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Time in Geographic Space: Report on the Specialist Meeting of Research Initiative 10 (94-9)

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Report on the Specialist Meeting of Research Initiative 10

Edited by

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National Center for Geographic Information and Analysis

Report 94-9

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1. Executive Summary

This report describes the Specialist Meeting of the National Center for Geographic Information and Analysis (NCGIA) Research Initiative on “Spatio-Temporal Reasoning in GIS.” This Research Initiative addresses space and time as it relates to objects and people in geographic space. The Specialist Meeting for the Research Initiative was held at Lake Arrowhead, CA May 8-11, 1993 to set and prioritize a research agenda. This meeting followed the workshop on Temporal Relations in Geographic Information Systems held in Orono (January 1990) and a joint seminar with European researchers on Methods of Spatio-Temporal Reasoning in GIS held in San Miniato, Italy (September 1992), which served as a forum to assess the state-of-the-art in reasoning about geographic space and time and started a dialog among different disciplines involved in space-time reasoning. The focus of the Lake Arrowhead-workshop was on “Time in Geographic Space.”

The primary goal of this report is to disseminate the results of the discussions and make them available to other researchers. Discussions at the workshop focused on cognitive and formalization issues as they relate to spatio-temporal reasoning. Participants identified a research agenda consisting of three complementary parts:

- studies of human cognitive representation, language, and culture with respect to geographic space and time;
- developments of formal systems for spatio-temporal reasoning; and
- efforts to bridge the gap between human and formal systems with appropriate means for communication and interaction.

Workshop participants found over 60 researchable questions, which they categorized according to this framework and subsequently prioritized. High priority was given to research that increases our knowledge of cognitive spatial representations and how such representations can be formalized. Also, the development of temporal taxonomies recurred throughout the discussions. Several times the need for alternatives to the *snapshot* space-time model were demanded, for instance by considering *processes*.

An edited book with revised and extended manuscripts of selected papers is in preparation and scheduled to appear in early 1995.

2. Acknowledgments

The initiative co-leaders want to thank everyone who contributed to the success of the workshop. The Steering Committee (Helen Couclelis, Andrew Frank, Stephen Hirtle, Gail Langran, David Mark, Daniel Montello, and Michael Worboys) provided invaluable input for the agenda and schedule of the Specialist Meeting. The participants' active contributions during the discussions at the Specialist Meeting made this Research Agenda possible. We appreciated the leadership provided by the discussants in the plenary sessions and the chairs of the small-group discussions. None of the participants should be singled out, though Barbara Tversky and John Kelmelis deserve special credit for defining the framework within which the researchable questions were organized and prioritized. Local arrangements at Lake Arrowhead were provided by Judith Parker. Scott Bell, Tom Cova, Mei-Po Kwan, and Jayant Sharma assisted during the meeting with note taking and recording of the sessions. Kathleen Hornsby, Karen Harp, Sandi Glendinning, and Blane Shaw supported the initiative co-leaders with administrative tasks during the preparation of the meeting. Thanks to everyone!

Special thanks go to Scott Freundschuh and Jayant Sharma, who worked from the notes taken and the tapes recorded during the meeting, and distilled the essence of the discussions. Scott also communicated with the participants in the aftermath of the Specialist Meeting, when individual researchable questions were categorized and prioritized.

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3. Research Initiative 10: Spatio-Temporal Reasoning in GIS

The U.S. National Center for Geographic Information and Analysis (NCGIA) is conducting a Research Initiative on Spatio-Temporal Reasoning in GIS. Its overall goal is to increase our understanding of reasoning processes that apply to geographic space and time. Considerable research in spatial and temporal reasoning has been undertaken in artificial intelligence. This research has been directed toward understanding the relative positions and movements of small parts, typical for mechanical systems, and concentrated on small-scale spaces. Spatial reasoning in large-scale geographic space may be different. Geographic space encompasses spaces that are beyond the (human) body and may be represented by many different metrics and geometries in many different scales. Only few researchers have focused on this problem.

This Research Initiative concentrates on geographic space, time, and change related to bounded objects in geographic space. It builds on efforts of behavioral geography, cognitive science, and environmental psychology and we plan to expand them in a strongly computational (i.e., formalized) framework. The audience of this Research Initiative is broadly interdisciplinary bringing together scientists from many different areas such as geography, cartography, engineering, computer science (primarily databases, artificial intelligence, and user interfaces), mathematics (primarily logic and topology), environmental and cognitive psychology, cognitive science, linguistics, and such application domains as anthropology, history, archaeology, geology, and climatology.

The objectives are:

1) to study spatial applications in order to identify properties of different time concepts such as continuous, discrete, monotonic, and cyclic;
2) to explore alternative mathematical formalizations to Cartesian coordinates and Euclidean geometry, which represent spatial and temporal reasoning processes better;
3) to formalize human reasoning processes about geographic space and time;
4) to build computational frameworks, within which geographic phenomena and processes, and their temporal changes, can be simulated; and
5) to examine computational reasoning methods with observations from human subject experiments about human spatial and temporal perception and cognition.

3.1 Related Work

The consideration of time and space is not an entirely new aspect of geographic data and geographic information systems. Time and space has been a reoccurring topic in geography, computer science, and artificial intelligence. Hägerstrand's Time Geography (1967) is a landmark work in spatial analysis. In GIS, the management of spatial data that changes over time has been addressed prominently by Langran (1989, 1992), and was followed up by several other Ph.D. theses (Hazelton, 1991; Kelmelis, 1991; Al-Taha, 1992). Complementary work in the areas of databases and artificial intelligence has been summarized in a recently edited volume on temporal databases (Tansel *et al.*, 1993). A comprehensive compilation of other references on the treatment of space *and* time in databases can be found in a bibliography by Al-Taha *et al*. (1994). Shortly after the

Initiative 10 Specialist Meeting, the database community held a workshop to identify the needs for a Temporal Database Infrastructure (Pissinou *et al.*, 1994).

Other NCGIA Research Initiatives have dealt with questions related to spatial, temporal, and spatio-temporal issues and GIS. This particular Research Initiative on spatio-temporal reasoning in GIS is most closely linked to one of the earliest NCGIA Research Initiatives, "Languages of Spatial Relations" (Mark *et al.*, 1989) and has been a reoccurring topic in several other Research Initiatives (e.g., Goodchild, 1989; Smith and Frank, 1989; NCGIA, 1991; Mark and Frank, 1992).

3.2 History of Research Initiative 10

The original NCGIA proposal (NCGIA 1988), included a Research Initiative 10 on "Temporal Relations in Geographic Information Systems" (Initiative leader: Andrew Frank). Its initial goals were to understand the modeling of time as it relates to GIS; to assess inference methods in temporal logic and deduction strategies in non-monotonic systems; to compare modeling of states to methods of modeling incremental changes in different GIS applications; to study the architecture of a temporal GIS; and to extend the methods for dealing with multiple and alternative representations to include temporal aspects. As part of the preparations for this Research Initiative, NCGIA organized in 1990 a two-day workshop on "Temporal Relations in Geographic Information Systems" with seventeen participants from Geography, GIS, and Computer Science (Barrera *et al.*, 1991). The major finding of this meeting was the identification of two significantly different paradigms of time: (1) time as a continuum and (2) time as a sequence of intervals and changes caused by events. Each paradigm influences considerably the design of and interaction with temporal GISs.

Based on insight gained from research in Initiative 2 ("Languages of Spatial Relations"), the NCGIA Scientific Policy Committee approved in 1991 to re-focus Initiative 10 to include a stronger consideration of cognitive aspects when dealing with time and space, and to investigate the interplay between formalizations and human performance. This change in focus also resulted in a new title for the Research Initiative, now called "Spatio-Temporal Reasoning in GIS," and a new pair of co-leaders, Max Egenhofer (University of Maine) and Reg Golledge (University of California, Santa Barbara).

