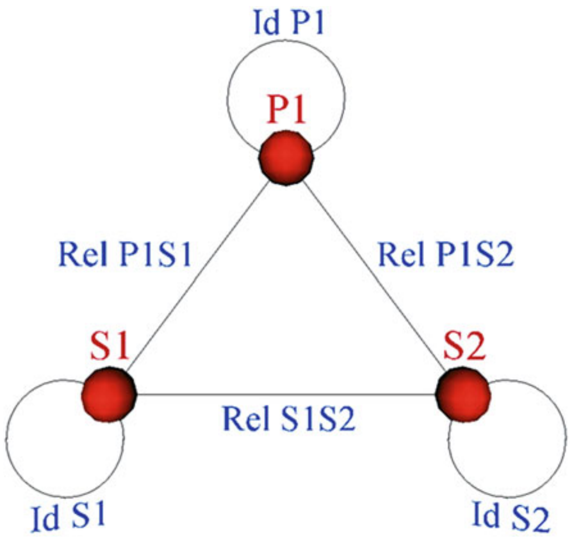


Fig. 5 Class relation network of a simple hierarchy with one superclass and two subclasses

"every *Waterfall* is an individual part of some *Watercourse*" it can be derived that "every *Waterfall* is an individual part of some *Waterbody*" (analogous to Bittner et al. 2009). Similar examples from the biomedical domain can be found in Donnelly et al. (2006). Although these papers provide some inference rules they only consider the inference of specific class relations. A generic solution is subject to future research. Therefore, the remainder of this section shall illustrate some obvious dependencies of the class relations between super- and subclasses in a class hierarchy.

For the following propositions it is assumed that all subclasses of a superclass are known and that all entities of the superclass belong to (exactly) one of the subclasses and vice versa. These assumptions are commonly made in ontologies (e.g. Bittner et al. 2009). Further, all subclasses have only one superclass, i.e., multiple inheritance is not considered here.

In a simple hierarchy with one superclass and two subclasses there are three edges between the classes and three edges for the identity class relations (Fig. 5). The superclass (P1) subsumes the subclasses (S1 and S2).[1] The class relations define cardinality restrictions of instance relations between the entities of the classes. Therefore class relations at a higher level or between the two successive levels subsume the class relations of the lower level. This leads to the following dependencies:

D1: The identity relation of the superclass (IdP1) subsumes the identity class relations of the subclasses (IdS1 and IdS2) and the class relations between the subclasses in both directions (RelS1S2 and RelS2S1) (see Fig. 6).

[1] Please be aware that all edges in Fig. 5 represent class relations that define cardinality restrictions and not the inheritance/generalisation relation between the classes.

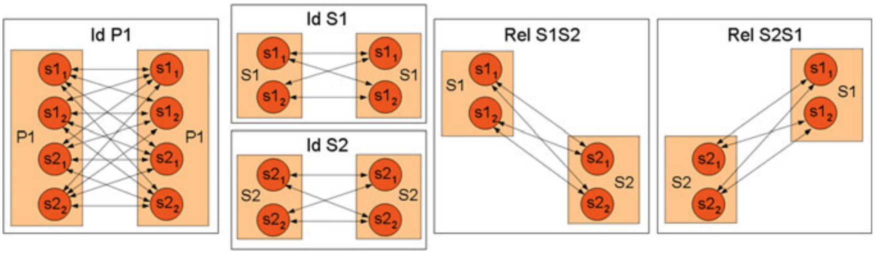


Fig. 6 Example for the subsumption of class relations of a lower hierarchy level in the identity relation of the corresponding superclass

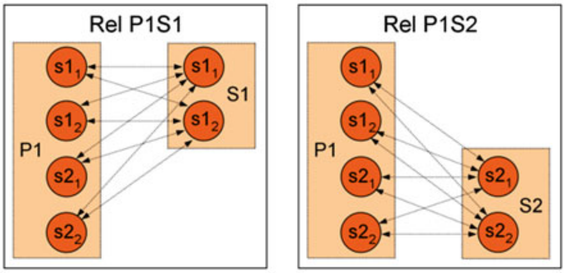


Fig. 7 Example class relations that connect the two hierarchy levels

D2: The class relations that connect the two hierarchy levels subsume the identity relation of the related subclass and the class relations of all other subclasses to this subclass. For the scene shown in Fig. 5 this means that RelP1S1 subsumes IdS1 and RelS2S1, and RelP1S2 subsumes IdS2 and RelS1S2 (see Figs. 6 and 7).

D3: Therewith the identity relation of the superclass (IdP1) also subsumes all class relations that connect the two hierarchy levels (RelP1S1 and RelP1S2).

Figures 6 and 7 schematically illustrate the class relations of the hierarchy of Fig. 5. In the figures both subclasses have two entities. Again, the arrows represent the relations between the entities, which could be for example one of the topological relations '*intersect*' or '*disjoint*'. Through the comparison of the arrows it is easy to comprehend the three interdependencies.

The following Eqs. (9)–(11) define the interdependencies D1–D3 for hierarchies with arbitrary many subclasses. The variables m and n are indices of the subclasses. Equations (12) and (13) define the interdependency for the class relations from the subclasses to the superclass (converse to the relations considered in Eqs. (10) and (11)).

$$\mathrm{Id_P} = \{Id_{S_1}, \ldots, Id_{S_m}, Rel_{S_1S_2}, Rel_{S_2S_1}, \ldots, Rel_{S_mS_n}, Rel_{S_nS_m}\}_{m \neq n} \tag{9}$$

$$Rel_{PS_m} = \{Id_{S_m}, Rel_{S_1S_m}, \ldots, Rel_{S_nS_m}\}_{m \neq n} \tag{10}$$

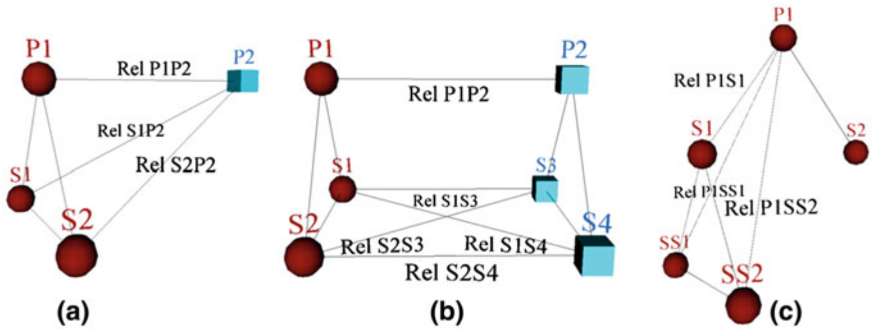


Fig. 8 Hierarchical settings with interdependent class relations

$$Id_P = \{Rel_{PS_1}, \ldots, Rel_{PS_m}\} \tag{11}$$

$$Rel_{S_mP} = \{Id_{S_m}, Rel_{S_mS_1}, \ldots, Rel_{S_mS_n}\}_{m \neq n} \tag{12}$$

$$Id_P = \{Rel_{S_1P}, \ldots, Rel_{S_mP}\} \tag{13}$$

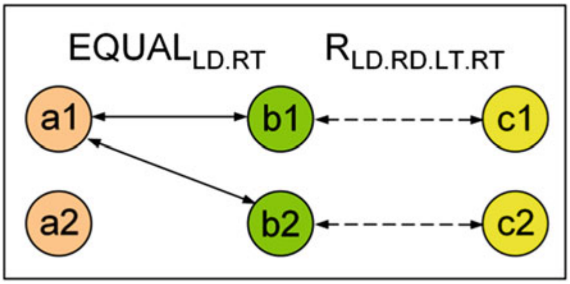
Similar interdependencies can be found for class relations between a class hierarchy and a class outside of the hierarchy (Fig. 8a), class relations that connect two independent class hierarchies (Fig. 8b) and class relations between three hierarchy levels (Fig. 8c).

These observations show that there are dependencies between the class relations of different hierarchy levels. The interdependencies of relations in class hierarchies result from the fact that the class relations at a higher hierarchy level subsume those of the lower levels. The entities of the classes of the subsuming relation are divided between the subclasses. Correspondingly, **class relation subsumption** means that the subsuming relation includes all instance relations of the subsumed class relations.

At this stage the constraints that the subsumption exposes on concrete class relations are not defined. A detailed set of rules to describe the dependency for a set of abstract class relations or directly for cardinality properties is subject to future research. These rules will extend the consistency requirements in class relations networks, which are implied by their compositions and converses (Sect. 6).

The four elementary hierarchical settings (Figs. 5 and 8) and their interdependencies can serve as building blocks for an analysis of more complex class hierarchies. Therefore the constraints that are exposed by the interdependencies must be defined independently of the number of involved subclasses and also independent of the number of involved hierarchy levels.

Fig. 9 Inconsistent combination of class relations



8 Further Open Issues

The described inference approaches separately analyze the reasoning properties of the abstract class relations and those of the instance relations. However, some combinations of instance and abstract class relations lead to conflicts that cannot be found in this way. For example, the combination of '$EQUAL_{LD\ RT}(A, B)$' and the abstract class relation '$R_{LD\ RD\ LT\ RT}(B, C)$' is impossible (Fig. 9). This is due to the specific identity properties of the '*equal*' instance relation and the cardinality properties of the two abstract class relations.

'$EQUAL_{LD\ RT}(A, B)$' requires at least one instance of '*A*' that is equal to at least two instances of '*B*', because it is defined as not *right-definite* (Eq. 4). Since equal is symmetric and transitive this implies that the corresponding '*B*' instances are also equal ('*b1*' equals '*b2*' in Fig. 9). Thus if one of these '*B*' instances has an instance relation to a '*C*' instance, the other '*B*' must have the same relation to this '*C*'. This means for the scene in Fig. 9 that both '*B*' should have the same instance relation to both '*C*'. This is in conflict with '$R_{LD\ RD\ LT\ RT}(B, C)$', because this class relation is defined as *left-definite* and *right-definite* (Eq. 5). A generic description of such conflicts is the subject of further research.

9 Conclusion

The interoperable exchange of data of different domains and application areas requires semantic descriptions of the data. The explicit knowledge about logical properties and interrelations between relations is fundamental for automated reasoning based on such descriptions (Bittner et al. 2009). The proposed class relations and reasoning methods provide a basis for the formalization of such knowledge. Nevertheless, the formal definition of class relations and their logical properties are still hardly researched yet.

A relation among the classes is not subject to the same logical properties as the applied relation between instances because the cardinality restrictions must also be considered for reasoning. In general, the reasoning algorithms at the class level are similar to those of the instance relations. However, due to the higher complexity of the class relations, the detection of conflicts and redundancies is more extensive. This chapter summarizes current research results with regard to class relation reasoning based on properties such as symmetry, composition and conceptual neighborhood. Therefore a set of 17 abstract class relations has been exemplarily used. This shall provide a basic framework, which can be extended for other possibly more complex types of class relations. Furthermore, future research should particularly concern the dependencies of class relations in class hierarchies, since the class concepts described in data models or ontologies are usually hierarchically structured.

