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ARTICLE

The world, the computer, and the mind: how Andrew Frank helped make human language and cognition cornerstones of geographic information science

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ABSTRACT

During the late 1980s and early 1990s, cognitive science was included as one of the key disciplines in the emerging multidisciplinary field of geographic information science (GIScience). One of the key proponents and popularizers of the study of human cognition as part of GIScience – and one of its major researchers – has been Andrew U. Frank. In this essay, we review the history of Andrew Frank's role as an innovator and champion for cognitive GIScience, and summarize some of his research contributions in this domain. Taken along with his contributions to other areas of GIScience, this review shows that Andrew Frank has been one of the primary figures in modern GIScience, and among its very broadest and intellectually-diverse contributors.

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1 Introduction

Cognitive geographic information science (GIScience) research concerns knowledge and knowledge processes that involve geographic information and geographic information systems (GIS) (Montello 2009). It includes both internal mental and external symbolic structures and processes. Cognitive GIScience considers a host of basic-science questions about human perception, thinking, reasoning, learning, memory, and communication involving information about the earth, the natural and human phenomena found there, and their spatially-referenced (and often temporally-referenced) representation, analysis, and depiction by digital information systems. It is practically motivated to improve the usability, efficiency, equity, and profitability of geographic information and GIS. It works toward the goal of tailoring GIS to different individuals and cultures, thus increasing information access and the equitable dissemination of technology. Professor Andrew U. Frank was a key innovator and proponent of cognitive research in GIScience, and in this essay, we discuss these contributions.

The history of cognitive research in geography, cartography, and GIScience is outlined by Montello and Freundschuh (2005). Cognitive science emerged in the

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1950s and 1960s as the multidisciplinary study of cognition incorporating the theories and methods of several disciplines, particularly psychology, philosophy, linguistics, neuroscience, and computer and information science. Cognitive research appeared in geography and cartography at least as early as the 1950s, but this was not recognized among the coalition of disciplines that came to be known as cognitive science until recently, and is no doubt still unrecognized in some corners of cognitive science.

From its earliest days as a distinct discipline in the late 1980s (with a variety of historical roots), the emerging field of GIScience asked questions about human understanding of earth phenomena and their representation, analysis, and depiction by GIS. Understanding and reasoning are, in part, cognitive acts, and cognition often concerns space, place, and environment. As we discuss below, Frank was a primary driver behind the National Center for Geographic Information and Analysis (NCGIA)'s – and soon, the discipline of GIScience's – embrace of the study of human cognition and language as cornerstones of the scientific and engineering study of geographic information. The first major publication on cognitive and linguistic issues specifically relevant to GIScience was the collection that Frank and Mark edited, *Cognitive and Linguistic Aspects of Geographic Space* (Mark and Frank 1991). Their interest in cognitive issues was explicitly continued with the formal naming of the discipline as *geographic information science* (GIScience). It was also included in the first version of the first-published research agenda of the University Consortium for Geographic Information Science (UCGIS), edited by McMaster and Usery (2005), but based on chapters started almost 10 years earlier. It also appeared in the *Encyclopedia of Geographic Information Science* (Kemp 2008) in the form of entries on 'cognitive science', 'mental map', 'spatial cognition', 'spatial reasoning', 'neural networks', 'ontology', and other cognition-related topics.

At the second International Symposium on Spatial Data Handling (SDH) symposium in Seattle, Washington, Frank co-authored a paper on applying artificial intelligence (AI) methods to spatial reasoning, later published in the *Journal of Surveying Engineering* (Robinson *et al*. 1986). This paper was an early manifestation of Frank's interest in cognition. He has continued to promote and contribute to cognitive GIScience throughout his still-active career, with something like 40 of his many articles, chapters, reports, and edited books dealing with it. In fact, it is challenging to say exactly how many publications he has co-authored or edited on cognitive and linguistic issues in geospatial information, as the study of both cognition and language have shown themselves to be so fabulously multi- and interdisciplinary since the late 20th century that one is unsure what to include as qualifying. That itself is a highly telling observation, however: Frank's career too has been fabulously interdisciplinary. His writings and lectures have engaged not only with surveying engineering, geography, and cartography, but also with cognitive psychology, linguistics, anthropology, information science, computer science, mathematics, philosophy, economics, history, political science, organization/management studies, and urban studies. This astounding variety points to Frank organizing his career around problems, not disciplines. We may not know of any scholar who has worked in GIScience that can claim such an intellectual breadth and diversity.