Initiative 10 gained considerable momentum in 1992 with the organization of the conference on "Methods of Spatio-Temporal Reasoning in Geographic Space" held in Pisa, Italy (Frank *et al.*, 1992). Over 100 conference participants attended the presentation of 25 fully refereed papers on various aspects of spatial and temporal reasoning. In conjunction with the Pisa conference, we held a workshop on "Reasoning about Geographic Space and Time" in San Miniato, Italy, which was co-funded by the Italian National Research Council (CNR). Organizers were Max Egenhofer (University of Maine), Andrew Frank (Technical University Vienna), and Giorgio Faconti (CNUCE-CNR, Pisa). The goal of the workshop was to compare the different methods and approaches used in spatio-temporal reasoning, to assess the state of the art in reasoning about geographic space, and to identify research needs. It brought together approximately 30 researchers from Europe and North America. Participants discussed primarily aspects of reasoning about geographic space, and they felt that discussion of time-reasoning in geographic space need to be based on a better understanding of reasoning about geographic space. Discussions centered around similarities and dissimilarities between space- and time-reasoning. Participants agreed that space- and time-reasoning may be inherently linked to each other, e.g., in geological applications in which one infers history (i.e., time) from space and from knowledge about processes (or motion). At the same time, it was acknowledged that humans employ different concepts for space (e.g., *Zubin* spaces), and participants questioned whether there were corresponding concepts for time ("Are there also *Zubin* times?") or multiple types of type, maybe similar to different types of space (e.g., table-top or large-scale). An argument for differences between space- and time-reasoning involved the fact that humans use spatial metaphors extensively and employ them for time; however, there are only very few temporal metaphors that are applied to space. A strong recommendation was made to consider cultural differences in the way humans think about space and time, or how they communicate about space and time. Participants were also interested in the development of a classification of different types of time, and it was suggested to consider such properties as continuous, discrete, cyclic, and non-monotonic. As a step towards such a classification, one should identify a (complete) set of time properties and formalize them.

3.3 The Specialist Meeting at Lake Arrowhead

The Specialist Meeting of Research Initiative 10 was held May 8-11, 1993 at Lake Arrowhead, California. To focus the attention on temporal issues, the Initiative co-leaders gave the meeting the title, "Time in Geographic Space." This was a consequence drawn from the San Miniato meeting, where participants frequently discussed space as it relates to time, and to a lesser degree the kind of spatial inferences one can draw from information about time and change.

The goal of the Specialist Meeting was to formulate a research agenda for spatio-temporal reasoning about geographic space. Such reasoning methods should be implementable in a Geographic Information System. Specific questions to be considered by the participants in the workshop included[1]:

- Will fundamental theories of spatial and temporal relations be found in the cognitive sciences?
- In formal reasoning systems, are the models reasonable representations of the real world?

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[1] Nick Entrikin gave explicit answers to some of these questions during his discussion of the papers in the session on Reasoning and Philosophy at the Specialist Meeting:

- "Will fundamental theories of spatial relations be found in the cognitive sciences?" Entrikin claimed the answer to this question is "yes," and "no"—cognitive science certainly has something to contribute to formulating fundamental theories of space and time, but there is work in other areas of the social sciences (i.e., geography) that have much to contribute.
- "In formal reasoning systems, are the models reasonable representations of the real world?" Entrikin responded "yes" and "no"— in limited domains, models can be robust, but in broader contexts, the models are lacking.
- "Are there different concepts of space, and are space and time separable cognitive categories?" "Yes," but they are limited to physicalist notions of space, and are influenced by culture (and probably vary across cultures). GIS has the potential to change how we view the world—reshaping our mental geographies (what places are, how they change, etc.) which provide us with a sense of who we are.

- In the context of geographical modeling, are there different concepts of space and time?
- Are space and time separable cognitive categories for geographers? For other disciplines?
- Are space and time perceptions influenced by culture, i.e., do they vary across cultures?

Approximately six months before the Specialist Meeting, the Initiative co-leaders issued a call for papers over several electronic mail listservers. In addition, 500 printed fliers were mailed to academic institutions and selected individuals who were working in the area of interest. Extended abstracts of 2,000 words were solicited from a broad audience covering social and natural sciences, as well as engineering. In response to this solicitation, we received 33 papers, covering a wide range of perspectives of the topic (e.g., philosophy, geography, computer science, environmental psychology, planning, linguistics, history, and archaeology). Each submitted paper was reviewed by three members of the Initiative's Steering Committee (Helen Couclelis, University of California Santa Barbara; Andrew Frank, Technical University Vienna; Stephen Hirtle, University of Pittsburgh; Gail Langran, Intergraph Corporation; David Mark, SUNY Buffalo; Daniel Montello, University of California Santa Barbara; and Michael Worboys, University of Keele, U.K.) and ranked according to its relevance to the theme of the Specialist Meeting, scientific quality, and clarity of representation. Steering committee members also made recommendations whether or not to invite the author to the meeting. A high preference was placed on papers that dealt specifically with issues germane to spatio-temporal reasoning.

From among the 33 papers submitted, 22 authors were invited to the Specialist Meeting. The group of participants was completed by some invited discussants, center members, and industrial and governmental representatives to fill gaps of topics or perspectives not represented by the papers or their authors. The 37 participants at the meeting came from different disciplines such as geography, computer science, surveying engineering, psychology, and linguistics. Nine of the participants had attended a previous NCGIA Specialist Meeting. Six participants were from the private and public sectors, the remaining participants were university-based researchers. Eight of the participants were graduate students, five from outside of the NCGIA. One participant was a representative of the GISDATA project, funded by the European Science Foundation (ESF). The participant list, with affiliations, is included in Appendix A to this report.

The Specialist Meeting was a mixture of plenary sessions and small-group discussions. The plenary sessions were primarily for the discussion of papers selected from among those submitted to the organizers of the meeting, and the presentation and assessment of the small-group discussions. A discussant presented for each of the six topics a critical commentary of the papers with respect to their contributions, positions, and questions raised. Following each discussant's comments, authors provided a brief statement to reemphasize and/or clarify comments made on their paper. Based on the questions raised in the papers, the discussants challenged working groups with specific questions, statements, or hypotheses, which served as a framework for a research program. The working groups, on the other hand, provided an environment within which to identify researchable questions. The working groups, comprised of six to seven members, attempted to define specific researchable questions at the granularity of a Ph.D. or Master's thesis, and to identify or recommend which research methodologies to use. A representative of each working group then reported in a plenary session the group's findings. These findings were discussed and modified via suggestions by all participants of the meeting. In a final plenary session, a working group charged with providing a synthesis of the discussions and points raised, presented a framework within which the researchable questions collected during the meeting could be organized and prioritized. This process happened over the next few months after the Specialist Meeting.

4. Discussions at the Specialist Meeting

Compiled and edited by

Scott M. Freundschuh[2] **and Jayant Sharma**[3]

Papers that were selected for inclusion in the meeting were grouped into six topical categories. Categorization was based on papers that addressed spatio-temporal issues either from a similar perspective, or with similar methods. The topical categories were:

- reasoning and philosophy;
- computer science, graphics, and cartography;
- social science perspective;
- spatio-temporal cognition;
- spatial behavior; and
- GIS perspectives.

Subsequently, we will summarize these discussions. Although we kept the chronology of the sessions, we tried to consolidate those discussions that relate to the same issues across different categories.

4.1 Reasoning and Philosophy

Discussant: Nicholas Entrikin.