Class relations can be used in combination with any type of instance relation. To enable a flexible use of reasoning algorithms, the inference rules must be defined in a generic way. This means they must hold for abstract class relations or directly for cardinality properties and separately integrate the logical properties of the instance relations.

A major advantage of class relations is their logical soundness. Their logical properties allow for the detection of conflicts and redundancies in sets of class relations. This is of interest for many application areas, for example for the management of spatial semantic integrity constraints (Mäs 2007), geospatial ontologies (Bittner et al. 2009), conceptual data modeling and usability evaluation (Mäs 2009b).

Most of the discussed reasoning algorithms have been implemented in a research prototype that is available at http://www.stephanmaes.de/classrelations.html. The tool is implemented as a plug-in of the Protégé ontology editor.

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References

Allen JF (1983) Maintaining knowledge about temporal intervals. Commun ACM 26(11):832–843

Agarwal P (2005) Ontological considerations in GIScience. Int J Geogr Inf Sci 19(5):501–536

Baumeister J, Seipel D (2006) Verification and refactoring of ontologies with rules. In: Staab S, Svátek V (eds) Managing knowledge in a world of networks, 15th international conference, EKAW 2006, LNCS 4248. Springer, Podebrady, pp 82–95

Bittner T, Donnelly M, Smith B (2009) A spatio-temporal ontology for geographic information integration. Int J Geogr Inf Sci 23(6):765–798

Brachman RJ (1983) What IS-A is and isn't: an analysis of taxonomic links in semantic networks. Computer 16(10):30–36

Cohn AG, Hazarika SM (2001) Qualitative spatial representation and reasoning: an overview. Fundamenta Informaticae 46(1–2):1–29

Donnelly M, Bittner T (2005) Spatial relations between classes of individuals. In: Cohn AG, Mark DM (eds) COSIT 2005. LNCS, vol 3693. Springer, Heidelberg, pp 182–199

Donnelly M, Bittner T, Rosse C (2006) A formal theory for spatial representation and reasoning in biomedical ontologies. Artif Intell Med 36(1):1–27

Egenhofer MJ, Herring J (1991) Categorizing binary topological relationships between regions, lines, and points in geographic databases. Technical report, Department of Surveying Engineering, University of Maine, Orono, ME
Egenhofer MJ, Frank AU (1992) Object-oriented modeling for GIS. J Urban Reg Inf Syst Assoc 4(2):3–19
Egenhofer MJ, Al-Taha KK (1992) Reasoning about gradual changes of topological relationships. In: Theories and methods of spatio-temporal reasoning in geographic space, International conference GIS—from space to territory: theories and methods of spatio-temporal reasoning, LNCS, vol 639, pp 196–219, Springer
Egenhofer M (1994) Deriving the composition of binary topological relations. J Vis Lang Comput 5(2):133–149
Egenhofer MJ, Mark DM (1995) Modelling conceptual neighbourhoods of toplogical line-region relations. Int J Geogr Inf Syst 9(5):555–565
Egenhofer M (2011) Reasoning with complements. In: De Troyer O, Bauzer Medeiros C, Billen R, Hallot P, Simitsis A, Van Mingroot H (eds) Advances in conceptual modeling. Recent developments and new directions; ER 2011, vol 6999 of Lecture notes in computer science. Springer, San Diego, pp 261–270
Frank AU (1992) Qualitative spatial reasoning about distances and directions in geographic space. J Vis Lang Comput 3:343–371
Freksa C (1991) Qualitative spatial reasoning. In: Mark DM, Frank AU (eds) Cognitive and linguistic aspects of geographic space. Kluwer Academic Press, Dordrecht, pp 361–372
Freksa C (1992a) Using orientation information for qualitative spatial reasoning. In: Frank AU et al (eds) Theories and methods of spatio-temporal reasoning in geographic space. LNCS, vol 639. Springer, Pisa, pp 162–178
Freksa C (1992b) Temporal reasoning based on semi-intervals. Artif Intell 54(1):199–227
Grigni M, Papadias D, Papadimitriou C (1995) Topological inference. In: Proceedings of the International Joint Conference of Artificial Intelligence (IJCAI), pp 901–906
Hernández D (1994) Qualitative representation of spatial knowledge, LNCS, vol 804 of Lecture notes in artifcial intelligence. Springer, Heidelberg
Hornsby K, Egenhofer MJ, Hayes PJ (1999) Modeling cyclic change. In: Chen PP et al (eds) Advances in conceptual modeling: Proceedings of ER '99 workshops on evolution and change in data management, reverse engineering in information systems, and the world wide web and conceptual modeling, LNCS, vol 1727. Springer, Paris, pp 98–109
Kurata Y, Egenhofer MJ (2006) The head-body-tail intersection for spatial relations between directed line segments. In: Raubal M et al (eds) Geographic information science, 4th international conference, LNCS, vol 4197. Springer, Berlin, pp 269–286
Mäs S, Wang F, Reinhardt W (2005) Using ontologies for integrity constraint definition. In: Wu L et al (eds) Proceedings of the 4th international symposium on spatial data quality, ISSDQ 2005, pp 304–313
Mäs S (2007) Reasoning on spatial semantic integrity constraints. In: Winter S et al (eds) COSIT 2007. LNCS, vol 4736. Springer, Heidelberg, pp 285–302
Mäs S (2008) Reasoning on spatial relations between entity classes. In: Cova TJ et al (eds) 5th international conference geographic information science (GIScience), Park City, Utah, USA; LNCS, vol 5266, pp 234–248
Mäs S (2009a) On the consistency of spatial semantic integrity constraints. PhD thesis, University of the Bundeswehr, Munich (published in: Dissertations in Geographic Information Science, GISDISS 004; IOS Press)
Mäs S (2009b) Harmonisation of spatial semantic integrity constraints. In: AGILE 2009 pre-conference workshop "challenges in geospatial data harmonisation", Hannover, Germany
Mäs S, Reinhardt W (2009) Categories of geospatial and temporal integrity constraints. In: International conference on advanced geographic information systems and web services, GEOWS 2009, pp 146–151, IEEE Computer Society

Rodriguez A, de Weghe NV, Maeyer PD (2004) Simplifying sets of events by selecting temporal relations. In: Egenhofer MJ et al (eds) Geographic information science. Third international conference, GIScience 2004, LNCS, vol 3234. Springer, Heidelberg, pp 269–284

Tarquini F, Clementini E (2008) Spatial relations between classes as integrity constraints. Trans GIS 12(1):45–57

Creating Perceptually Salient Animated Displays of Spatiotemporal Coordination in Events

Thomas F. Shipley, Sara Irina Fabrikant and Anna-Katharina Lautenschütz

Abstract Geographic phenomena exist within a multi-dimensional space–time continuum. Dynamic geographic phenomena at all levels of scale can be conceptualized and represented as spatiotemporal patterns, space–time processes, or events—changes within or between objects that are experienced as bounded by psychologically discreet beginnings and ends. Humans rarely care about spatiotemporal entities in isolation. Visualization and analysis approaches that focus on individual spatiotemporal phenomena in isolation are likely doomed to failure because they miss the relational structure humans use to process and reason about events. We contend that a static and geometric decompositional approach to spatiotemporal patterns and processes limits the tools that can be applied to a broad class of spatiotemporal data that are important to users. This class includes events where there is a spatiotemporal coordination among or within objects, such as a car changing its movement direction because of an approaching car, or a hurricane not making landfall because of changing atmospheric conditions. Often such coordination allows inferences about causal relations among the components of an event. In this chapter we argue for the need for perceptually salient and cognitively inspired animated displays that help humans more effectively and efficiently detect relationships in complex events.

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1 Introduction

Dynamic geographic phenomena can be generally conceptualized and represented as spatiotemporal patterns (e.g., trajectories of people or animals, flows of chemicals, or movements of eyes over maps), space–time processes (climate change, urban growth, human spatial cognition), or events (discrete changes over time e.g., earthquakes, Winter Olympics, or human eyes fixating on a perceptually salient object in a scene). Here we use the term *event* to refer to changes over time that are discretized by the observer and are defined as "a segment of time at a given location that is conceived by an observer to have a beginning and an end" (Zacks and Tversky 2001 page 3; for further elboration see e.g. Kurby and Zacks 2008). Events are mental units and are considered as our building blocks of the temporal realm (Schwan and Garsoffky 2008; Shipley 2008). There may be an objective basis for the psychological boundaries in time in an event. For example, an earthquake begins when the ground begins moving and ends when the movement ends. However, there is not always a clear objective beginning or end to a psychological event. For example, does *a wedding* begin when the first guest arrives, or when the bride enters the church—there is no defining moment of wedding onset in the flurry of nuptial activities, yet humans treat the event as well bounded in space and time. Note, events are not necessarily brief abrupt changes; events may be spread out over time, such as a war, or an ice age.

With increasing interest in and use of animations to present and explore complex spatiotemporal data, the research community has developed highly sophisticated visual analytic tools to analyze spatiotemporal patterns for experts and impressive animation tools to present spatiotemporal data to a broader audience (Andrienko et al. 2008, 2010). Animations of spatiotemporal phenomena have been widely used to try to reveal and understand environmental processes and the relations between changing objects (Harrower 2004; Dorling and Openshaw 1992). Cartographic animations include the visualization of events in chronological order e.g., diffusion processes of diseases, human migration, or traffic simulations (Harrower and Fabrikant 2008). In each case, structure or regularities that exist over time might be invisible, or at best obscure, in static snapshots. As these tools develop it will be important to specifically consider research on the information that users can get from animations (e.g., Lowe and Schnotz 2008), as the perceptual and cognitive systems of the users will determine the salience of the patterns and ultimately how effective users will be in detecting and reasoning about spatiotemporal patterns.

Users are often unreliable in their estimates of the quality of information they can get out of animations, and in judging the best visualizations for extracting specific information (e.g., Hegarty and Kriz 2008; Hegarty et al. 2009). Here we consider two aspects of animation design, the number and spacing of moving elements, that influence what can be seen in motion displays. Basic movement properties (Dodge et al. 2008) are not always clearly visible to the viewer in displays with multiple motions due to masking of one motion by another. Furthermore, in cluttered animations attention problems can arise due to limits imposed by the cognitive load of keeping track of multiple variables (Harrower 2007) or by perceptual bottlenecks (Fabrikant and Goldsberry 2005). The result is that it can be hard to extract information about the motion of one or a few points due to other motions. It should be noted that broad arguments about failures of animations are at present limited by the relatively narrow set of domains in which research has been conducted. Many of the studies on animation conducted by cognitive scientists focused on mechanical systems, or processes with real, observable movement of objects that are constrained by physical properties (e.g., moving parts of complex mechanical systems). These studies have not yet addressed the relative efficiency of static and animated displays for geographic visualization of abstract, non-tangible dynamic processes represented in maps (e.g., diffusion, tectonic subduction, meteorological changes, etc.). While Tversky and colleagues have written extensively about the lack of benefit of animations over static depictions of space–time phenomena (e.g., Tversky et al. 2002), there is still an open question, is the failure of animations to live up to their expected potential an inherent problem with presenting information over time, or simply a consequence of poor choices in the design of most animations (Fabrikant et al. 2008a)? With the development of visual analytic tools it will be important to consider research on the information that users can get from animations (e.g., Lowe and Schnotz 2008), as the perceptual and cognitive systems of the users will determine the salience of the patterns and ultimately how effective the user can detect and reason about spatiotemporal patterns.