2 Andrew Frank's role in the origins of cognitive GIscience

2.1 *Andrew Frank promotes cognition at the NCGIA*

During the 1980s, GIS went from a type of software to become an academic field with conferences and peer-reviewed journals (the field would come to be called GIScience). Frank was involved as a key figure and innovator in all of these developments.

The NCGIA became an established, well-funded research center in the late 1980s, located at the Universities of California-Santa Barbara, Buffalo (SUNY), and Maine. Frank was the founding director of the Maine site and an associate director of the entire Center. In November 1986, a meeting of key researchers was organized by Duane Marble and held at the University at Buffalo. Frank was a prominent participant in that workshop, which had a strong influence on the research priorities of the NCGIA solicitation, released by NSF in June 1987 (Abler 1987). Frank's influence was seen in at least two of the main research areas that NCGIA proposals were expected to address: 'A general theory of spatial relationships and database structures' and 'Artificial intelligence and expert systems relevant to the development of geographic information systems'.

At Buffalo, one of us (Mark) had been working with an interdisciplinary cognitive-science research group. So, in the context of writing the Santa Barbara-Buffalo-Maine (SBBM) NCGIA proposal, Frank and Mark collaborated to forge a research agenda for a cognitive and linguistic approach to identifying the general theory of spatial relationships called for in the NCGIA solicitation. The SBBM proposal (NCGIA 1989) was organized around five major areas of research. Especially the third area, 'Spatial Relations and Database Structures', included an innovative discussion of 'cognitive impediments' that considered individual and group differences among GIS users in their spatial perception, cognition, and communication, proposing that these differences were not well understood but needed to be before maximally effective GIS could be created. The authors of the proposal recognized this would have to be an interdisciplinary effort, including linguists, psychologists, and artificial intelligence researchers – cognitive scientists. The fourth area in the proposal, 'Artificial Intelligence and Expert Systems', recognized the value of representing human intelligence and thought in formal systems, and the fifth, 'Visualization for Display and Analysis of Spatial Data', identified the need to understand human perception and understanding of spatial concepts in order to design maximally effective geographic information displays.

The SBBM proposal for the NCGIA included 12 research initiatives, a mechanism that Frank borrowed from another scientific organization and suggested for the NCGIA. Another eight were eventually added. Depending on exactly how one interprets the titles of the initiatives, as many as six of the 19 that were eventually conducted included some concern for human cognition and communication, and four of them were primarily focused on human cognition relevant to GIS. Research Initiative 2 was called 'Languages of Spatial Relations', with Frank and Mark as co-leaders. The Specialist Meeting for this initiative was held in Santa Barbara in January 1989 (Mark and Frank 1992a). Subsequently, the NCGIA conducted Initiative 13, 'User Interfaces for Geographic Information Systems'. Its Specialist Meeting was held in June 1991, with Mark and Frank as co-leaders again (Mark and Frank 1992b). Two other NCGIA research initiatives with cognitive themes were 10 ('Spatio-Temporal Reasoning in GIS') and 21 ('Common-Sense

Geography'). These began after Frank left Maine (and the NCGIA) and moved to the Technical University of Vienna.

2.2 *Las Navas and the progenitor of the COSIT conference series*

Part of the NCGIA model for a research initiative was a closing specialist meeting. For Initiative 2, 'Languages of Spatial Relations', Frank and Mark decided to apply for a NATO Advanced Study Institute grant to conduct an international symposium in Spain and produce a book. NATO awarded the grant, and a group including NCGIA researchers and some leading cognitive scientists such as Zenon Pylyshyn, George Lakoff, and Leonard Talmy, met for two weeks in July 1990 in a castle at Las Navas del Marqués, Ávila Province, Spain. The resulting book edited by Mark and Frank (1991), *Cognitive and Linguistic Aspects of Geographic Space*, established the topic as a coherent and important one. It was the first major publication (not a technical report) on cognitive and linguistic issues specifically relevant to GIScience.