Separation of objects from subject

The paper by Helen Couclelis titled *Making Space for Time: Towards a Truly Temporal Geography* is concerned with putting time and process into GIS, focusing specifically on time in GIS. She used Zeigler's discrete-time and discrete-event model as a methodology for putting time into GIS. In this model, space and time are seen as taxonomic categories. Space and time are removed from human experience—we experience the world as a whole and cognition allows or enables us to isolate concepts such as space, time, and perception. Under this view, objects are separate from subject. This approach works well for physical geography, spatial analysis, and social sciences. Entrikin, however, questioned how space and time relate to particular phenomena within this framework. He took the position that one has to consider space and time as a connection between subject and object, if one wants to look at a broader space-time relationship.

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Physical vs. human time

Couclelis further suggested that maybe we should not make such a big distinction between physicalist time (clock time) and human experience (body time), because we do experience physical time. Humans live in a physical as well as cultural worlds—the physical science view "gets our foot in the door."

Separation of space and time in GIS

In a decentralized view of space, GIS represents time from the perspective of physical sciences, while human (social) science centers time on individual experience. Entrikin suggested to also consider in this model *place* as experience of milieu over time—the value of place as an agent in the world. Similar to previous discussions at the San Miniato workshop, the question was raised whether we can talk about space and time in GIS as interrelated, not separate.

The same issue of the separation of space and time came up again in the discussion of Freksa's paper, though in a somehow different setting. Freksa argued that it is possible to represent space and time in some representational medium, like the computer. In computer science we have propositional representations (logic) vs. pictorial representations (something that we see). Do we really have these type of representations, and if so which one(s)? We can use pixels, which are propositional, to represent the world. We can look at individual pixels and can swap pixel for pixel, this really does not matter. But the resultant picture does not make sense. Where pixels actually belong so that the image does make sense is dictated by time. In other words, we need *time* to provide order to *space* for understanding. For this particular application, time and space cannot be separated.

Papagno in his paper *Seeing Time*[4], made the same argument, suggesting that we need space to talk about time, and vise-versa. Looking at the effects of people on the landscape over time is one way to model changes in space over time. His paper raised the question how do processes or human's activity shape or modify the landscape so that we can *see* time in this landscape.

The relation between formal models (e.g., rules) and reality

The paper by Freksa titled *Temporal and Other Issues in Qualitative Spatial Reasoning* explores qualitative spatial reasoning in a natural language system. It seems that the rules are more developed for time than for space. When developing formal spatial inference systems, how does the model relate to the reality being modeled? Were do we locate rules in the world? What do these rules mean? Should one look at human behavior as simply rule-based? Can the fundamental relations of human space be found in cognitive science? This is mostly an experiential view, i.e., knowing the rules without being conscious of them. Entrikin argued that geographers have a contribution to make here. The spatial-temporal reasoning question must be broader. The models must be integrated to human experience. Our cognitive categories pull the parts apart, while our investigations attempt to put them back together assuming an experiential view. GIS is limited to physical notions of space. We must view this in a broader context and discover how to merge culture and GIS, in order to make GIS trans-cultural. Entrikin concluded if GIS is used to redesign space, it has the potential to reshape our geographies.

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[4] This paper was discussed in the session on the Social Science Perspective, but addresses issues equally relevant to the consideration of separating time and space in GIS.

Freksa warned to look very carefully at the representation of the *real world*. Our goal is to create representations to model aspects of our *cognitive world*, and we have to realize that these representations are undergoing continuos revision.

4.2 Computational Aspects of Spatio-Temporal Reasoning

Discussant: Michael Worboys.

The discussions about formal aspects of spatio-temporal reasoning continued from the perspective of *computational* theories, focusing on the development of models for dealing with spatial and temporal information. Mike Worboys pointed out that this is the view taken by Computer Science, the *science of the artificial*, in that it deals with human constructions rather than the real world in the way geography does.

Designing computational tools

The paper by Cohn *et al.* titled *Exploiting Temporal Continuity in Qualitative Spatial Calculus* presents a logic-based framework for reasoning about spatial knowledge. The goal is an axiomatic theory of space and time that can provide a formal basis for explicit representation and reasoning in Artificial Intelligence systems. Their formalism works for either spatial or temporal regions and provides a suite of primitive relations and inference mechanisms. In particular, they define a composition table for the set of primitive relations. This table can be used for checking the consistency of spatio-temporal constraints or even the spatio-temporal evolution of the regions' properties. In the spatial domain their definitions of primitive regions and composition table are the same as those developed independently by Max Egenhofer and his colleagues (Egenhofer and Franzosa, 1991; Egenhofer *et al.*, 1994). Thus while Cohn's group were not explicitly concerned with GIS, their work has potential application in the design and construction of such systems.

It was discussed whether Allen's (1983) work essentially solved the problem of representing temporal relations. This was not Allen's goal; rather it was an approach to temporal reasoning that has a solid formal foundation and hence proved to be a successful starting point for many researchers. The fundamental operational question is: Are we building tools or constructing models of human behavior? As yet we are dealing with tools, GIS being one of them. These tools could either support human reasoning or simulate it. Thus, Cohn pointed out, that while Allen's and their work does not necessarily solve the problem of representing temporal relations and temporal reasoning, it does provide a computational tool that has its definite uses.

Tobler observed that while graphics is considered as mainly a display mechanism, it actually is a powerful visualization tool that allows one to determine new patterns in data. Since human cognition is visual, the tool is important and powerful.

A finite set of spatio-temporal operations and relations

This led to another fundamental question of whether there exists a finite set of spatio-temporal operations and relations? The answer lies largely in the definition of the formalism. A simplified and restricted model could have a well-defined finite set of primitive relations and operations however their utility would be in question. Cohn stated that the group intended to test their ideas by applying them to various domains such as qualitative physics an GIS.

Chrisman asked people to consider the artifact of coordinates. These are simply a tool for encapsulating metric information that is so vital for much of spatial reasoning.

Bitemporal models for GIS

Mike Worboys' paper, *A Generic Model for Spatio-Bitemporal Geographic Information,* describes a model that handles objects that may be embedded in two orthogonal spatial and two orthogonal temporal dimensions. A purely spatial generic object model is extended using bitemporal elements that account for temporal referencing of the objects. An example of a bitemporal reference being the distinct event time, when an event occurred, and the database time, that is when the event was recorded in the information system.

The distinction between event and database time brought up the issue of how would an information system deal with legacy or historical data? The problems are: (1) legacy data may not fall neatly into the current data model; (2) the volume of data may be too large to successfully physically load it into the database; and (3) the legacy data has a certain semantics, context, and structure. How can this be preserved?

Collaboration between domain specialists and computer scientists

The paper by Liu *et al.* titled *Spatio-temporal Reasoning in Atmospheric Science Databases* describes techniques for tracking and detecting evolving physical phenomena in the very large datasets of atmospheric and ocean global models. The approach is mainly an engineering one, constructing a software system, and the project was at the time of the Specialist Meeting in the prototype stage. The particularly attractive aspect of this approach was that a team of computer scientists worked with a team of atmospheric scientists. They used primarily existing atmospheric and ocean global models to determine and define the spatio-temporal constructs.

Designing and implementing temporal GISs

The major concerns of this implementation are the sheer volume of data, and extending and integrating systems that allow rule-based spatio-temporal reasoning. The basic building block is a deductive database system, LDL++, extended with spatial and temporal construct suitable for the application domain of atmospheric sciences. The temporal reasoning capability is provided by an Event Pattern Language based on regular expressions and logic. The rationale behind the Event Pattern Language was providing a means for detecting and reasoning about sequences of temporal events. More specifically their interest was identifying spatial features and tracking them over time, an example being monitoring a cyclone and cloud formations. The question arose whether their event time model was sufficient for the application considering that many atmospheric phenomenon are cyclic in nature. The benefits of this effort are the practical and quantifiable experiences gained in design and implementation of a temporal GIS for a specific application domain.