2 Our Perspective

2.1 Thoughts on Animations

Lowe's (1999) research on complex interactive weather map animations is often cited as an example where animations fail. However, one of Lowe's (1999) research findings was that participants tended to extract information based on perceptual salience rather than thematic relevance. Lowe (1999) offered several reasons why the animations might have failed, including, participants' lack of relevant domain expertise, the complexity of the depicted system, and more importantly the manner in which the system was depicted. So, rather than animations being inherently problematical, one should focus on interactions between the design characteristics and user characteristics.

Cartographers have proposed design principles for animated maps, but rarely, if at all, have these proposals been experimentally tested. DiBiase et al. (1992) suggest that Bertin's (Bertin 1983) visual variables, and later extensions proposed by Morrison (1974) for static maps, are applicable to map animations, such as the addition of color saturation, pattern, crispness, resolution, transparency and arrangement. MacEachren (1995) and DiBiase et al. (1991, 1992) demonstrate the successful implementation of Bertin's variables in map animations in educational material. DiBiase et al. (1992) and MacEachren (1995) further suggest additional design variables specifically for the display of spatiotemporal geographic phenomena. The six variables are: (1) display moment or display date/time (e.g., when in a display does an event become visible), (2) scene duration (e.g., how long a scene is displayed), (3) scene frequency (e.g., frame rate per second, or how fast graphic frames follow one another), (4) scene order (e.g., sequence in which graphics are displayed), (5) rate of change between scenes (e.g., the magnitude of change visible between two sequentially displayed scenes), and (6) synchronization (e.g., the juxtaposition of two concurrent events in the same display). Except for synchronization all six variables have been evaluated, but only in an exploratory and qualitative fashion (Köbben and Yaman 1996). In Blok's (2000, page 18) words: "Synchronization is the possibility to run two (or more) temporal animations simultaneously, and shift them in time so that patterns are in phase, and relationships between data sets can be discovered (e.g., the pattern between emission levels of pollution and the occurrence of certain diseases may be similar, but may only become clear if the time lag has been removed). The question arises whether synchronization can be seen as a variable." We would argue that of these variables synchronization is a critical area for attention as it captures a psychologically critical aspect of events, namely the temporal relationship among changing elements.

2.2 Thoughts on Perception of Movement

In this chapter we argue that research on visualizations should work to develop techniques for presenting and highlighting spatiotemporal relations, because relations are the focus of human perceptual processes. The Gestalt psychologists first made an argument for the centrality of relations (Kohler 1947) and the principle has been embraced by all modern approaches to visual perception.

First, consider two classic examples, the perception of shape and the perception of apparent motion (the appearance of motion when images of stationary objects are presented in rapid succession and thus are seen to move). Object shape is perceived based on relationships within the contours or parts of an object. For example, a triangle may be defined by just three points—one at each vertex. Three non-collinear dots are sufficient to see a triangle, but remove one dot and the viewer is not left with two-thirds of a triangle. There is an emergent property, triangular shape, only visible when three elements (dots) are present; this observation was key to the Gestalt psychologists' argument that human perception could not be understood by accumulation of aspects of individual elements. A similar analysis applies to the appearance of motion in movies. There is no motion evident in any single frame; the motion is only evident by virtue of the relationship between locations of objects and the time between their appearance and disappearance from one frame to the next.

Lest the reader think that this idea is restricted to the highly simplified cases of triangles made of dots and frame-flip animations, we offer a common experience that reveals the deeply relational nature of perception and will perhaps serve to give pause to reductionist inclinations. Imagine a pigeon walking along the ground. Most people will report the pigeon to appear to be moving its head back and forth as it walks (this will be true whether you imagine the scene or you stop reading this chapter and find a walking pigeon). The actual movement of the pigeon's head relative to the environment is an alternation of quick forward movements followed by relative stability, as the body of the pigeon moves forward. This pattern of movement provides the pigeon a stable platform for vision with a relatively short period of time when the movement of the eye would make detection of a moving predator difficult. Why does the pigeon appear to move its head forwards and backwards? Because the movement of the head is not perceived in isolation. All things are seen to move relative to other things. In the case of the pigeon the likely explanation is that the visual system extracts the common forward motion of all of the parts of a pigeon. This common motion is seen as the movement of the object, relative to the larger environment. The local motions of the pieces are then seen in relation to each other. Here the common vector of the forward motion is removed from the local motion vectors and thus the head appears to move back and forth—as it does, relative to the body, but not relative to the larger environment (Johansson 1973).

Humans rarely care about any elemental feature of a scene in isolation. Thus approaches to information displays that focus on individual elements are likely doomed to failure because they miss the relational structure humans use to behave. This idea may be counter intuitive and thus counter to a scientist's natural inclination to analyze and decompose a complex phenomenon into its elements.

2.3 Thoughts on Visualizations

Only a few researchers have looked specifically at modeling and visualizing relationships of spatiotemporal coordination within events (Laube et al. 2005; Andrienko and Andrienko 2007; Stewart and Yuan 2008), and even fewer have done so using animated displays to depict spatiotemporal information in a perceptually salient and cognitively inspired manner (Fabrikant and Goldsbery 2005; Griffin et al. 2006; Klippel and Li 2009). Visualization analyses that consider spatiotemporal information often collapse location information over time to highlight path relationships (Laube et al. 2005). For example, data on the locations of animals over time may be used to analyze how they move through a landscape. Such relationships are analogous to shape relationships, as many of the geometric properties that are important for perceptual processing of static shapes are also relevant for perception of paths (Shipley and Maguire 2008; Maguire et al. 2011).

Analyses that collapse time, however, obscure another important class of relations, temporal relationships among objects. By collapsing across time it is hard to see relationships among object movements. For example, the relationship between predator movements and prey movements would be lost when time is collapsed (indeed it would be hard to distinguish the chaser from the chased). At a larger scale plotting the location over a year of a Sooty Shearwater would make visible an incredible flight path from Chile to Alaska, but the relationship between time of year, or weather patterns, and migration would be lost. The perceptual system is designed to extract relational information because such information allows smooth coordination with ongoing events. The spatiotemporal dependencies among the parts of an event (for example moving objects) can reveal something of the event's dynamics. Understanding the dynamics can in turn allow predictions about what actions will influence ongoing events.

Shipley and Zacks (2008) describe events as things that happen with a reference to a location in time. Events are mental units and are considered as our building blocks of the temporal realm (Schwan and Garsoffky 2008; Shipley 2008). Although events often involve motion, their unitary nature allow analogies to be drawn between events and objects (Casati and Varzi 2008; Schwartz 2008; Shipley 2008; Shipley and Maguire 2008). While objects belong to the spatial dimension without a temporal frame of reference, events are set in the temporal dimension (Casati and Varzi 2008; Shipley 2008; Tversky et al. 2008) and occur when objects change or interact (Shipley 2008). The challenge from the perspective of creating visualizations is knowing how to convey information about temporal interactions. Here the key is to make salient a spatiotemporal relationship among elements. Below we briefly review two cases from event perception research that indicates the visual system picks up patterns that are defined by temporal relations among objects—action recognition and perception of causality. These cases make it clear that users can readily pick up some very complex inter-element coordination. A critical research goal in this area should be to understand what makes certain spatiotemporal patterns salient.

In perception research, one of the most carefully studied cases where the visual system combines information across multiple elements is the case of biological motion perception in point-light displays. For this research human action is reduced to thirteen points, one for each of the major joints on the body—head, wrists, elbows, shoulders, hips, knees, and ankles. In isolation each element's motion appears complex but not human-like (it may look, for example, like a fly buzzing around). When animated together the motions of these points reveal a human acting. These animations can reveal complex aspects of the events, including the gender of the actor, and even the weight of an invisible object from the lifting motion (Koslowski and Cutting 1977; Runeson and Frykholm 1981).

Extracting information about action requires all (or most) of the joints to be visible. A single point's motion is insufficient to reveal the whole action.

Some readers may be familiar with work by Troje (e.g., Troje and Westhoff 2006) who has shown that observers can detect the presence of an animate being from the motion of a single dot tracing the path of a foot. This is not a counter example to our argument. Troje and Westhoff (2006) have argued that this phenomenon represents a low-level pre-attentive visual process that detects the presence of an animate being. This process appears to act something like an accumulator and detects the shape of the motion path. The process can detect a foot moving, but not identify action, which is evident only in the relations among parts of the body.

The basis for recognition of events in such displays appears to be an ability to extract information about the event dynamics, i.e. the forces acting on the bodies in the scene. The spatial structure of the objects is less important than the coordinated acceleration pattern that defines such forces (Troje 2002; Shipley 2003). Analogously, an analysis of motion paths may allow detection of basic event properties but not allow a more sophisticated understanding of interactions among objects evident in higher order spatiotemporal regularities. Indeed subjects find it hard to align static snap shots of an event to a depiction that includes the event dynamics (Lowe et al. 2011).

The visual processing of spatiotemporal coordination of elements in events is not restricted to human action, humans also perceive more complex categorical features of events such as cause (Michotte 1963), and social interactions, like chasing and following (Heider and Simmel 1944). Although the processing of basic physical and social motion patterns may be near universal, even more complex dependencies may be picked up with experience. For example, professional European-football players can recognize patterns of movements based on plays where novices are much less accurate (North et al. 2009). Skill in detecting higher order spatiotemporal regularities may be acquired through a type of perceptual learning where repeated exposure to a complex spatiotemporal pattern allows the visual system to extract parts of the pattern that spatially or temporally predict other parts (e.g., Aslin et al. 1998). Although such learning can occur without direct instruction, guiding an observer's attention to the regularities will likely facilitate learning. We contend that a static and geometric decompositional approach to spatiotemporal patterns and processes will limit development of tools that can be applied to a broad class of spatiotemporal data, or events, that are important to users.

3 Implications for Animation Design

Cartographers generally choose appropriate visual variables to make thematically relevant information perceptually salient, to align with the theme of the map, to fit the purpose of the map and its usage context, and to fit the audience (Dent 1999).