The Las Navas meeting happened at a pivotal time for the evolution of GIScience theory. That summer, the 4th Spatial Data Handling meeting was held in Zurich again. In a keynote talk at that meeting, Michael Goodchild referred to 'spatial information science'. This dubbed the launch of a newly crystallized academic field, soon renamed 'geographic (geographical) information science', a term that was in common use by NCGIA researchers and widely introduced when Goodchild's keynote talk was published in the IJGIS (Goodchild 1992). But it was the efforts of Frank and others within the NCGIA, rather than Goodchild, that firmly established cognition as an important part of GIScience. The NCGIA's follow-up research project, 'Advancing Geographic Information Science' (the Varenius project), offered three subfields as foundational for GIScience: cognition, computation, and societal impacts (Mark *et al*. 1999).

The Las Navas meeting was the closing meeting for Initiative 2 but the opening of a research theme that became an important component of GIScience over the following decades. In 1992, Frank and Irene Campari (one of the participants in the Las Navas meeting) convened a symposium in Pisa, Italy, the proceedings of which were published by Springer-Verlag's *Lecture Notes in Computer Science* series (Frank *et al*. 1992). This meeting included cognitive and linguistic work as one of its central components. Frank co-organized another symposium for the following year on the island of Elba, Italy, that had the title 'Conference on Spatial Information Theory' (COSIT). Again, in 1995, Frank co-organized a COSIT in Semmering, Austria, and the COSIT series has continued in alternate years to the present. The vitality of the COSIT research community was instrumental in establishing a new scholarly journal, *Spatial Cognition and Computation*. In 2010, the 20th anniversary of the Las Navas meeting was celebrated at the same location, out of which another volume of papers was published (Raubal *et al*. 2013).

2.3 *A mentor to cognitive GIScientists*

Another important contribution Frank has made is mentoring young scholars, many of whom would go onto make their own significant research contributions in cognitive GIScience. Frank directly supported and inspired these young scholars by suggesting topics and problems, and guiding research and professional activities: discussing theories, concepts, and methodologies; helping to obtain resources; supporting attendance and participation at relevant conferences; etc. He has also inspired young scholars indirectly through his passion and enthusiasm for ideas, and by providing a role model for a successful multidisciplinary GIScientist, including one who embraces the study of cognition as a major research goal. Frank served as doctoral or habilitation advisor for several GIScientists who went onto make influential contributions to cognitive GIScience, including themselves mentoring future scholars at universities around the world. Of course, Frank greatly influenced scores of additional scholars for whom he did not officially serve as advisor; for example, the two of us both acknowledge his influence on our own careers.

3 Specific domains of Andrew Frank's cognitive research

3.1 *Ontologies in GIScience*

The value and utility of an information system depends in part on how well the information system represents the external reality that it models. During the 1970s and 1980s, the process of documenting the relevant aspects of reality and formalizing representations of these aspects was usually known as data modeling. Frank carried out research on data modeling during the 1980s and 1990s (Frank *et al*. 1986, Frank 1992a). In the early 1990s, Gruber introduced the term *ontology* from ancient Greek philosophy to refer to this process. He defined ontology as a 'formalization of a conceptualization' (Gruber 1993, p. 199). Concepts are, in part, mental entities, and thus deducing a conceptualization involves studying cognition. At the same time, the study of ontology is not solely in the cognitive domain – it is not exclusively mental – but involves issues of concern to philosophers, information scientists, anthropologists, political scientists, and legal scholars. Thus, a good deal of work on ontology, including some of Frank's, is not of direct concern to a discussion of cognitive research.

When the term ontology became known to GIScience researchers, Frank and his group were poised to lead research on it. In 2000, Frank and his group in Vienna organized a EURESCO workshop entitled 'Geographical Domain and Geographical Information Systems: EuroConference on Ontology and Epistemology for Spatial Data Standards', held in La Londe-les-Maures, France. The workshop was chaired by Stephan Winter, and brought together many of the leading researchers in geographical ontology. Most importantly, participants contributed articles to a special issue of IJGIS on the topic. Andrew Frank's own article in the IJGIS Special Issue (Frank *et al*. 2003) introduced some novel and important ideas about geographic ontology. He presented a 'five-tiered' ontological framework for space-time in GIScience that starts from a 'physical reality', followed by 'observable reality' (observations/measurements from a point in space-time), 'object world' (portions of delimited reality), 'social reality', and, finally, 'cognitive agents'. The latter recognizes that human agents actively seek to understand and reason about reality; this provides the basis for their direct comprehension of reality.

3.2 Comparing formal and cognitive models

One of Frank's primary cognitive research contributions has been relating formal models of geographic space and spatial reasoning to cognitive models. Frank has long promoted relating cognitive models of space to formal models as perhaps the central aspiration of cognitive GIScience.