Complementary aspects of implementing temporal GISs were described in Bill Hazelton's paper titled *Some Operational Requirements for a Multi-Temporal 4-D GIS*. He focused on a GIS that can handle various models of time, describing the functionality requirements, followed by an outline of a software architecture that would provide such functionality. The temporal functionalites considered were (1) the inclusion of multiple temporal concepts such as linear, cyclic, branching, or multidimensional time; (2) the treatment of topological integrity and sharing of data objects; (3) spatio-temporal indexing of the data to provide efficient retrieval times; and (4) dynamic modeling capabilities. Of interest was the concept of branching time, which Hazelton explained as the temporal concept in those situations where there is no total order between sequences of events or phenomenon. The similarity to versioning was recognized.

4.3 Social Science Perspective

Discussant: David Mark

Spatial metaphors

The paper by Háj Ross titled *Path, Points and Proforms* explored paths and movements in time, and how they are expressed in space. In Ross's model, the description of a moving object's path is composed of the elements source, trajectory, direction, distance, speed, totality, goal, and mode. Mark noted that duration, an element which can be derived from the elements of distance and speed, is not listed explicitly in Ross's model. Ross commented that duration is not a general constituent or notion in language as compared to extent. Examples of extent are prices rising from $1.11 to $2.24; the sky changed from red to yellow through orange; it is 450 miles from Los Angeles to San Francisco; the play ran 5 days from Monday through Friday. How space is represented in language is relevant in understanding how we think about space. We put the world into motion to explain static objects, e.g., "the road runs through the mountain." Space is a common source for metaphors, e.g., dead ends, line of thought. The path schema is central to this idea. Is space the grounding base for the conceptual models that we are interested in here? If we use language to structure our data models, care should be taken so that we do not limit ourselves to studying only the English language. Must consider all languages.

Spatial processes

In the paper *Temporal Dynamics and Geographical Information Systems* Stephen Stead contends that the real world operates along a time line that is a single ordered line, upon which the temporal extent of data values are plotted. Stead focuses on systems that deal with modeling time in archeological applications. He offers an alternative method to the standard *time-slicing* technique, which stores snapshots of the landscape that are used as interpretive back-cloths. Stead's solution is to represent known data elements in four dimensions (x, y, z, and t). From these, real world processes can be modeled. Stead added that his interest is societies and human behavior and how they are dictated by the space they live in. Can we reconstruct space that people once lived in? How likely is the model's predictions of the reconstructed space to be true or close to the truth?

Irene Campari's paper *Morphological, Topological and Chronological Time in Urban Development* views the development of towns as a dynamic and continuous process, which is evident in human actions and events of limited durations. Time becomes a basis for the analysis of relationships between spatio-temporal events in urban space. Time is defined in terms of sequences of events. How do time and space constrain human spatial behavior? Both this paper and Papagno's paper suggest that processes leave traces in space as they evolve in time. Is this a valid view or way of linking time and space? Campari asked, "Does cognitive science look at the effects of space on human cognition?" In other words, if the space changes does the cognition change? How do people feel about the places where they live—e.g., a resident's view of the city vs. a traveler's view.

4.4 Spatial and Temporal Cognition

Discussant: Stephen Hirtle

Though the topic of the Specialist Meeting was on time *and* space, critical to the cognition of time and space is the representation of spatial knowledge. There is general agreement that spatial knowledge is acquired through temporal processes, but what is not fully understood is how spatial information is acquired, how spatial concepts are represented, and if the internal representation is dependent on the acquisition process.

Distinctions of landmark, route, and survey

Tversky, in her paper *Acquiring and Updating Spatial Knowledge from Language*, reported the results of several experiments, one of which explored spatial knowledge acquired from narrative (travel books) and from maps. Whether one learns a route or looks at a map, these are inherently different types of information and they lead to different performance. Does this distinction carry over if you acquire spatial information from narrative? The results of Tversky's experiment suggested that the answer to this question is "No"—the results argued for a single representational schema, regardless of how information is acquired. In this study, subjects read route or survey descriptions of naturalistic environments, after which they answered verbatim or inference questions that required either route or survey knowledge to answer. Verbatim statements were verified faster than responses to inference questions, but there were no differences in responses to inference questions dependent on the route/survey distinction. In a second set of studies, Tversky (with Franklin and Bryant) explored spatial knowledge acquisition from small scale scenes described in narrative where objects in the scenes were described in terms of up/down, front/back, and left/right of a protagonist. Results supported the spatial framework model which purports that space is conceptualized in terms of three axes corresponding to bodily position.

The paper by Montello titled *A New Framework for Understanding the Acquisition of Spatial Knowledge in Large-Scale Environments* argues for a modification of the simplistic landmark/route/survey distinction (which he termed the *dominant framework*) of spatial knowledge. Montello provided a new framework for spatial knowledge which consisted of five major tenets. The first tenet is that there is no stage at which only pure landmark or route knowledge that contains no metric information about distance and direction exists. Metric configurational knowledge begins to be acquired on first exposure to a novel place. The second tenet suggests that with increasing familiarity and exposure to places, there is a relatively continuous increase in the quantity (quantitative rather than qualitative shift), accuracy, and completeness of spatial knowledge. The third tenet indicates that the integration of knowledge about separately-learned places into more complex hierarchically-organized knowledge structures represents a significant and relatively sophisticated step in the microgenesis of spatial knowledge. The fourth tenet suggests that individuals with equal levels of exposure to an environment will differ in the extent and accuracy of their spatial knowledge. The final tenet indicates that linguistic systems for storing spatial knowledge provide for the existence of relatively pure topological knowledge, or at least non-metric knowledge; however, such non-metric knowledge exists in addition to metric spatial knowledge, not as a necessary precursor or intrinsic part of it.

Space-time relationships

The papers by Block and Freundschuh focused on space/time relationships. Freundschuh, in his paper *Cognitive Distance at Various Geographic Scales* analyzed when humans use time in lieu of space to estimate distances. The focus of this study was to explore how people normally think about and express cognitive distance in their everyday lives. This approach was in contrast to previous studies in which subject testing occurred in unnatural experimental situations, where subjects were constrained as to the kind of answers they could provide (i.e., provide distance estimate, provide time estimate). In the present study, subjects were queried during a typical conversation about how far it was to other places. The results indicated an inverted U-shaped curve that suggests that time is used for intermediate distance estimates (331km - 2,080km), and space is used for short (< 10km) and very long distances (8,000km).

Block, in his paper *Psychological Time and the Processing of Spatial Information*, turns the argument around and looks at how time perception can provide a framework for space perception. He makes important distinctions between position and duration, personal experiences vs. general knowledge, and prospective vs. retrospective. Block proposed a contextualistic model of temporal, and by extension, spatial experience. The model looks at how several variables interact to influence duration and other kinds of temporal experiences, behaviors and judgments. The variables included personal characteristics of the experimenter, contents of time period, activities during the time period and temporal behavior. This model can be extended to space.

4.5 Spatial Behavior

Discussant: Waldo Tobler

People moving in geographic space

Two papers in this section studied how people move through space, at different levels of temporal detail. The paper by Stutz *et al.*, *Present and Future Diurnal Circulation of Population in a Large City*, studied spatio-temporal parameters of population distribution. Travel diaries during a 24 hour period were kept for 2,754 households in San Diego, which recorded factors of trips by time of day and type of trip. These data were used to document the maximum population for census tracts. Stutz's finding is that most people travel at 11:00 AM.