There is an open question as to whether controlled changes in an animation design, i.e., making the thematically relevant information perceptually salient through (carto)graphic design principles can overcome the observed drawbacks of animation discussed above (Fabrikant and Goldsberry 2005; Harrower and Fabrikant 2008). Recent empirical findings from eye-movement experiments provide support for the contention that generally, static small-multiple displays (for example, where multiple graphics that depict variations in different quantities for the same time period are grouped together) cannot be computationally and informationally equivalent to non-interactive animations (Fabrikant et al. 2008a). Here *informationally equivalent* means that any information (value or relationship between values) encoded in one type of display can be found or inferred in the other, and *computationally equivalent* means that any inference from information in one display can be made with equivalent ease by the user in the other display. Simply put, due to differences in the way humans process static displays and animated displays equal information is not equally easy to use to make inferences, and making displays equivalently easy to use might require adding information to one or the other display type.

Despite claims about animation failures, the computational and informational properties of displays (Larkin and Simon 1987) depend on the task, the information extraction goal, and the decision-making context (Fabrikant et al. 2008a). Eye-movement studies have shown that animation design principles can alter people's viewing behavior (Fabrikant and Goldsberry 2005; Fabrikant et al. 2008b). The ease of extracting information from an animation (as evidenced by eye movement behavior) is influenced by the subject's task (i.e., simple or complex tasks) and display design (i.e., interactivity, animation speed, or tweening). Fabrikant and colleagues have suggested, based on preliminary results from a series of experiments on animations (Fabrikant et al. 2008b), that static and animated displays cannot be informationally and computationally equivalent at the same time (Fabrikant et al. 2008a). They found that participants ran interactive animations at significantly higher speeds in a tweened condition (Fabrikant et al. 2008b). This might mean that tweening, which allows the user to more easily track the change of specific elements or features helps people detect small changes because they can be anticipated. Successful anticipation in turn allows participants to run the animation at higher speeds, and to take advantage of visually continuous motion paths for more efficient change detection. They also found that even though participants had a choice to run the animation forward and backward in the interactive map animation condition (to make the interactive animation computationally equivalent to a static small multiple display), they chose to run the animation significantly more often forward than backwards. In other words, just providing interaction mechanisms (i.e., a backward animation function) does not automatically mean that users will employ them, even though this function might help them to make better and faster inferences.

Generally humans orient toward regions of visual discontinuity. Thus, if a critical relationship in an animation is known and the designer has the intent of focusing the users' attention on that relationship, then elements of the relationship could be conveyed in such a way that they appear discontinuous from the background. This could be achieved by signaling the information with luminance transients (dots or regions changing brightness, e.g., blinking on and off), or velocity discontinuities (e.g., a region in a field of uniformly moving elements where some elements are moving in a different direction). Alternatively, if the designer does not want to commit to a particular relationship, they should work to avoid having the viewer distracted by transients that could occur with abrupt changes in luminance, motion, or element density. Here tweening could help avoid confusing velocity signals.

There is a context dependent trade-off that a display designer has to make. If an animation is interactive then it will be necessary to either add additional information between frames, or estimate using interpolation (tweening) between map frames, to avoid attentional blindness effects. On the other hand, if a non-interactive animation is used, then informational content (relative to static small multiples) must be reduced as well. Here simplifying the data might involve depicting less complex individual map frames (i.e., reducing the numbers of classes) in the animation, or reducing the animation speed, to avoid cognitive overload—as has been suggested by Harrower (2003, 2007). The efficiency with which the observer can extract information from displays differs for different types of displays. Sound space–time visualization requires a cognitive conceptual framework for animation development (Lautenschütz 2011). Generally, understanding how humans process spatiotemporal data must be a part of the development of a GIScience of spatiotemporal visualizations.

Understanding users' cognitive limitations and strengths should help to establish "best practices" for display solutions and guides researchers to consider how to better design visual analytics displays of spatiotemporal data. In turn, empirically validating design choices for animations may lead to an enhanced understanding of when animations work to convey information and which factors are important to understand movement.

4 Conclusion

In sum, we suggest that analyzing space–time phenomena in a reductive, decompositional, fashion and focusing on geometrical analyses of patterns in isolation will limit users' understanding of dynamic environmental phenomena and processes. Animations used to represent and analyze space–time phenomena have arguably not lived up to early expectations, however, good animation design principles are not yet established. Animation design principles must provide guidance for both the properties of an individual element over time, and the spatial and temporal context. Furthermore, the user must also be considered. Their expertise and familiarity with complex spatiotemporal patterns will influence how they process animations, and their specific task will also guide attention to specific spatial and spatiotemporal locations. We conclude that an approach to visualizing spatiotemporal patterns and processes requires a solid consideration of the perceptual and cognitive processes of the user to develop tools that can be applied to a broad class of spatiotemporal data.

References

Andrienko N, Andrienko G (2007) Designing visual analytics methods for massive collections of movement data. Cartographica 42(2):117–138

Andrienko G, Andrienko N, Dykes J, Fabrikant SI, Wachowicz M (2008) Geovisualization of dynamics, movement and change: key issues, and developing approaches in visualization research. Special issue on geovisualization of dynamics, movement and change. Inf Vis 7(3):173–180

Andrienko G, Andrienko N, Demsar U, Dransch D, Dykes J, Fabrikant SI, Jern M, Kraak M-J, Schumann H, Tominski C (2010) Space time, and visual analytics. Int J Geogra Inf Sci 24(10):1577–1600

Aslin RN, Saffran JR, Newport EL (1998) Computation of conditional probability statistics by 8-month-old infants. Psychol Sci 9:321–324

Bertin J (1983) Semiology of graphics: diagrams, networks maps. University of Wisconsin Press, Madison

Blok C (2000) Dynamic visualization in a developing framework for the representation of geographic data. Cybergeo, article 135, "3O ans de sémiologie graphique. http://cybergeo.revues.org/index509.html. Accessed 7 April 2010

Casati R, Varzi AC (2008) Event concepts. In: Shipley TF, Zacks JM (eds) Understanding events: from perception to action. Oxford University Press, New York

Dent BD (1999) Cartography. Thematic map design. Wm. C. Brown, Dubuque

DiBiase D, MacEachren AM, Krygier JB, Reeves C, Brenner A (1991) Animated cartographic visualization in earth system science. In: Proceedings of the 15th conference of the international cartographic association, Bournemouth, U.K. 223–232

DiBiase D, MacEachren AM, Krygier JB, Reeves C (1992) Animation and the role of map design in scientific visualization. Cartography Geogr Inf Syst 19(4):201–214, 265–266

Dodge S, Weibel S, Lautenschütz A-K (2008) Towards a taxonomy of movement patterns. Inf Vis 7:240–252

Dorling D, Openshaw S (1992) Using computer animation to visualize space-time patterns. Envirn Planning B: Planning Des 19:639–650

Fabrikant SI, Goldsberry K (2005) Thematic relevance and perceptual salience of dynamic geovisualization displays. In: Proceedings, 22th ICA/ACI international cartographic conference: A Coruña, Spain, 9–16 July 2005

Fabrikant SI, Rebich-Hespanha S, Andrienko N, Andrienko G, Montello DR (2008a) Novel method to measure inference affordance in static small multiple displays representing dynamic processes. Cartogra J 45(3):201–215

Fabrikant SI, Rebich S, Montello DR, Andrienko G, Andrienko N (2008b) A visual analytics approach to evaluate inference affordance from animated map displays. GIScience 2008 Pre-Conference workshop on Geospatial Visual Analytics, Park City, UT. http://geoanalytics.net/GeoVisualAnalytics08/a15.pdf. 23 Sept 2008

Griffin AL, MacEachren AM, Hardisty F, Steiner E, Li B (2006) A comparison of animated maps with static small-multiple maps for visually identifying space-time clusters. Ann Assoc Am Geogr 96(4):53–740

Harrower M (2003) Tips for designing effective animated maps. Cartogr Perspect 44:63–65

Harrower M (2004) A look at the history and future of animated maps. Cartographica 39(3):33–42

Harrower M (2007) The cognitive limits of animated maps. Cartographica 42(4):269–277
Harrower M, Fabrikant SI (2008) The role of map animation in geographic visualization. In: Dodge M, Turner M, McDerby M (eds) Geographic visualization: concepts, tools and applications. Wiley, Chichester
Hegarty M, Kriz S (2008) Effects of knowledge and spatial ability on learning from animation. In: Lowe R, Schnotz W (eds) Learning with Animation. Cambridge University Press, Cambridge
Hegarty M, Smallman HS, Stull AT, Canham M (2009) Na cartography: how intuitions about display configuration can hurt performance. Cartographica 44:171–187
Heider F, Simmel M (1944) An experimental study of apparent behavior. Am J Psychol 57:243–249
Johansson G (1973) Visual perception of biological motion and a model for its analysis. Percept Psychophys 14:201–211
Klippel A, Li R (2009) The endpoint hypothesis: a topological-cognitive assessment of geographic scale movement patterns. In: Stewart HK, Claramunt C, Denis M, Ligozat G (eds.) Proceedings of Spatial information theory, 9th international conference, COSIT 2009 Springer, Berlin
Köbben B, Yaman M (1996) Evaluating dynamic visual variables. In: Ormeling FJ, Köbben B, Perez Gomez R (eds.) Proceedings of the seminar on teaching animated cartography, Madrid, Spain, August 30–September 1, 1995. International Cartographic Association, pp 45–51
Kohler W (1947) Gestalt psychology. Liveright, New York
Koslowski LT, Cutting JE (1977) Recognizing the sex of a walker from a dynamic point-light display. Percept Psychophys 21:575–580
Kurby CA, Zacks JM (2008) Segmentation in the perception and memory of events. Trends Cogn Sci 12(2):72–79
Larkin J, Simon H (1987) Why a diagram is (sometimes) worth ten thousand words. Cogn Sci 11:65–99
Laube P, Imfeld S, Weibel R (2005) Discovering relative motion patterns in groups of moving point objects. Int J Geograph Inf Sci 19(6):639–668
Lautenschütz A-K (2011) Assessing the relevance of context for visualizations of movement trajectories. Dissertation, University of Zurich
Lowe RK (1999) Extracting information from an animation during complex visual learning. Eur J Psychol Educ 14:225–244
Lowe R, Schnotz W (eds) (2008) Learning with animation. Cambridge University Press, Cambridge
Lowe R, Schnotz W, Rasch T (2011) Aligning affordances of graphics with learning task requirements. Appl Cogn Psychol 25: . doi:10.1002/acp.1712
MacEachren AM (1995) How maps work, representation, visualization, and design. The Guilford Press, New York
Maguire M, Shipley TF, Brumberg J, Ennis M (2011) Similarities in object and event segmentation: a geometric approach to spatiotemporal path segmentation. Spatial Cogn Comput 11:254–279
Michotte A (1963) The perception of causality. Basic Books, New York
Morrison JL (1974) A theoretical framework for cartographic generalization with the emphasis on the process of symbolization. Int Yearb Cartogr 14:115–127
North JS, Williams MA, Hodges N, Ward P, Ericsson KA (2009) Perceiving patterns in dynamic action sequences: investigating the processes underpinning stimulus recognition and anticipation skill. Appl Cogn Psychol 23(6):878–894
Runeson S, Frykholm G (1981) Visual perception of lifted weight. J Exp Psychol Hum Percept Perform 7(4):733–740
Schwan S, Garsoffky B (2008) The role of segmentation in perception and understanding of events. In: Shipley TF, Zacks J (eds) Understanding events: from perception to action. YorkOxford University Press, New
Schwartz R (2008) Events are what we make of them. In: Shipley TF, Zacks J (eds) Understanding events: from perception to action. Oxford University Press, New York