> The formal specification of spatial objects and spatial relations is at the core of geographic data exchange and interoperability for … GIS. It is necessary that the representation of such objects and relations comes close to how people use them in their everyday lives, i.e. that these specifications are built upon elements of human spatial cognition. (Frank and Raubal 1999, p. 67)

Frank has seen both cognitive (experiential) and formal models to be abstractions of the same real world.

A formal model (formal language) consists of axioms that define entities and states according to a finite set of necessary and sufficient properties, together with mathematical or logical rules to infer conclusions from these axioms. Frank has pushed for identifying models of spatial reasoning that would be compatible with human cognition so they could assist in the design and implementation of GIS (Mark and Frank 1996). The latter, Frank has claimed, requires cognitive models to be expressed formally. And formalization allows hypotheses to be precisely stated, which facilitates their evaluation by data from human-subjects studies.

Frank's thinking has been shaped by a handful of theoretical approaches to understanding cognition, coming primarily from cognitive science, cognitive linguistics, and robotics and AI (Hayes 1978, Rosch 1978, Talmy 1983, Hobbs and Moore 1985). Especially influential on Frank has been the theory of *image schemata* from Johnson (1987) and Lakoff (1987). Image schemata are mental structures that are more abstract and generic than mental images, but more concrete and iconic than language. They are historically related to mental schemas as theorized by Bartlett, Piaget, and others. Johnson and Lakoff claim they provide the link between sensori-motor experience in the physical world and abstract linguistic cognition, solving the symbol grounding problem.

In the very first issue of the journal *Spatial Cognition and Computation*, Frank and Raubal (1999) presented their detailed effort to formally specify image schemata. As in other work, Frank distinguished the ways people interact with small-scale ('table-top') spaces from their experience of geographic ('large-scale') spaces. Here, he and Raubal distinguished small-scale image schemata (CONTAINER, SURFACE, LINK) from large-scale (LOCATION, PATH, REGION, BOUNDARY). After reviewing different computational approaches to formal model creation and evaluation, they introduced the cartographic image we show in Figure 1 as their test case. The authors created statements that expressed various spatial relations one might use to describe this image; they translated the natural-language statements into formal statements. For example:

- Es gibt einen Weg von Wien nach Baden. (There is a path from Vienna to Baden.)

  path (a, b) <=> path (b, a)

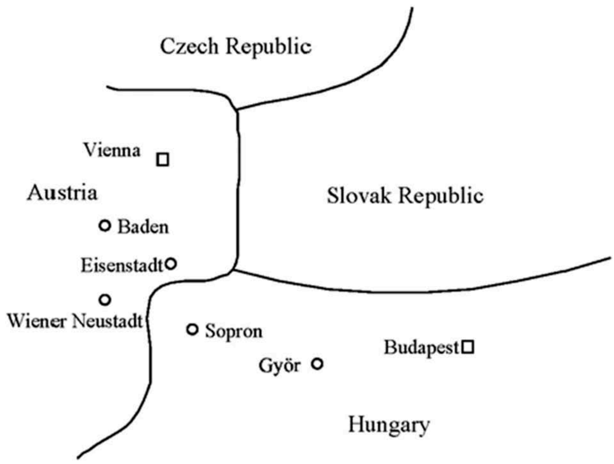

Figure 1. Map of Eastern European area used by Frank and Raubal (1999) to demonstrate how image schemata could be used to formalize qualitative spatial relations in GIScience.

- Du kannst von Baden nach Wien fahren und am Abend wieder zurück. (You can drive from Baden to Vienna, and back in the evening.)

  conv (path (a, b)) = path (b, a) = path (a, b)

- Wenn du von Wien nach Budapest fährst, dann fährst du durch Györ. Der Weg von Graz nach Wien führt über Baden und Wiener Neustadt. (If you drive from Vienna to Budapest, you will drive through Györ. The way from Graz to Vienna goes through Baden and Wiener Neustadt.)

  ind-path (a to b via c) = > path (a, c) & path (c, b)

Frank and Raubal went onto discuss formalizing statements about regions, borders, paths, and path intersections, as well as statements about the locations and movements of people. Similarly, Frank (1998a) discussed formalizing English spatial relations; particularly, the spatial frames of reference involved in locational statements.