The temporal level of detail and the methodology where different in Odland's paper *Longitudinal Analysis of Migration and Mobility Behavior: Investigations of Spatial Choices in an Explicitly Temporal Context*. Tobler pointed out a methodological aspect of space-time analysis in that longitudinal modeling contrasts with cross-sectional studies, which are very common in geography. The interaction table that would result from longitudinal modeling would be interesting, and big. The table would include location history of individuals, a cross-sectional treatment of location, the timing of migration (employment status is important for migration).

In terms of travel time, there is a difference between time-space and space-time—there is an asymmetry. This is easy to handle by imposing a vector field. Hägerstrand's work holds time as the third dimension. Constraints of space and time are imposed by society. Such data is expensive to collect.

In the paper *Geometric Approaches to the Nexus of Time, Space, and Microprocesses: Implementing a Practical Model for Mundane Socio-Spatial Systems*, Pip Forer views space as a series of snapshots. Access is always a function of time and space. In terms of defining action spaces, is it possible to define what could happen and what is likely to happen? Forer noted that Hägerstrand studied peoples' position in time. Can we have a discrete version of time? The raster approach is quite useful. A GIS view focuses on actual time, whereas Forer focuses on what individuals do, what freedom they have and what they can do. Solution is likely a mixture of such models as network and grid models. The aim is to achieve accessibility. What sort of query language should we use?

Movie vs. temporal GIS

GIS tends to represent a static environment. Of course, the environment is not static. When viewing a movie, how often do we only look at one frame? We usually do not. We view each frame in relation to the others and from that extract the plot. Odland replied that movies are an interesting analogy to time-movement in space. To make sense, there has to be continuity in many objects (not too much movement). Space-time snapshots would be interesting in a GIS context; however, in a census framework, for example, the snapshots are 10 years apart. It could be possible to label the change of pixels or objects by their time. This would help understand how many snapshots per time-frame to record.

Route planning

Steve Smyth's paper, *A Representation Framework for Route Planning in Space and Time* used path finding as an example. The basis of this paper was the methods used by people when determining a route. People were asked how they provided routes, so as to define the rules for route description (i.e., direction giving). These rules were then formulated into a computational model for developing route planning. The concepts were determined from language. In this paper, only one system (GIS) is referred to (i.e., AUTOMAP), therefore it is possibly too narrow in its approach. Tobler indicated that more realistic on-line routing is used with current GPS technology.

4.6 GIS Perspectives

Discussant: John Herring

John Herring defined a *temporal GIS* as a filter and a macro scope that interprets, reduces, integrates, and presents temporally related, geographic data in a human consumable form. A systems that reduces spatial information to a scale that you can deal with. The concept of a paper map is static and limited—due to physical limitations. In a GIS, one can interact with the data—zoom in for more detail if it exists, shift (or pan), or change scales if the resolution of the data allows. Tobler noted that current GISs do not handle movement of objects through space and time very well. It seems there has been little focus on the development of temporal GIS by vendors, possibly because there has been no market for it. But there are probably other constraints as well.

Herring pointed out that the papers he reviewed addressed specific questions. Andrew Frank's paper *Different Types of Time in GIS* asked, "What is time?" and "How many answers might we find to this question?" The paper by Chris Weber, titled *The Representation of Spatio-Temporal Variation in GIA and Cartographic Displays: The Case for Sonification and Auditory Data Representation* asks, "How can time be represented in human computer interfaces?" Specifically, Weber's paper explores sonification. What other methods are possible? Nick Chrisman's paper *Beyond the Snapshot: Changing the Approach to Change, Error and Process* asked, "What is change, and how can it be detected and represented?"[5] John Kelmelis's paper *Process Dynamics, Temporal Extent, and Causal Propagation as the Basis for Linking Space and Time*, on the other hand asked, "How does change work as a process?"

[5] The question of representation of change was also raised earlier by Stephen Stead (Section 4.3), whose perspective came from a particular application domain.

5. The Research Agenda

5.1 The Process

Following the plenary sessions during which reviews of papers were presented, the questions put forth by the discussants and the audience were placed into the following nine categories:

- language and linguistic issues;
- communication and cartographic issues;
- cultural aspects with respect to spatio-temporal reasoning;
- micro-macro issues;
- propositional representations vs. image schemas;
- primitives (location, time, or motion);
- topological and metric spatial knowledge;
- temporal taxonomies; and
- implementation issues for temporal GISs.

Based on these categories, the participants of the workshop broke into working groups comprised of 6 to 7 members. Working groups, using as the basis of their deliberations the categorized questions, identified specific research questions and tasks at the granularity of a Ph.D. or Master's thesis. A representative of each working group then reported in a plenary session the group's findings. These findings were discussed and modified via suggestions by all participants of the meeting.

At a later stage, the researchable questions and tasks that were formulated by the working groups were placed into the following framework:

- questions and tasks related to studies of language structure, culture-specific principles, and human cognitive representation and behavior;
- questions and tasks related to formal logical systems; and
- questions and tasks that bridge human and formal systems.

This list of researchable questions and tasks was subsequently distributed to the participants of the Specialist Meeting who were asked to (1) comment on the completeness and representatives of this list, and to (2) rank the questions in terms of relative importance (most important to least important). This was not to suggest that some of the questions raised at the workshop were not important, but rather to identify which questions should be addressed first in terms of a research agenda. The workshop participants were told that the purpose of this ranking process was to determine a research agenda for the NCGIA, for the participants of the Specialist Meeting, and for researchers interested in spatio-temporal issues in GIS. The remainder of this section describes researchable topics and key questions under each of these areas. Note that the questions under each topic are listed in rank order as identified by participants in the Specialist Meeting.

5.2 Language, Culture, and Human Cognitive Representation and Behavior

The overall objective in this area is to get a better understanding of how *people* deal with geographic space and time. It relates to the discussions in the sessions on Reasoning and Philosophy, the Social Science Perspective, and Spatio-Temporal Cognition, where the following questions and research tasks were identified:

- Does behavior change space, or does space change behavior? How does one influence the other?
- Is there a link between the type of process to be studied and the scale or study area used to study it (including resolution or granularity in both space and time)?
- What studies of long term changes in knowledge about the environment would be useful?
- Can people build survey knowledge from just living in an environment (i.e., can one develop a configurational mental map from just direct experience)?
- What spatial terms (or language) should be used for interaction between the user and a GIS (including written and graphical/iconic languages)?
- Can we substitute space for time as a research methodology?
- What is the difference between social time in addition to administrative and scientific time, and how do they interact?
- Explore the persistence of identity of geographical entity.
- Explore the evolution of models and types (change in definition).

Of particular interest were questions on linguistic and cultural issues, on which two working groups focused their attention, and the distinction between propositional and image representation. A fourth working group theme, closely related to cognitive representation and behavior, was topological vs. metric spatial knowledge. Since it had more overlap with the category on formal systems, details will be provided in Section 5.3.

5.2.1 Language and Linguistic Issues

Language is used to describe time, space, and sometimes both together. In natural language, however, there seems to be an asymmetry between time and space. Space seems more important than time—spatial concepts are acquired sooner than temporal concepts in children (and apes). There are more terms to describe spatial relationships than temporal relationships. Time is ephemeral and private; you cannot revisit events.

What kinds of models of the world does language yield? The temporal model that our language provides is very strange. Most languages do not allow you to assign a temporal name to a spatial object. Language gives you wonderful economy in describing space. The ambiguity is often considered a disadvantage, but is it? There is a default meaning that we apply based on context. Language allows ambiguity. Is the ambiguity helpful or is it a negative? Verbal instructions will probably become more important in GIS. “Take the next exit” works better than looking at a map in a Vehicle Navigation System. What element of the instructions are spatial vs. temporal? Language can more precisely capture uncertainty than graphics. What kind of spatial-temporal phenomena are better understood/utilized via language (e.g., driving directions) and what kinds are better understood/utilized via graphics (e.g., maps).