Shipley TF (2003) The effect of object and event orientation on perception of biological motion. Psychol Sci 14:377–380

Shipley TF (2008) An invitation to an event. In: Shipley TF, Zacks J (eds) Understanding events: from perception to action. Oxford University Press, New York

Shipley TF, Maguire MJ (2008) Geometric information for event segmentation. In: Shipley TF, Zacks J (eds) Understanding events: from perception to action. Oxford University Press, New York

Shipley TF, Zacks JM (eds) (2008) Understanding events: from perception to action. Oxford series in visual cognition. Oxford University Press, New York

Stewart Hornsby K, Yuan M (eds) (2008) Understanding dynamics of geographic domains. CRC Press, New York

Troje NF (2002) Decomposing biological motion: a framework for analysis and synthesis of human gait patterns. J Vis 2:371–387

Troje NF, Westhoff C (2006) Inversion effect in biological motion perception: evidence for a "life detector"? Curr Biol 16:821–824

Tversky B, Morrison J, Betrancourt M (2002) Animation: can it facilitate? Int J Hum Comput Stud 57(4):247–262

Tversky B, Zacks JM, Martin Hard B (2008) The structure of experience. In: Shipley TF, Zacks J (eds) Understanding events: from perception to action. Oxford University Press, New York

Zacks JM, Tversky B (2001) Event structure in perception and cognition. Psychol Bull 127(1): 3–21

Exploring and Reasoning About Perceptual Spaces for Theatre, New Media Installations and the Performing Arts

Geoffrey Edwards, Marie Louise Bourbeau, Gérard Ligozat, René Dupéré and David Duguay

Abstract This work extends earlier efforts to develop perceptual models to support qualitative spatial reasoning. Earlier work by the same team led to the development of powerful visual and proximity models. We discuss these models and their use to support analysis and design of theatrical productions. This analysis highlights a significant feature lacking from these models—the ability to model soundscapes. A new model is presented that addresses this lack—the model draws on the Huygen's Principle of Wave Propagation to supplement the earlier models with a component that handles sound. The resultant segmentation of space is presented via a worked out example. Then, as a way of testing the relevancy and power of the new model, an artistic presentation was designed and presented to the conference. Using Homer's Odyssey to provide the narrative structure, a 22-minute real-time performance involving dozens of virtual sound sources moving around in space was constructed, supported by in-house software developed to handle the manipulation of the audio tracks and virtual sound sources, and interfaced with a Denon 7.1 sound system. The artistic performance consisted of reproducing several virtual sound geographies in a manner consistent with the narrative. The use of a qualitative perceptual model to drive the real-time manipulation of virtual sound sources is, to our knowledge, a first. The artistic presentation served not only to illustrate the use of the model, but also to explore its power and relevancy to design initiatives with the performing arts.

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1 Introduction

As part of an ongoing effort to develop qualitative models of environmental space in support of spatial reasoning, there is an interest in extending earlier work aimed at understanding visual and proximal spaces to incorporating sound spaces. Beyond an interest in completeness, one of the applications of this work we have been exploring is in support of the performing arts—in particular theatre, whether within a traditional theatre (i.e. an interior space) or *extra muros.* For the dramatic arts, a full model necessarily includes an understanding of sound and the spaces it creates, along with visual and proximal considerations. Furthermore, contemporary use of sound within a theatrical setting has become multiplex. Traditionally limited to the voices of the actors and some form of ambient sound available to highlight certain events, the modern use of sound may include a variety of pre-recorded sound "projections" into various parts of the dramatic space and may include sounds that are created and modified "live" through gesture or other dramatic devices. In addition, audiences are sometimes called upon to participate in sound production in the case of, for example, new media installations.

With such applications in mind, we propose to review our earlier work dealing with visual and proximal spaces (Ligozat and Edwards 2001; Edwards and Ligozat 2004), to explore how this may be used to support applications in theatre and the performing arts, and then to lay out the precepts for a similar, qualitative model of aural space. We propose to explore the use of this sound space model for spatial reasoning, and then to use this model as a structuring principle to support an artistic exploration of sound space within a theatrical context.

2 Qualitative Visual and Proximal Spaces

Qualitative models of visual and proximal spaces segment space into regions where some significant aspect of our perceptions of the environment are stable (Ligozat and Edwards 2001; Edwards and Ligozat 2004). In our earlier work, we modeled proximal spaces through the use of Voronoï diagrams—the partitioning of a space of objects into regions that are closest to each object is, by definition, a Voronoï diagram (Okabe et al. 2000)—see Fig. 1. Mathematically, we break objects down into points and line segments—from this representation, a Voronoï diagram may be generated. There are a variety of public domain software tools for creating and manipulating such Voronoï diagrams, and the resulting partitioning of space has been successfully used to support spatial reasoning for a range of applications for many years (Edwards and Ligozat 2001; Edwards 1993). Proximity is an important

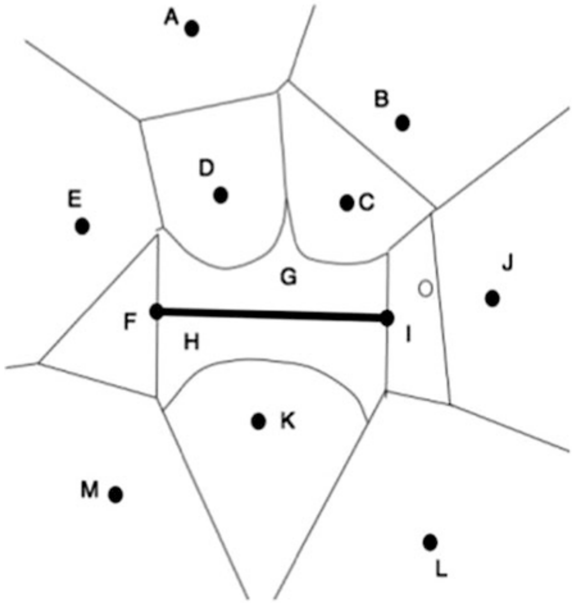

Fig. 1 Voronoï diagram showing proximal regions for *points* and *line* segments. *Note* that the *line* segment has two sides with distinct regions on each side (Note that whether one views a line segment as two objects with distinct regions on each side, or one object with a single region that straddles the two sides is a matter of choice—in our models, we keep "half-line segments" distinct, and we also keep the end points, which is why there are boundaries orthogonal to the line segment at F and I). The boundaries between the proximal zones of the *line* segment and the points are by definition parabolas. The observer is located at O in the figure (within the proximal region I)—if the observer moves slightly to the right, he or she will enter the proximal region of J, at which point it is assumed that their experience of the space will be different

feature of our perception of environmental space and hence these proximal space models serve as a useful grounding for models of perceptual space.

For visual spaces, we exploited the concept of "panoramas" based on the calculus originally introduced by C. Schlieder (1995)—these are cyclic orderings of salient objects on the visual horizon (Fig. 2). The core idea here is that we conceptualize regions visually based on the angular ordering of salient features of the landscape. As long as salient features "line up" in a similar way, we understand that we are in the "same space"—but when the order changes, we sense we have entered a different visual space. The boundaries of these zones are defined by the alignments between visible objects. For example, in Fig. 2, the observer is located in a sliver whose boundaries are formed partially from within which the cyclic order of visible objects is {J–L–K–I–segIF–F–E–D–A–C–B}, with object M hidden from view, and partially by the boundary between objects I and J in the Voronoi diagram. If the observer moves only very slightly downard to the right,

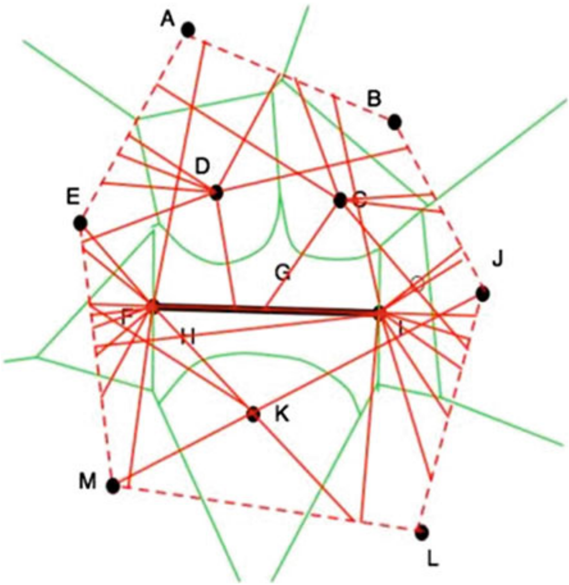

Fig. 2 Homogeneous perceptual zones based on panoramas for the same observer O as in Fig. 1, within the convex hull defined by the exterior-most objects (shown as *dashed lines*). *Note* that only "exterior alignments" generate boundaries—that is, alignments that are visible by directly sighting from the observer's viewpoint. Alignments that must be inferred by swiveling one's view 180° are suppressed in this model. The diagram also shows the Voronoï proximal zones in green

M comes into view between K and I, resulting in a different panorama. When changes cluster,[1] so that over a short distance, several different things "change places", then we conceptualize the change as a "gateway" or "doorway" between distinct spaces (the opening between the two barriers shown in Fig. 6 constitutes a gateway in this sense). Schlieder's principle of cyclic ordering, combined with the Delaunay triangulation which forms the dual for the Voronoi diagram, allow one to reason about these changes, and to infer information about the organization of space based on these perceived changes as we move through the space (Schlieder 1995; Ligozat and Edwards 2001).

By combining the Voronoï model of proximal space with the panoramic model of visual spaces, we defined "zones of perceptual stability" as zones where both Voronoi neighbors and panoramic stability are preserved, and considered the presence of "transition zones" and "gateways" between these zones of perceptual stability, where one crosses several of either (but usually both) boundary. This allowed us to develop a rich reasoning model for perceptual space, and to be able to infer most of the structure of the world based on path-based qualitative observations. This mode of reasoning was explored in our earlier papers (especially Ligozat and Edwards 2001).

[1] When changes don't cluster, because they are more evenly spaced, then we are in a "transition zone", a more general concept than a "gateway".