3.3 *Qualitative spatial relations and vagueness in geography and geographic information*

A central issue for GIScience has been understanding imprecise or *vague* entities, measuring and modeling them, computationally representing them, and depicting them cartographically. Cognitive GIScience has recognized the value of understanding vague human conceptualizations of entities, as well as conceptualizations of vague entities. Indeed, the very focus on vagueness stems not only from the ubiquitous pragmatic issue of dealing with measurement error in geographic information research and administration, but also from recognizing how often humans reason and communicate about entities that are fundamentally vague or uncertain – and with apparent ease and naturalness. In the geographic context (e.g. Frank *et al*. 2001a), this is most often uncertainty about the spatial location of entities, including the location of a region's boundaries, and thus, the spatial extent of a region. Humans are exceedingly comfortable reasoning with vague properties, such as expressed in verbal properties and relations like 'small', 'near', 'high', 'over', 'there', and 'southwest'. Reasoning with such nonmetric (including non-Euclidean), nonquantitative concepts has been dubbed 'qualitative reasoning' (Kuipers 1994). In the case of spatial reasoning, however, the qualitative nature of concepts is clearly restricted not only to spatial information at the ordinal or nominal level; but at the metric level, even though substantially imprecise. The latter has been called 'approximate quantitative' or 'qualitative metric' reasoning (Dutta 1988, Hernández 1991, Frank 1992b).

Frank has contributed important work on qualitative spatial reasoning concerning distances and directions, particularly cardinal directions. In Frank (1992b), he presented a scheme for transitive inference about the distance and direction of point C from point A, given only qualitative statements about the distance and direction from point A to B, and from B to C. He offered a linguistic expression such as the following as an example (p. 344):

> *Chicago is far and north of St. Louis, Los Angeles is near and south of San Francisco, St. Louis is far and east of San Francisco, New Orleans is near and south of St. Louis.*

Given these statements, Frank suggested that one can conclude that *Chicago is north of New Orleans*; he wanted to provide qualitative reasoning rules to account for this. Here, he specifically considered the qualitative distance statements 'far' and 'close', and the qualitative direction statements 'north', 'east', 'south', and 'west' (NSEW). He concluded that his axiomatic system allows spatial deductions that are 'at least "Euclidean-approximate"…for any combination of input values' (p. 343).

In Frank (1996), Frank offered an expanded analysis of qualitative reasoning with cardinal directions. He contrasted two approaches to generate cardinal directions at the resolution of either 4 or 8 directions, e.g. either NSEW, or NSEW and the 4 intermediate directions. One approach uses *cones*, which emanate from a point (such as a person) (Figure 2).

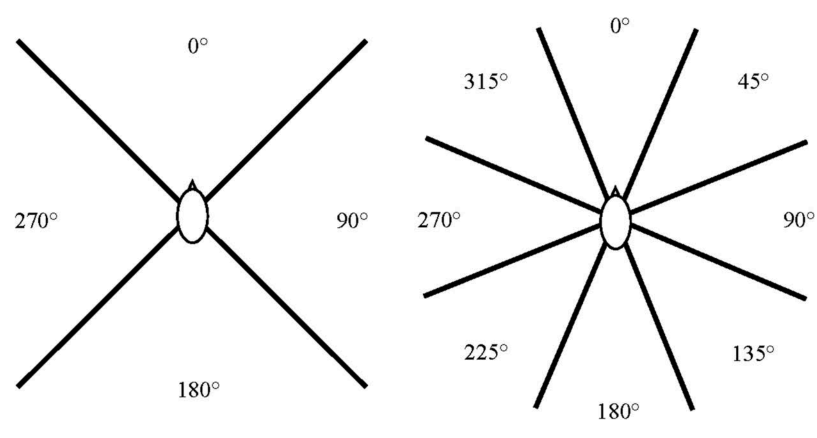

Figure 2. Qualitative directional reasoning with 4 or 8 cones (redrawn from Montello and Frank (1996), Figure 2).

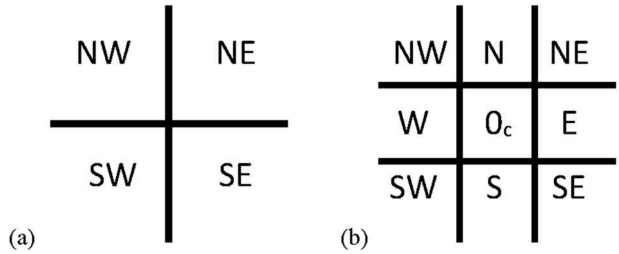

Figure 3. Qualitative directional reasoning with two half-planes (a) without or (b) with a central neutral zone of indecision or non-direction (redrawn from Frank 1996, Figures 8–9).