There are differences in the representational power of language. In giving directions you can choose how specific to be. There is flexibility to jump to any scale as required. In a temporal GIS, granularity should change as required. If there is no change, then the temporal scale has the flexibility to get coarser.

Three approaches can be employed to explore language issues: (1) one could study language by looking at forms of knowledge that are relatively linguistic—implication is that language is a window to cognition; (2) one could also conduct experiments to access cognitive processes that cannot be observed directly through language; and (3) one could also employ both of the above approaches (i.e., experiments on language).

Several questions were raised about what would be interesting findings about language for space and time:

- Can one explore the structure of narrative to discover parallels with space and time structures? Narrative (i.e., language) has the characteristic of being topological.
- Can we extend this notion and develop a qualitative GIS, and for what purposes would this be useful? What kind of temporal models of the world does language allow?
- What kind of spatial models can one build from narrative?
- Language about space seems to be more qualitative than quantitative. One can get a metric representation from qualitative descriptions. Can we develop a qualitative GIS system?
- What would the consistency of a qualitative GIS be as compared to a quantitative GIS?

5.2.2 Cultural Aspects with Respect to Spatio-Temporal Reasoning

Culture is an issue for GIS and temporal GIS, because GISs have for the most part, been developed from a mono-language community. What kind of influence does culture have on understanding and representing time? Different cultures manage time differently. This may be a good way to approach the problem of working with a cross-cultural space-time GIS. There are three different temporal scales which evolve: (1) the evolution of humans, (2) the individual, and (3) the culture that individuals are members of. The cultural aspects of time are built on all three scales. One is the biological makeup of our bodies which makes us share fundamental approaches to time. Life itself is a process. The heartbeat is the basic clock. In terms of the individual scale, our time of birth is exactly recorded. In between these two there is the effect of culture on our conception of time. First, is the comparative view of time. The multi-cultural view is relevant in this country. If we have an agency with varying people, how does that affect GIS. Then there is the historical concept of time. Also, there are the varying subcultures within a nation (social and economic influences).

People perceive their landscape by taking the physical landscape and warping it to the perceived (cultural) landscape. Land ownership is a good example of an application in GIS which has a necessary temporal component. Are there places where the decisions a society makes is actually different. In the U.S. there exists the Hopi Indian land dispute which is based on historical land ownership. One proposed solution is to buy some land and give it to the Hopi or Navajo. There are different conceptions of land-ownership, which often boil down to a political situation. In Latvia, they are trying to recreate old geographies to get back to the old land ownership rules. An interesting study would be to stand back and look at these cultural-problems and how they evolve over time. Would cross-cultural studies of databases or data-collections be fruitful in understanding how different cultures deal with time?

One needs a temporal GIS, because people are not working in the current time. One can simultaneously have separate cultural views of the same space. Some of the GIS cultural problems are interface problems. In Britain, some corporate cultures are changing GIS to fit their corporate culture. To what extent is a GIS obligated to conform to a given subculture? Can we identify a research question that will allow us to see how GIS affects a culture?

5.2.3 Propositional vs. Image Representation

A smallgroup discussion on propositional vs. image schemas pointed out that the difficulty to define them and to distinguish between them. A propositional schema seems to be something with a truth value, whereas image representations use space, particularly distance, direction, and orientation, in meaningful ways. This dichotomy does not do justice to the richness of possible representations and to making hybrid nature of many of them. What has been called imagery, for example, may include visual, spatial, and kinesthetic/motor imagery, all of which are separable.

The group concluded that are three types of representations: (1) those in the mind (supposedly), (2) those in computer programs, and (3) those in the world, i.e., on paper or on a computer screen or a physical model. It is difficult to talk about representations without talking about the processes performed on them.

5.2.4 Researchable Questions

Spatial cognitive representations

- How do people model spatial knowledge/behavior as well as temporal knowledge /behavior? What are the various models we should consider?
- What kind of spatio-temporal phenomena are better understood/utilized via language (e.g., driving directions) and what kinds are better understood/utilized via graphics (e.g., maps)?
- How do/should individual differences in spatial ability impact the mode of communication—low spatial ability subjects perform better with text, high spatial ability subjects perform better with graphics?
- What are the components of a temporal taxonomy?
- How do humans preserve metric knowledge over time?
- What qualitative spatio-temporal cognitive models should be tested, and how?
- Which spatio-temporal inferences are easier for people?
- How do people resolve incomplete or insufficient spatial and temporal knowledge?

- Does structuring time structure space? Does space structure time? Is this domain-specific?

Influence of the task environment on spatio-temporal cognitive representations

- How do people update conceptions of environments as they change? As the environment changes?
- What are the space/time categories/scales relevant to human activity?
- How do people plan and alter routes?
- How do we read and interpret maps and other visual displays?
- What kind of spatial models can one build from narrative (e.g., linear vs. two dimensional)?
- For which spatial situations (tasks, environments, etc.) is it more meaningful to think of space in terms of *temporal units*, and which situations is it more meaningful to think in *spatial units*?
- What factors distort space-time judgments ?
- How do we distinguish the roles of different types of imagery (visual/spatial/acoustic/kinesthetic) in conceptions of space and time? Does the lack of one sensory system, such as vision, matter?

Communication about space and time, and the influence of culture

- How do people talk about space and time?
- How do people describe change in their environments?
- In developing temporal primitives and operators, we are examining linguistics and social constructs. Should we look at different social scales to determine the primitives or should we consider operators at different scales?
- How do people (cross-culturally) talk about space and time?

5.3 Formal Systems

The need for formal systems for spatio-temporal reasoning comes from the desire to build GISs that can be used to perform spatio-temporal reasoning tasks. Formalisms are also useful in comparing different models. Questions and tasks for this category were supplied by the discussions in sessions on Computational Issues, Spatial and Temporal Cognition, and the GIS perspectives. They included:

- Data models for time include a variety of models: discrete vs. continuous models; linear, cyclic, near cyclic (Lorentz attractors) models; determinate vs. indeterminate (order) vs. cumulative models; system vs. administrative vs. scientific models; non-linear time models including alternate future (past) and multipath-temporal lattices.
- Process models include event detection vs. continuous chance models; causation models such as change propagation and models based on spatial-temporal statistics; complex system models such as multi-scale multi-process interaction and quantitative/qualitative analysis.
- What are spatio-temporal operations and relations of interest? How can these be determined and defined? Are they application- or domain-

specific? How do we ensure then that a case study is indeed useful and proves a point?

- Space, location, time, and motion: which do we specify or leave out? Which is the most basic or fundamental notion (e.g., motion vs. time)?
- Is it because spatio-temporal dimensions impose special constraints that there can be no general computational model such as the relational model for traditional data processing tasks?
- The semantics, context, and structure of legacy data can be captured by metadata about it. How do we construct this metadata uniformly across applications?
- There is a need for further research on temporal topology and one should develop data models and data structures for topological maps and their change. Is there a difference in using a fixed frame vs. a relative frame in our temporal model? Can a taxonomy of time be built?
- How do we confirm that any formalism developed does indeed capture the intended spatio-temporal concepts?
- Spatio-temporal query and analysis includes modeling languages; spatial query and temporal query languages and the modeling of spatial as well as temporal relationships; temporal topology, time series analyses (i.e., digital signals); and causation models (relative vs. real) including propagation through time and space, and temporal statistics (e.g., one throw probability). we should explore change detection from snapshots and error improvement. How can we characterize (represent) phase change and continuous change?
- Implementation includes database and collection issues, such as cost and size of data sets; their availability or access to data; storage models such as versioning vs. variable attributes and spatial and temporal indexes; lack of continuous data due to inadequacy of snapshots (i.e., static maps) and error vs. change (real change vs. taxonomic change); feature identity through time universal identifier systems including inadequacy of value based keys and schema evolution. It is important to understand that how things work internally, i.e., in a database management system, has nothing to do with cognition. It is the communication channel (the interface) that introduces the human component.
- What is the effect of scale on time mapping? How do we choose the temporal scale?
- An issue that crossed the boundaries between human perception and formal models were alternative formal models of spatial cognition. The field of spatial cognition has been constrained by the tricotomy of landmark, route, and survey knowledge. We tend to allow this framework to dominate the literature—written descriptions of environments tend to follow either route or survey (or a combination of these) perspectives, but no others. Some alternate models that we might consider are:
    - local metric neighborhoods;
    - strip maps (are they the same as route maps?);
    - categorical information;
    - hierarchical information;
    - temporal sequences; and

- propositional representations.