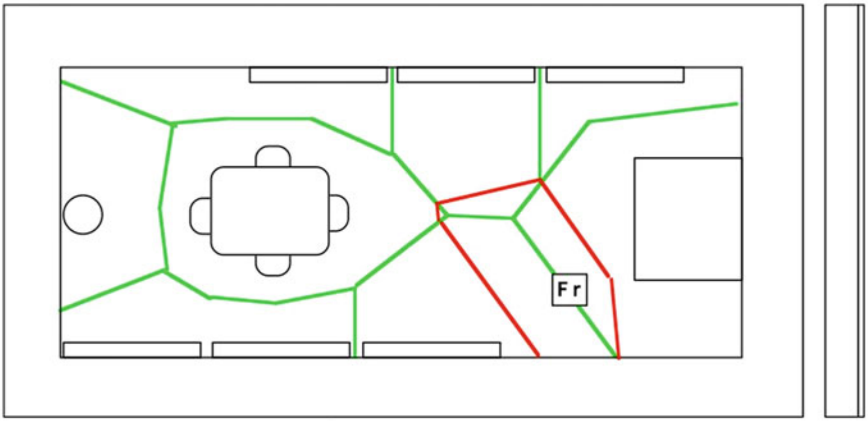

Fig. 3 The stage for the *Green* Dragon[2] oriented with the north at the *top*. Shown in *green* are the proximity regions for each of the stage objects, and in *red* the proximity region (Vorono zone) for one of the main characters, Françoise, following her entrance (her proximity zone "steals" area from her Vorono neighbors—see Gold 1989 for the area stealing model)

3 The Use of Qualitative Visual and Proximal Models for Understanding Theatrical Space

During a series of observations (Edwards 2003) carried out in February of 2003 with the company Ex Machina under invitation by Robert Lepage, Quebec City's preeminent playwright, these models were developed and applied (Figs. 3 and 4). Ex Machina was, at this time, engaged in the process of putting together a remake of the Dragon Trilogy, 15 years after the first exercise was completed. This production was used as a laboratory to develop and test ideas concerning spatial referencing in support of theatrical production. We were in particular interested in exploring the possibility of developing aids for the design process, not so much to assist Lepage as to encapsulate some of the principles he uses in stage design so that others might benefit from this experience. From a spatial information theory perspective, the problem of design in a theatrical space offers an opportunity to work out configurational reasoning processes in a kind of miniature laboratory where every design choice carries meaning and significance. Furthermore, understanding how meaning emerges from configurational aspects of stage representation is itself a task of interest to both spatial theorists and stage designers.

The overall set design as defined for the first act (the Green Dragon) is shown in Fig. 3. It should be noted that this is not a precise portrayal of the set from the specifications of the play, but rather a sketch that shows the qualitative features of the set design. The overall thematic context of the play is to follow the evolution of

[2] The play is divided into three acts, each named after a Dragon—Green, Red and White. These correspond to different epochs and cities.

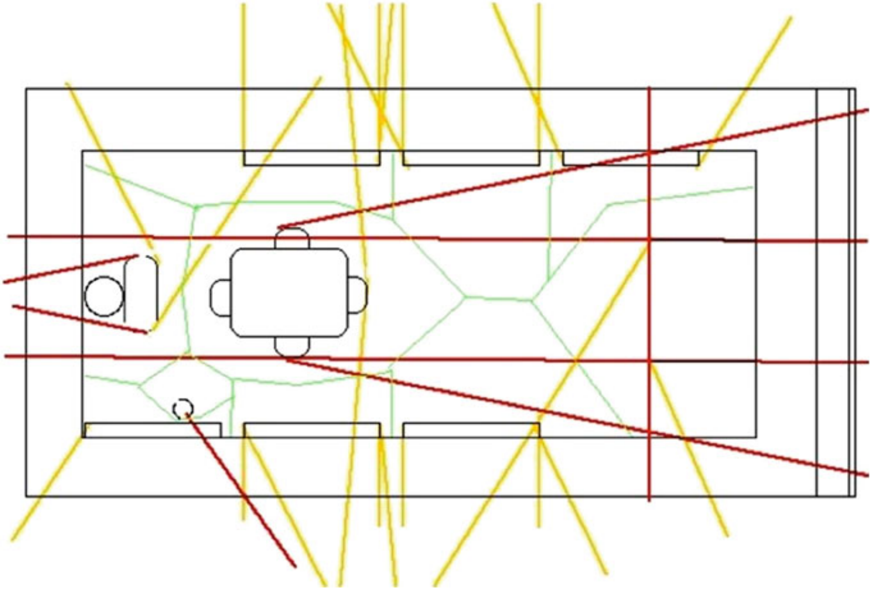

Fig. 4 The visual zones of perceptual stability for the *Green* Dragon staging, from the actors perspective within the stage

the interaction between Asiatic (Chinese and Japanese) and white families across three different spatio-temporal contexts—Quebec City in the 1920's, Toronto in the 1940's and Vancouver in the 1990's. The play is, at least in part, concerned with how space and time interact and work out their effects in people's lives.

The objects shown in Fig. 3 include the round cross-section of a mast on the left (west) edge, a table and four chairs in the middle section, a square cabin on the far right of the central section, and three paving slabs on each side of the central section (north and south). The whole central section is a sandbox (floored with sand), surrounded by a wooden boardwalk on all four sides, with a raised screen and platform on the right hand (east) side. In the diagram, the location of one of the actors is shown (Fr), along with the Voronoï zone associated with her as she moves into the space. This shows that Fr is located between the pavement slabs, the table and the cabin (based on her Voronoï neighbors).

In Fig. 4 are shown, overlaid onto the Voronoï zones, the homogenous perceptual zones generated by the panoramas, from the perspective of the actors on the stage,[3] at a somewhat later point in the play's development (hence the addition of a couple more props—the commode located in front of the mast and a fire hydrant located just above (north) of the left-most pavement slab at the bottom (south) edge of the diagram. In yellow are shown the perceptual zones for weakly salient objects (usually objects at the level of the floor) while in red are the perceptual zones for

3 Hence following the alignment construction principles illustrated in Fig. 2.

strongly salient objects (the mast, table and chairs, cabin, fire hydrant and screen), where salience is determined by how much of the visual field the objects occupy.

As the actors move around in this space, it is possible to determine their approximate location simply by remarking within which pair of regions (Voronoï, Panorama) they are located in, just as one could reconstruct the space in a general way by drawing on information about the changing regions and which objects are associated with them via proximity or alignments. For example, the cabin sides form a very regular alignment that extends across the stage (the parallel lines from the right to the left in red)—actors who stay within that region are, in some sense, "confined" by these alignments. Likewise, the table has similar size and reinforces that feeling of confinement. Lepage's staging exploits that confinement at many points in the unfolding action of the play. The paving slabs also "structure" the stage space in interesting ways, especially given their staggered configuration. In addition, the audience will necessarily experience the play differently depending on where the actors are located on the set, based on association between symbolic meanings assigned to different objects and how these are "transferred" to the actors and unfolding events based on, at least in part, where the actors are located.

From the perspective of an audience located outside the stage space (in Lepage's play, the audience is located on either side of the stage on the long edges, "North" and "South" in the terminology of the play's scenography), these configural elements play a role in how we perceive and understand the play. However, increasingly today, for example in performances organized within the framework of what are often called New Media, the audience moves through the space and may even be a direct participant. Within this perspective, these proximal and perceptually homogeneous tiles gain considerably greater significance—it is possible to exert an intense influence over a participating member of the audience based on particular scenarios that exploit proximity or distinct visual environments.

Interestingly, just as we can use the spatial partitions generated by the Voronoï proximal regions and the regions of constant alignment generated by the panoramas to reason about these theatrical spaces and movement through them, we could also use these ideas to assist in the design of these spaces, either as an intuitive framework or as part of a formal design process. For example, imagine we wished to deliver very different experiences of the same play to different segments of the audience. This highlights the interplay between spatial reasoning on the one hand, and spatial design on the other.

4 Extending the Perceptual Models to Include Sound Spaces

As indicated earlier, this is all very interesting, but falls short of the mark for dealing adequately with theatrical spaces because there is no obvious way to integrate how we perceive sound within this framework. Sound is integral to both performance, and, increasingly, installation spaces—how a sound experience is delivered to an audience requires design tools that incorporate sound. Within the performance arts, increasingly “spatialized sound” is being used. This term is used to describe the ability to project particular sounds to particular locations within the performance space using sophisticated computer control over loudspeaker systems that may include dozens, even hundreds of loudspeakers located throughout the performance or installation space. However, even being able to track sounds from only a few sources would also be of use to reasoning about and designing performances or installations.

It is, of course, possible to use a variety of quantitative sound models that have been developed by researchers. However, these models quickly become highly complex and require a great deal of expertise to use effectively. They also may be able to tell the user what intensity and frequency of sounds they might hear at any given location, but they do not make it easy to infer the location of source sounds or to understand the relationships between regions with different sound characteristics. This is similar to the problem with visual spatial modeling—the latter requires sophisticated software environments that exploit ray-tracing or radiosity calculations, can be used to generate an image with a graded and realistic range of intensities and colors, but cannot be so readily used to infer how a space is perceived visually. It is for this reason that we developed the qualitative modeling tools discussed above, which clearly overcome these limitations and provide a powerful environment for understanding and reasoning about visually perceived spaces. We need a similar approach for sound—that is, on what basis can we segment a space to produce regions within which sound experiences are perceived as being similar, but when one crosses to another region the sound experience changes?

The most obvious way to model sound production is via circles—each sound source will produce a sound perception circle (or an aural influence zone). We may manage sounds of different intensity by assigning a scale factor to each circle based on its average relative intensity. In Fig. 5, audio source A is of small relative intensity and the observer hears no other sound when passing through this region of space. Following this, he or she hears nothing until he or she enters the influence zone of audio source B, a relatively loud sound. After a moment, the observer also enters the influence zone of audio source D, with a sound intensity similar to that of A—while within the influence zone of source D, he or she also continues to hear (or has the potential of hearing[4]) audio source B (hence the zones associated with sounds of low volume are modelled in such a way that they overlap with the zones associated with loud sounds). After exiting the influence zone of D, he or she turns slightly and encounters audio source C while remaining in the zone of influence of B. Perhaps this is an unpleasant sound, and the observer turns away from the sound and exits to the left, still within the influence of audio source B however. Eventually, the observer leaves the influence zone of B and enters a region of silence again.

[4] A sound source may be continuous or intermittent within the circle, hence the circle actually indicates whether the sound would be heard if it is actually actively being generated.