The second approach uses half-planes (Figure 3). Figure 3 also depicts the possible inclusion of a neutral area in the middle; this neutral zone represents complete uncertainty of direction, either no direction or one that is too uncertain to even approximate. That is, Frank here introduced the notion of a 'zero' region, an innovation that made the algebra of qualitative spatial reasoning considerably more workable. Frank's system would then allow composite directions reflecting the outcome of inferences (Table 1); the resulting inferences may be relatively certain quantitatively, relatively approximate, or so uncertain as to be null.

As stated above, one reason Frank has advocated for the formalization of cognitive models is to facilitate empirical evaluation of those models by comparing their output to data collected in human-subjects studies. Frank collaborated with one of us (Montello and Frank 1996) to do just that for his cone-based models of qualitative directional reasoning. The human-subjects data they used came from estimates of path angles walked in a large room made by Sadalla and Montello (1989) research participants. Montello and Frank created 4-cone and 8-cone models of direction knowledge, and sampled directional estimates uniformly within each cone. This simulated the situation where each person knows accurately within which cone a direction fell but not where inside the cone. Of course, this is not generally true about human cognition of directions, but such ad-hoc decisions must typically be made when one attempts to fully realize a formal model of human cognition. This highlights an important difficulty with this aspect of the formalists' program, namely that formal models typically specify details of a fully functioning behavioral system only incompletely. For example, Frank's models

Table 1. Composition of directions derived from a cone-based system for qualitative directional reasoning (redrawn from Frank 1996).

	N	NE	E	SE	S	SW	W	NW	0
N	N	n	ne	0	0	0	nw	nw	N
NE	n	ne	ne	e	0	0	0	n	NE
E	ne	ne	E	e	se	0	0	0	E
SE	0	e	e	SE	se	s	0	0	SE
S	0	0	se	se	S	s	sw	w	S
SW	0	0	0	s	s	SW	sw	w	SW
W	nw	0	0	0	sw	sw	W	w	W
NW	n	n	0	0	0	w	w	NW	NW
0	N	NE	E	SE	S	SW	W	NW	0

The null value (0) indicates no or completely uncertain direction. Lower case denotes approximate Euclidean inference; upper case denotes exact inference.

of qualitative reasoning focus on knowledge resolution but not accuracy. Ad hoc, partially arbitrary assumptions must be implemented to fully formalize the model so that behavioral data can be simulated. That said, the output of the 8-cone simulation did match the magnitude of variable errors from the human-subjects experiment of Sadalla and Montello fairly well, supporting the idea that human directional resolution in this context is something like 360°/8. Resolution aside, other research with human subjects clearly suggests that a better fitting formal model will have to treat the cones as unequal in width, because human knowledge is more precise in some directions (such as straight ahead) than others (such as behind) (Klippel and Montello *et al*. 2007).

3.4 *Cultural issues in geospatial cognition*

In his summary of the COSIT conference series in the *Encyclopedia of GIScience* (Kemp 2008), Frank notes that the original meeting at Las Navas discussed in the preceding sections inspired several research themes. One of these was: 'Investigations of cultural differences in spatial cognition and what is common for all humans (so-called universals)' (p. 51). One of us was inspired to begin a career-long research program on these issues (Mark 1993, Turk and Stea 2014).

Campari and Frank *et al*. (1995) provided a rather thorough overview of this topic in the context of GIScience. They noted that cultural issues were numerous in the context of GIScience, with important implications for GIS design and use, and presented an innovative taxonomy of approaches for studying cultural differences in GIS. At its highest level, their taxonomy distinguished approaches directly associated with GIS from those indirectly associated. The former involve relationships among GIS designers, users, and technologies, and include topics such as how GIS are designed and used, and how geographic information is administered. An obvious example would be that verbal expressions must be translated into the language where the GIS is being used. The indirect approaches involve cultural issues the authors claimed have implications for understanding human aspects of GIS, although they are not specifically about GIS, but about larger human questions like those that might be asked by basic social and behavioral scientists. Two of these three indirect approaches are cognitive – 'human spatial and temporal conceptualization', and 'language'. Even the third approach of 'human territoriality' involves human conceptualizations about control of the earth's surface.