Participants spent more time on identifying specific issues in the areas of categorizations of time (temporal taxonomies) and what primitives are; the difference between topological and metric knowledge; the linkage among different scales (micro-macro issues); and concerns about the implementation of temporal GISs.

5.3.1 Temporal Taxonomies

A number of models exist for representing time. The following is a list of models that could be explored (individually or in comparative studies) for implementation in a temporal GIS: (1) mechanical time, (2) event-driven time, (3) absolute time, (4) discrete vs. continuous time, (5) relative time, (6) direct determination/measurement, (7) indirect determination/measurement, (8) work-flow or process time, (9) partial orderings and (10) fully ordered. Processes operate in the world and are embedded in time. Elements of a taxonomy of time can be continuous or discrete, as are processes. Cycles are a property of processes, not time—we can derive time through measurements. Processes can be observed and measured. Observation can be direct or indirect. There are a number of ways to represent time. We can use interval methods, such as calendars and clocks which are absolute, or we can use ordinal methods which are relative. We can also represent time with cyclic representations—the storage of repetition of information or by propositional information.

Examples of temporal topologies included linear complete ordering, branch (forward and backward) versioning, dendritic as an example, braided (lattice) partial ordering, and cyclic or quasi-cyclic (*a la* Lorentz attractors). Problems arise when defining the granularity of measurement, determining connections between time and measurement, dealing with imprecise relative dates and indirect dates, and attempting to discretize space, time, and attributes—Sinton's model (1978) suggest that, "you cannot measure all three."

Several research tasks and researchable questions related to temporal taxonomy are:

- Characterize the correlation between database time and world time. Compare different applications. For example, legal vs. environmental change, implication for representation, implications in terms of outcomes.
- Examine the fragmentation (segmentation) expected from temporal database.
- Investigate human brain (particularly representation of change and association) as a potential model for indexing or organizing spatio-temporal data.
- What are methods for representing error and imprecision as distinct from change. Is detected difference change or error? Granularity, scale, precision are important issues here.
- Explore associatively problems such as links to indexing and access, hierarchical retrieval and query, and backwards vs. forwards.

5.3.2 Primitives (location, time, motion)

These discussions were motivated by the question of whether or not space and time are separate categories. Can we substitute space for time as Kant did? In some models, we can substitute space and time to answer different questions. An example is the use of graph theory to answer questions about connectivity (topology) and order (as in a pert chart). But, plausible interpretations of 2-d maps (such as a fertility time-slice) led to the rejection of these inferential techniques until the addition of the time dimension. Therefore, in these instances, time and space cannot be separated as has been done historically in geographic thought.

More detailed research tasks and questions about space, time, and motion were formulated:

- Time and space are a set of dimensions, therefore, can we formulate a model to determine how many dimensions are needed for a GIS query? In other words, are there natural social processes that do not involve time? Population can be answered with 1 dimension, population distribution can be answered in 2 dimensions, and rate of population growth requires 3 dimensions.
- Which combinations of location, time, and motion should be used? Is it domain-specific? Motion is a function of location and time. Rate can be a function of time and/or space. What is the advantage of using one combination vs. another? For which applications are one or the other advantageous? Compare computational effort and storage cost, and consider the nature of the data.
- What is a plausible taxonomy of time? Can we categorize measurements about time as nominal, ordinal or interval/ratio information? Cyclical time does not exist, but rather cyclical phenomena in linear time. In a binary is/is not situation, there can be nominal categories. Likewise we may know that there are, for example, 5 events that must have happened and could not all have happened at the same time. They may or may not happen again, therefore, they are nominal until they can be ordered.
- What are typical queries in a spatial-temporal system (including potential queries)? Queries are application- or domain-specific. Can we classify temporal queries by difficulty or type? Specific domains could be researched, if we know the types of information users need or want.
- What is the link between process, and scale and granularity? Given a scale and granularity, what can you observe?

5.3.3 Topological and Metric Spatial Knowledge

There is a need to define what we mean by topological, metric, configurational, qualitative and quantitative metrics when discussing spatial knowledge types. This need arises because of the diverse academic backgrounds of researchers involved in this area of inquiry (geography, psychology, mathematics, computer science, cognitive science). In this group, it was discovered that different disciplines define similar terms using various terminology. There was confusion as to what was meant by terms such as *qualitative* and *quantitative metric*. One of the tasks of this group was to formulate common definitions.

Alternative geometries formally defined by mathematicians as determined by what spatial properties remain invariant under transformations of one type or another. Some disciplines use the term *geometry* to refer only to metrics—this discussion group generally agreed that all of the spatial knowledge types listed above constitute *geometries*. There were several questions/issues raised concerning these geometries:

- Metric as quantitative—properties of interval or ratio scale—ordinality?
- Distance is clearer than direction—greater uncertainty about what constitutes metric vs. topological direction.
- Are certain frames-of-reference necessary—e.g., cardinal frame for directions?

In terms of how humans reason spatially, there were a number of issues raised by this group:

- the dichotomy of how people can reason vs. how they typically do reason;
- the apparent evolutionary adaptiveness of metric knowledge;
- creative navigation (detours, shortcuts), path planning, and path choice;
- path completion (integration) requires metric knowledge:
  - walking two or more legs of a path, estimating straight-line direction to start;
  - humans can do this non-randomly, as has frequently been empirically demonstrated, but exactly how precisely?
- interesting hypothesis that there is a decay in memorial precision of spatial knowledge with extended delays (months, years, decades).

Another area of discussion concerned the explanation of qualitative metrics and its existence:

- concept from the qualitative reasoning branch of AI formal modeling;
- qualitative metric as small, finite number of quantitative categories (e.g., 4 directional categories, 3 distance categories); and
- need to empirically evaluate with human data.

5.3.4 Micro-Macro Issues

Do processes have natural/characteristic spatial and temporal scales? To answer this question, studies that examine data at different granularities (i.e., scales) in space, in time, and in space and time are needed. This would require a fairly detailed database, in addition to problem definition and guidance on the gathering of the data. Examples of some research topics include examining various physical models (such as hydrologic surficial flow or forest fire) using different resolutions of digital elevation models, examining social questions in a like manner using data sets (perhaps census at a fine resolution and at an aggregated level)—perhaps focusing on housing the market as an example, and examining epidemiological or unemployment data as a process.

Are spatial and temporal scales logically linked? Some links between spatial and temporal scales are clear. For example, daily commuting is associated with maximum length of work trips and that limits extent of urban size. Structuring time structures space. Do processes examined at one scale correlate or describe processes at another scale? Can we use aggregation techniques that will address this issue? What are their rules? Examples of some research topics are to examine biodiversity at a patch or landscape scale. Particular research tasks are to develop aggregation rules and determine if they hold over a variety of scales; examine biodiversity as a dynamic process rather than a collection of species at one time; examine a process at a very cartographically large scale (carbon sequestration) and determine if a smaller cartographic scale will result in a different temporal evolution or if the process can be represented at all; and translate time series methods to spatial temporal series.