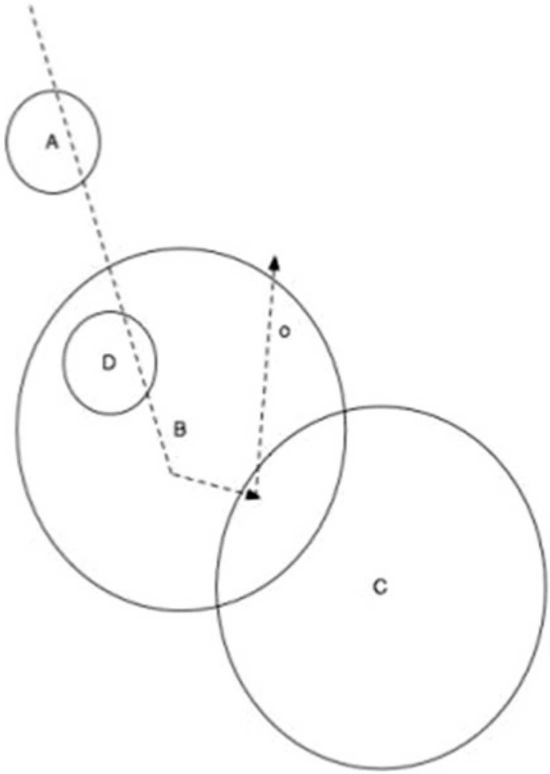

Fig. 5 Qualitative model of sound spaces for four audio *sources* (*A*, *B*, *C* and *D*), showing an observer's motion through the spaces via the dashed line

One of the primary advantages of reasoning about circles from a spatial reasoning perspective is that circles are a subset of the Region Connection Calculus (Randell et al. 1992; Cohn et al. 1997). Hence we are assured that all possible relations between circles are specified by the eight relations of RCC8—disconnected, externally connected, equal, partially overlapping, tangential proper part, tangential proper part inverse, non-tangential proper part and non- tangential proper part inverse (Randell et al. 1992). In addition, if we restrict our interest to paths composed of straight line segments, then we can use Allen's Interval Algebra (AIA: Allen 1983) as a framework for reasoning about path intervals within the circles. Relations between path intervals are hence similarly restricted, albeit to thirteen possible relations—before or after, meets or inverse meets, overlaps or inverse overlaps, starts or inverse starts, during or inverse during, finishes or inverse finishes, and is equal to. The normal relations apply for interval Y with respect to X (e.g. X overlaps Y if X starts before Y), whereas the inverse relations apply for interval X with respect to Y (e.g. X inverse overlaps Y if Y starts before X).

However, real spaces are rendered complex by the existence of barriers that interrupt the sounds. What makes the development of a qualitative model for sound, hard, is the presence of such barriers. How can we incorporate the effects of barriers without rendering our model overly complex? Framing this question slightly differently, how might we need to modify the use of the RCC8 or AIA to address the presence of boundaries?

Here is one, rather elegant solution to this problem. Our idea is to use Huygen's Principle of Wave Propagation. Huygen's principle "recognizes that each point of an advancing wave front is in fact the center of a fresh disturbance and the source of a new train of waves; additionally, the advancing wave as a whole may be regarded as the sum of all the secondary waves arising from points in the medium already traversed" (statement excerpted from the "Huygens-Fresnel Principle" article on wikipedia.org). For our purposes, we are more interested in the first part of this statement. Essentially, whenever the wave encounters a barrier, we may treat the barrier as the source of a new set of waves centered on the barrier, with radii reduced appropriately (either as a function of distance from the original source or this in combination with a modulation or absorption factor characteristic of the barrier itself).

In a sense, what we propose to do is to replace the barriers (and the original sound source) by these new sound sources whenever the observer's path crosses or passes by a barrier segment. As a result, our "circle" model of sound is preserved, but at the cost of allowing the model to be updated whenever the observer crosses an "update event location" on its path of movement. Figure 6 shows an example of what such a model might look like, with Fig. 6a representing the situation before the observer crosses update event location α, while Fig. 6b represents the situation after the observer crosses update event location α.

Hence in the modified example shown in Fig. 6, two barriers with an opening between them were introduced into the space originally shown in Fig. 5. Up until the observer crosses the point α, the model remains as it was in the case of Fig. 5. Once the observer crosses location α, however, the circles that intersect the barriers

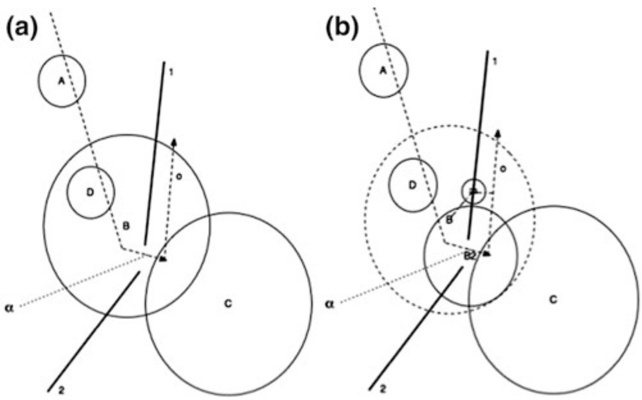

Fig. 6 Qualitative model of sound influence zones in the presence of barriers. **a** before the path crosses the "update event location α"; **b** after the path crosses the update event location α. In (**b**), the original influence zones are shown as *dashed* lines, and several new zones are introduced centred on the barriers. Only zones that intersect the barriers are affected by the changes

are updated. In the example, it is assumed that the barriers absorb part of the sound, resulting in lower intensity for the influence zones regenerated from the boundary itself. In the gap between the two boundaries, however, the new circle must be tangent to the original circle in order to drop below the sound threshold at the same location as it would have originally. Hence the observer is within the modified influence zone B2 to begin with, then in the overlap region between B2 and C, turns away from C as before, reenters the B2 influence zone, then enters a silent region much sooner than was the case earlier. This is because the barrier absorbs too much sound to be heard even at relatively short distances—if the barriers absorbed somewhat less of the sound, the observer would still hear a sound greatly reduced in intensity as he or she followed the barrier away.

The process of reasoning about the sound spaces is rendered more complex by the need to update the perceptual model whenever the observer passes a sound barrier, [5] but we may reliably reason about the local sound environment using the full power of the RCC and AIA reasoning tools. Furthermore, by preserving the circle-based model, we ensure that the set of possible intersections between pairs of audio sources is always well defined. Likewise, the changing context within which reasoning is conducted will limit our ability to infer the original configuration of the audio sources based on an observer's movements through the space. The model proposed has a number of additional weaknesses. It does not deal explicitly with different sound frequencies—in general, it can be expected that sound barriers will filter higher pitched sounds differently than low pitched sounds. The model as stands does not deal with sound reflections, but it can be modified in a relatively straightforward manner to do so (by introducing additional reflection circles on the "nearside" of boundaries). It does deal with the phenomenon of diffraction, however (the fact that sound curves around objects).

Human perception will sometimes cause secondary sounds to be less easily perceived in the presence of a dominant sound—the model does not deal with such effects. Also, as mentioned in the introduction, modern sound apparatus often exploits an arrangement called "spatialized sound"—essentially the use of large numbers of loud speakers and computer control to saturate an area with sound but in such a way that sound may be arbitrarily "projected" into any given location. Because such systems saturate the space with sound, the model, if applied in a brute force manner, will simply treat such cases as "equality" of sound zones or heavily "overlapped" zones. However, the model could also be applied more carefully by assigning audio sources to each projected sound region—in principal, spatial reasoning about the sound spaces generated in this way could still be carried out using the model.

[5] This is reminiscent of the manner in which the Voronoï diagram and its triangular dual must be updated to accommodate the dynamic movement of objects within the diagram (Okabe et al. 2000).

5 Using the Perceptual Model as a Substrate for Artistic Performance

For the purposes of showcasing the use of this model in support of an artistic performance, we designed a real-time performance using the model proposed here, a performance which was presented to the Las Navas 2010 conference audience. We chose to work with Homer's Odyssey as a Mediteranean theme that would be widely known to both North American and European audiences. Working with a well-known composer (René Dupéré, long time composer for the Cirque du Soleil), a set of ten musical tableaux was constructed. Each of these musical pieces represented an incident in Homer's Odyssey (see Table 1). Not all incidents were included, for lack of time and resources—rather a representative set was constructed.

In addition to the music, pertinent ambient sounds were included (column 3 in Table 1). For the entire sequence, we used a virtual geographic space (Fig. 7) and allocated the relevant incidents from the Odyssey according to scholarly efforts to reconstruct these locations (we drew on several different sources for this reconstruction, and chose those that suited the purposes of the performance the best). Within our global virtual sound space, each landmass was treated as a sound barrier (represented by the thick red lines in Fig. 7), and each incident location as a sound source. We then constructed a path beginning with Troy and ending at Ithaca that corresponded to the reconstructed trajectory followed by Homer and his men.

Using the principles presented above for the Auditory Perceptual Model, we developed a real-time software-based implementation, interfaced with a Denon 7.1 Sound System. The model was implemented in C++ on an Apple MacBook running under Windows Vista. Within the software implementation, a set of up to 255 virtual sounds was created. Each virtual sound is assigned a starting location, a path, and an auditory track. The software also included the virtual location of the

Table 1 The musical segments associated with incidents in Homer's Odyssey

#	Incident	Ambient sounds
1	The battle of troy	Battle noises, gong, waves
2	The lotus eaters	Waves
3	The cyclops	Waves, bleeting sheep, giant's footsteps, splash as rock hits water, storm winds
4	Circe	Pigs' grunts, feet running, many voices partying
5	Hades	No extra sounds used, only the music
6	The sirens	Waves, rowing, creaks of the oars
7	Scylla and charybdis	Whirlpool, waves, shrieks
8	Calypso	Waves
9	Nausicaa	Girl's laughter, waves
10	Ithaca—the return home	Waves, many voices partying, cocks crowing

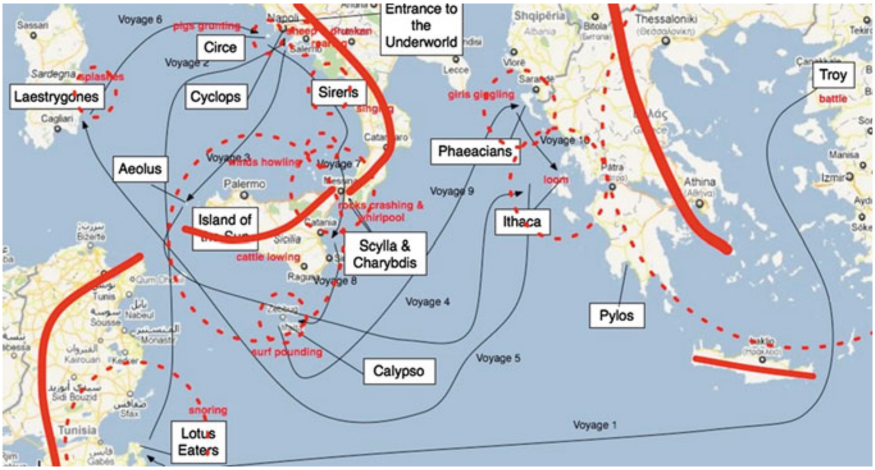

Fig. 7 Geographic virtual soundscape for the Virtual Odyssey performance. Thick *red* lines represent the locations of sound barriers. The locations of sound sources are provided by the *white*, named boxes. The *dashed circles* indicate the region of influence of each sound *source* (that is, it's relevant intensity). The thin *black* line shows the trajectory of Ulysses

observer/listener. Then, at each instant of time (10 ms), the software determines the relative location and intensity of the virtual sound with respect to the observer/listener, and updates the signal to be sent to the set of speakers so as to simulate the corresponding sound emanating from its appropriately identified location. The location and size of source "circles" and of linear "barriers" were included in the calculation. Also, we simulated stereo by locating a left and a right virtual source, separated as appropriate (depending on distance between the observer/listener and the source). The result is the ability to project a complex real-time sound experience that incorporates up to 255 moving virtual sound sources at any one time.