Frank updates his thinking about cultural aspects of geospatial thinking in Frank (2009). He recognized that cultural differences per se are plainly evident: 'It is trivial to observe differences between cultures: People use different languages, have different modes of building houses and organize their cities differently, to mention only a few' (p. 1). He noted that interest in cultural differences for GIS may be increasing with the advent of web mapping, volunteered geographic information, and the like. Turning specifically to possible cultural difference in geospatial cognition (one of the indirect issues noted by Campari and Frank *et al*. 1995), he identifies the Whorfian hypothesis of *linguistic determinism* as being at the 'heart' of concerns about cultural differences and GIScience. This is the idea that the language one speaks determines the concepts one can think of and perceive in reality. A weaker version of this idea, but nonetheless quite relevant to culture and GIS, is *linguistic relativity*, the idea that one's language does not determine one's thinking or perception but partially shapes it, directs it, and constrains it. In the context of GIS, linguistic relativity may well have implications for how different language communities conceive of and communicate ideas about spatiality, temporality, and thematic features (such as lakes, forests, mountains, cities). The core practical concern here is how well or how poorly the world's people – at all levels of education, social status, economic systems, etc. – can achieve geographic information tasks using one or a small number of databases, software packages, hardware technology, and so on.

In his 2009 article, Frank expressed what he has come to conclude about the significance of cultural differences for GIS, after decades of thought and experience involving culture and GIScience. He does not doubt that there are various substantial and important societal and cultural issues for GIS, many of them dependent on factors that are administrative, economic, physiographic, etc. With respect specifically to cultural differences in geospatial cognition, Frank seems to recognize that variations in natural language are not the only bases for thinking about cultural differences relevant to GIScience. Humans at different locations on Earth and in different historical eras still have very similar physical bodies with very similar sensory systems, live in similar (not identical) physical environments, have similar needs for food, shelter, mates, social affiliation, and so on. At the same time, he recognizes that there are regional or societal variations in geospatial cognition found among people who speak the same language. Frank appears to find himself concluding that it depends critically on how much we rely on language differences as our bellwether of cognitive differences, or relatedly, how much a particular GIS task or element of infrastructure depends on natural language and its relation to cognition.

3.5 *Other domains*

We have focused in this essay on several specific domains of cognitive GIScience work to which Frank has contributed, but his contributions to cognitive GIScience go beyond these domains. Frank and his colleagues and students have written on the design of GIS interfaces from the perspective of cognitive human factors. He has felt for some time that making more effective user interfaces is the most blatant reason that system designers need to understand human cognition. Along with one of us, Frank co-led NCGIA's Research Initiative 13 on 'User Interfaces for Geographic Information Systems' and co-authored the summary report on the meeting (Mark and Frank 1992b). Those authors saw the Initiative as an outgrowth of Initiative 2 on 'Languages of Spatial Relations', inspired by the recognition that humans 'interact' directly with digital geographic information via the computer display that suggests what is in the database, what operations may be performed on the data, and what are the results of carrying out these operations. 'The user interface is the part of the system with which a user interacts. It is the only part directly seen and thus "is" the system for the user' (Frank 1993, p. 12). The perception and interpretation of the words, numbers, and images shown on the monitor (the standard computer interface modality thus far) would largely determine how the person (the user) would understand the content and meaning of the database, and what he or she could do with it to understand it further. Frank has collaborated on prominent theory exploring the meaning of GIS interfaces as systems of metaphors for users (Kuhn and Frank 1991).

Another topic Frank identified early on as a central research paradigm for exploring spatial cognition in GIScience is wayfinding, the part of navigation that involves planning and decision-making. He identified wayfinding as likely to be so central because it is such a common way that virtually everyone interacts regularly with spatial information at geographic scales. As in other areas of cognitive research he has worked on, Frank's preferred research method to study wayfinding cognition has been computational simulation. His first major proposal for such a computational simulation of wayfinding focused on the use of cartographic maps to communicate spatial situations (Frank 2000, see also Frank *et al.* 2001b), as when one person uses a map to show another person which way to travel. In his article, he offered a theoretical framework and computer implementation for simulating what a person believes about reality, how a map is produced from these beliefs, and how another, navigating, person interprets the map. This multi-agent model simulated the environment and the cognitive operations of the people in the environment. Hochmair and Frank (2000) further developed a simulated software agent which navigated in a simulated street network with various types and amounts of error in distance and direction knowledge. They used this simulation to examine the implications of errors in spatial knowledge on applications of the *least-angle strategy*, a heuristic that people have been found to apply when wayfinding with uncertain knowledge in which they prefer to choose routes most directly headed initially toward the destination. Hajibabai *et al.* (2007) created an agent-based simulation to study wayfinding during emergency building evacuation that focused on the impact of signage in the building. Karimipour *et al.* (2016) examined the effectiveness of verbal spatial descriptions for urban wayfinding. They compared standard addresses from map databases to human- and computer-generated route descriptions.

Additional topics Frank has written on include representing and reasoning with time and temporality in GIS, including extensive work on its cognitive ontology (e.g. Frank 1998b): 'Movement in space is a fundamental part of spatial thinking and without motion we will not capture how people think about space' (Frank 2010, p. 2). He and Weiser (Weiser and Frank *et al.* 2013) did some recent work on a communication model for people exchanging spatial information in which a socially shared spatial semantics is created via 'cognitive transactions' across different levels of resolution. Also recently, Frank has co-authored some innovative work with Hobel and Fogliaroni (Hobel *et al.* 2016) that assesses cognitive regions by analyzing internet records, performing computational natural language processing on user-generated content (social media postings, etc.) to identify the extent of informal regions such as the 'historical city center' of Vienna.

3.6 *Frank's topics today*

Our review makes it clear that Frank introduced or at least nurtured several of the major topic areas which went onto structure cognitive research in GIScience. These topics include ontologies of space-time-theme, the comparison of formal and cognitive models of geospatial information, qualitative spatial relations and vagueness in geography and geographic information, cultural and linguistic issues in geospatial cognition, GIS user interfaces from the perspective of cognitive human factors, and GIScience and wayfinding. One might ask how well these topic areas have survived – what are their current prospects as research foci for young researchers going forward?

We find that each of the topics in cognitive GIScience that Frank worked on is still an active area of research and scholarship. Since 2010, to pick an arbitrary recent date, hundreds of books and articles have been published on these topics by scholars, work that is notable for its multidisciplinarity, involving geography, cartography, GIScience, psychology, linguistics, anthropology, computer science and AI, philosophy, and more (e.g. Denis 2018, Fabrikant *et al*. 2010, Hirtle 2011, Klippel *et al*. 2011, Mark 2011, Podobnikar and Ceh 2012, Waller and Nadel 2012, Raubal *et al*. 2013, Tenbrink *et al*. 2013, Richter and Winter 2014, Ishikawa 2016, Gao *et al*. 2017). Numerous entries on cognitive GIScience concepts (such as on spatial thinking, qualitative spatial reasoning, and geospatial ontologies) litter all of the recent reference works in geography and GIScience, including the *International Encyclopedia of Geography*, the *Encyclopedia of Geographic Information Science*, and the *Encyclopedia of Geoinformatics*. The latest research on all of these topics continues to be presented, often as central themes, at a variety of prominent international conferences, including the *Conference on Spatial Information Theory*, the *International Conference on Geographic Information Science, Geospatial Semantics, Spatial Data Handling, GeoComputation*, the meetings of *The Association of Geographic Information Laboratories for Europe*, the *International Cartographic Conference, AutoCarto*, and the *International Conference on the Ontology of Spacetime*.

4 Conclusion

Andrew Frank was a key early advocate for understanding human cognition of space, place, and environment as a way to increase our understanding of geographic information and geographic information systems, and thereby make them more effective tools – more efficient, more useful, more equitable, and so on. He had substantial impact on the direction of the NCGIA and of the multidisciplinary field of GIScience. This has been true in terms of both theory and methodology, combining approaches from science, engineering, mathematics, and philosophy. It has also been true in terms of the direct and indirect influences he has had on generations of future and contemporary GIScience scholars. This essay has overviewed Frank's contributions to the study of cognition in GIScience, making the case that those contributions are considerable. We reviewed his work in cognitive areas as diverse as ontologies in GIScience, formal models of geospatial cognition, qualitative spatial relations and vagueness in geography and geographic information, cultural issues in geospatial cognition, user interfaces for GIS, wayfinding, and temporal cognition in GIScience. At the core of his influence was (and is) his belief, for which he has eloquently argued over the course of four decades, that geographic information tools are essentially cognitive tools and must therefore be understood in relation to human cognition.

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