It should be noted that this is, to our knowledge, the first time this has been done in this way. Normally, to generate a performance using spatialized sound, the mix of sounds and virtual locations must be determined well in advance of the performance and all the sounds are premixed to support this kind of performance. The ability to generate this kind of performance in real time, using a single computer, for 255 separate sound sources is new to this work.

For the global auditory experience of the Virtual Odyssey, we located the audience in one of Ulysses' boats—hence with the sounds of waves striking the boat from all around as it sailed between locations (the virtual waves were co-located with the virtual boat to generate this effect). Then the boat was moved to each incident location along a pre-determined trajectory, while each segment was played from its source location. In addition, ambient sounds were given other virtual locations as appropriate, according to the relative locations of the audience (as Ulysses' men) and the other elements involved in each of the incidents.

For a very simple example, the segment of music for the Lotus Eaters was allocated to a small peninsula on the northern coast of Tunisia. The boat initially moved directly towards this source, but eventually veered away along the coast and turned north towards the French coast. The audience heard the sound segment shift from straight ahead to the port side as the boat sailed by.

As a more complex example, note the realization of the Cyclops sequence (Fig. 8)—here again, the audience is co-located with the crew. The boat grounds on the coast and the men disembark, then climb into the hills and encounter the giant sheep (bleats all around). The crew follows these into the cave (bleats in front). Polyphemus then enters the cave (giant footsteps moving closer). Ulysses stabs the giant in the eye, who cries out, then the men escape on the bellies of the sheep and run back to the boat, while the Cyclops rages behind them. As they flee in their boats, the Cyclops hurls a giant boulder into the sea after them (splash behind, waves all around).

Each incident is characterized by a local sound geography that is distinct from the global sound geography in this way. At certain times, the distant sources may be heard, as appropriate. Hence, during the Hades sequence, there are echoes of Penelope's voice in Ithaca as well as the sounds of the suitors who are partying. In addition, on segments where the boats were between incidents, we provided the sound of waves lapping against the boat hulls and the creaking of the latter.

A sequence of particular interest occurs when the boats pass through the narrow straight of Medina between Italy and Sicily, and encounter the whirlpool of Charybdis and the monster Scylla. We traced the trajectory between these two locations as described in the Odyssey, but had the boats pass closer to the monster than to the whirlpool. In addition, because of the opening between the sound

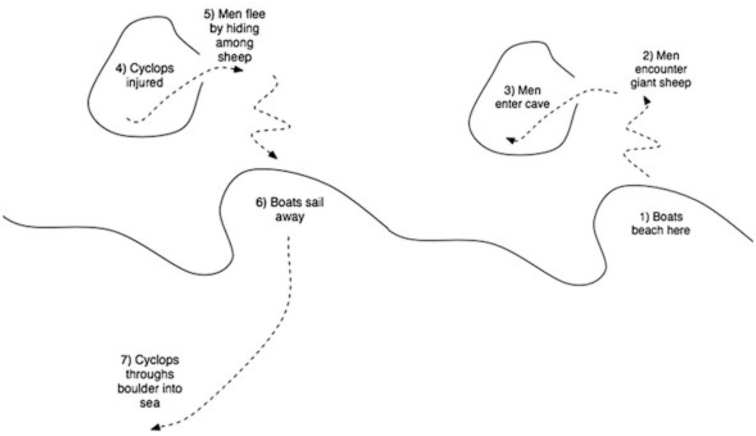

Fig. 8 Local virtual geography for the Cyclops incident. In the leftmost diagram, the boats are beached, the men climb into the hills and encounter the giant sheep and then they follow them into the cave. In the rightmost diagram, the Cyclops discovers the sailors, Ulysses blinds him, the men escape and Ulysses heaves a boulder into the sea after them. The virtual sounds are located in a manner consistent with the observer/listener being with Ulysses' men

barriers created by the landmasses of Sicily and Italy, the more distant sounds change dramatically as the boat enters the straight, losing the sounds of Circe, Polyphemus, and the Sirens and gaining the sound of Calypso. This is an example of a gateway in the soundscape we created.

The sequence ends with the arrival in Ithaca, the killing of the suitors and the renewal of family life for Ulysses and Penelope, which we symbolized with the crow of a rooster. The whole sound experience lasts some 22 min. For the Las Navas 2010 conference, we brought with us our own Denon sound system. Our audience consisted of the roughly 50 conference attendees. The scenario was provided in summary form and then the experience was played out in the dark.

In addition to the show itself, we were able to provide an interactive component wherein the audience could indicate where they would like to steer the boat within the global soundscape.

The artistic performance not only served to showcase the application of the theoretical model, it also served to highlight the use of these kind of modeling/simulation tools to designing and delivering a complete, self-contained experience. The implemented model captured and reproduced all of the relevant elements of a complex aural experience, underlining the fact that the model indeed provides a powerful means of representing aural space, reasoning about it, and designing experiences based upon it. To our knowledge, the use of a qualitative model in this way is unique to this application. The artistic performance as we designed it focused uniquely on the auditory experience. However, combined with the visual and proximal models, a complete tool will undoubtedly serve the design of complex multi-modal performance experiences as well.

6 Discussion and Conclusion

In many ways this paper crowns a collaborative effort that spans more than a decade of research, first with regard to the development of a qualitative spatial reasoning framework for handling perceptual spaces, and secondly with regards to the exploration of methods of combining scientific and artistic interests within a single framework. These two goals are intimately connected in that the spatial reasoning framework acts as the backbone for the latter effort.

This combination of scientific and artistic programs, in turn, serves as a fascinating fulfillment, not only of the efforts portrayed in this paper, but also of the whole program to investigate the relationships between formal spatial theory on the one hand and the cognitive and linguistic dimensions of space within an applied context on the other, the program that defines the two Las Navas meetings, one in 1990 and one in 2010.

At the first Las Navas meeting, Edwards made a point of identifying the linking of science and art as a long term goal that he expected and hoped would come out of the work being done at Las Navas, and, eventually, through the series of conferences (COSIT in particular) that grew out of that meeting. Certainly the academic career of Edwards bears witness to this interweaving—the artistic presentation showcased in connection with this paper was but one of a number of joint science-art collaborations (many also involving Bourbeau) undertaken over the past 6 or 7 years (e.g. Bourassa et al. 2009). In addition, Edwards has been funded to implement a joint science-art laboratory within a hospital devoted to physical rehabilitation—all of this work came out of the cognitive geomatics focus initially put into play by the Las Navas 1990 meeting. Spatial modeling and reasoning is but one of the ways in which science has intersected with the arts within these initiatives—other areas where intersections have been of consequence in the authors' work include the application of Gibson's affordance theory to the development of unusual, interactive environments, the application of image schemata to performance design (Edwards and Bourbeau 2005), the role of mirror neurons in understanding dance performance, and our understanding of near-body spaces to assist in the development of immersive and aesthetic installations that illustrate or witness life as experienced by people with disability.

We hope that this paper inspires others to "square the circle" in similar ways, to close the loop and help bring science and the arts back into harmony in interesting ways.

References

Allen JF (1983) Maintaining knowledge about temporal intervals. Commun ACM 832–843

Bourassa R, Edwards G Bourbeau ML (2009) Son, espace et corporéité: effets de présence et performativité sonore dans un théâtre expérientiel. Journées d'étude-CRI-CNRS sur le Son et le Théâtre: Rencontres à Paris, les 20 et 21 novembre

Cohn Anthony G, Bennett Brandon, Gooday John, Gotts Micholas Mark (1997) Qualitative spatial representation and reasoning with the region connection calculus. GeoInformatica 1:275–316

Edwards G (2003) La géomatique cognitive et les arts de la scène—Bilan des séances d'observation chez Ex Machina pour les répétitions de La Trilogie des Dragons, Rapport produit pour Ex Machina

Edwards G (1993) The voronoi model and cultural space: applications to the social sciences and humanities. In: Andrew F (ed) Conference on spatial information theory, Lecture Notes in Computer Science, Vol 716, Springer, Elba pp 202–214

Edwards G, Bourbeau ML (2005) Image schemata—a guiding principle for multimodal expression in performance design. Int J Perform Arts Digit Media 1(3):189–206

Edwards G, Ligozat G (2004) A formal model for structuring local perceptions of environmental space. Cogn Process 5:3–9

Gold CM (1989) Chapter 3—Surface interpolation, spatial adjacency and G.I.S. In: Raper J (ed.) Three dimensional applications in geographic information systems. Taylor and Francis Ltd., London, 21–35

Ligozat G, Edwards G (2001) Implicit spatial reference systems using proximity and aligment knowledge. Spat Cogn Comput 2(4):373–391

Okabe A, Boots B, Sugihara K (2000) Spatial tesselations: concepts and applications of voronoi diagrams, 2nd edn. Wiley, Chichester

Randell DA, Cui Z, Cohn AG (1992) A spatial logic based on regions and connection. In : Proceeding 3rd International Conference on Knowledge Representation and Reasoning. Morgan Kaufmann, San Mateo, pp 165–176

Schlieder C (1995) Reasoning about ordering. In: A Frank WK (ed.) Spatial information theory: a theoretical basis for GIS, Lecture Notes in Computer Science, Vol 988, Springer, Berlin pp 341–349

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Geoffrey Edwards* was originally trained as an astrophysicist (Ph.D. in 1987 from Laval University). He has published numerous articles in areas of 'classical' geomatics (image processing, cartographic generalization, spatial data structures, spatial analysis, uncertainty evaluation, etc.). Since awarded the Canada Research Chair in Cognitive Geomatics (2001–2014), he concentrated his efforts on the development of cognitively-informed tools for accessing and processing geospatial data. More recently, he has developed a research program that brings together a cognitive understanding of space within an artistic perspective, with applications to physical rehabilitation and museology. He was Associate Director of the GEOIDE Network of Centres of Excellence from 1999 to 2001 and then Scientific Director from 2001 to 2003. He has been director of the Centre of Research in Geomatics at Laval University, and is currently director of the new EMIR laboratory (Exploration of Media Immersion for Rehabilitation). In addition to his academic career, Dr. Edwards is CEO of a fashion design company.

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