Participants of this working group formulated further questions that should be investigated:

- How does the issue of complexity affect spatio-temporal relations? What are the generalization issues? Can we summarize time distribution in terms of recurrent intervals? One could study the same process at different spatial and temporal scales. Should different time and space scales be used based on the density of data? In terms of event time and space vs. absolute time and space, what is the appropriate time step?
- Macro vs. micro issues are probably application-dependent. What are the time scales relevant to human activity? To explore how different scales are used in GIS, develop a set of GIS macros to aggregate (or change scale). Test the results against processes.
- In developing temporal primitives and operators we are examining linguistics, and social constructs. Should we look at different social scales to determine the primitives or operators at different scales? One could relate different concepts in linguistics to some overall social constructs to determine if there are different scale relations.
- Identify what questions can be asked at different scales. Do we construct geographies of regions from geographies of local places? Do we develop social constructs from individual constructs?
- Can we infer a process from observing different states? Determine the rules of a game, chess for instance, by seeing the board every five moves with a resolution of four squares. We try to do this on the earth with remote sensing. Can we infer the cause of land use change by observing maps of the land over the last two hundred years? What ancillary data will we need and at what granularity?
- Many problems have similar themes in space and time. They are addressed differently by different disciplines. However, geographers and historians use a similar method of aggregation, neither of which relies completely on absolute space or time. Historians aggregate time into epochs and geographers aggregate space into regions. Both of these are process or feature depended. How do we aggregate such things as birth of features or bifurcation?
- Temporal identity may differ between different objects. As an analogy, people retain the same identity form birth to death in spite of the fact that their cells and concepts may change and grow. Political organizations retain the same identity even though their members and objectives may change. Is this the same kind of identity as for individuals?

- Other issues to be considered include overlapping vs. disjoint sets; distinct vs. non-distinct boundaries—i.e., fuzzy time; motion in space vs. change in time.

5.3.5 Implementation Issues for Temporal GIS

Numerous critical implementation issues must be considered in the development of a temporal GIS. A number of questions were raised that were considered either computer engineering issues or computer science issues.

Computer Engineering Questions: An important first step in developing a temporal GIS is to create a taxonomy of spatio-temporal information systems. Such a taxonomy should be based on current and proposed data models, temporal utility, indexing models, and query facilities. Indexing methods need to be developed for spatio-temporal behavior, features, events and processes. Transfer formats for temporal spatial data (an *interlingua*) also need to be developed. Efficiency and implementation issues concerning existing formal spatio-temporal models include data representation, spatial indices and query optimization. Need to exploit cognitive science research in representation of spatio-temporal data.

Computer Science Questions: These include the development and implementation of spatio-temporal query algebras, computational formalisms for temporal topology, and parallel computing algorithms for spatio-temporal data.

5.3.6 Researchable Questions

System design and development

- What might the components of a Temporal Query Builder for a GIS be? For example, ways of establishing temporal intervals, defining the dynamics of dimensions, and defining temporal metrics.
- Develop spatio-temporal query algebras.
- Develop a taxonomy of spatio-temporal information systems.
- Develop computational formalism for temporal topology.

Error, imprecision, and uncertainty in spatio-temporal data

- In terms of data capture and display, how can we deal with error, uncertainty, imprecision?
- How are error and imprecision represented and understood as being different from change? Is detected difference indicate change, or error? (issues of granularity, scale, and precision).
- Examine the fragmentation (segmentation) expected from temporal database.
- What are the generalization issues regarding error and imprecision?

Implementation of spatio-temporal GISs

- In a broad sense, what are the implementation issues that must be addressed concerning software and hardware?
- What spatial and temporal summary statistics are needed? For example, can spatial and temporal autocorrelation be combined?
- Develop transfer formats for spatio-temporal data (an interlingua).
- What are the efficiency and implementation issues concerning existing formal spatio-temporal models.
- Develop parallel computing algorithms for spatio-temporal data.
- Should different time and space scales be used based on the density of data?

Domain-specific aspects of formal systems for spatio-temporal reasoning

- Characterize the correlation between database time and world time, and compare different applications. For example, legal vs. environmental change, implication for representation, implications in terms of outcomes.
- Investigate different kinds of time series applications and develop a time series taxonomy for applications. In addition, evaluate the display techniques for time series analysis. For example, animation vs. static displays (such as dimension shifts).
- Examine social questions in a similar manner using existing data sets (perhaps census data at a fine resolution and at an aggregated level). Another example would be to focus on the housing market.
- Can we infer the cause of land use change by observing maps of the land over the last two hundred years? What ancillary data would be needed, at what granularity?

Modeling processes of natural systems in a temporal GIS

- Do processes have natural characteristic spatial and temporal scales?
- Do processes examined at one scale correlate or describe processes at another scale?
- Macro vs. micro issues:
  - Are they application-dependent?
  - What questions can be asked at different scales?
  - Do we construct geographies of regions from geographies of local places?
  - At a patch or landscape scale, examine biodiversity. Develop aggregation rules and determine if they hold over a variety of scales. Examine biodiversity as a dynamic process rather than a collection of species at one time.
  - Study the same process at different spatial and temporal scales.
  - Are spatial and temporal scales logically linked.

- Examine various physical models (such as hydrologic surficial flow and forest fire) using different resolutions of digital elevation models. How does that relate to temporal granularity?
- Examine a process at a cartographically (very) large scale (e.g., carbon sequestration) and determine if a smaller cartographic scale will result in a different temporal evolution or if the process can be represented at all.
- Examine epidemiological or unemployment data as a process.
- Can we infer a process from observing different states?

5.4 Bridging Human and Formal Systems

A critical role is taken by the linkage between human thinking and a formal system (such as a GIS). This involves communication, as well as interaction and presentation. User interfaces considerations may be based on temporal metaphors such as 3D and 4D (dimension shifting); multiple dimensional rendering; animation (scale shifting); simulation which involves statistical process modeling; other dimensions that include sound or sonic metaphors (music or time sequences) and color including raster false color (synthetic imagery).

At the level of research methodologies, participants suggested to (1) conduct specific case studies on the system level *and* the user level, and (2) compare cross-sectional studies to longitudinal studies.

- Consider the integration of multi-media in time representation.
- How can we animate socio-economic and cultural processes (show time)?
- Develop systems that use several communication channels (sound and color as examples) in parallel.
- What systems can be developed for pattern detection (both spatial and temporal data) in different modalities (e.g., audio, devices for handicapped people, etc.)?
- What error models should be considered for space and time, and how should error be conveyed to a user?

5.4.1 Communication and Cartographic Issues

Communication is the transfer of information to the user. Communication is both aspatial and spatial. Aspatial communication includes charts, graphs, and reports for time series whereas spatial communication involves both static and dynamic mapping techniques. Static techniques include dimension shifting, which displays data on a temporal axis (e.g., accident data, time slice map with space constant), and symbology, as when displaying migration and other flow data. Dynamic techniques include animation and dimension shifting. Animation provides the illusion of movement to show time variability with time-dependent multivariante symbols and icons such as graduated symbols, histograms and time-lines. Can one consider either procedural or database animation, for example, the illumination of terrain by the sun over time to show the movement of shadows or the depiction of changes in the shoreline at different times.

There are a number of issues and questions surrounding sonification of spatial/temporal data. Are musical sound types effective for display of data (empirical)? If so, what kinds of data would sound convey effectively, and what sound types would be effective in conveying the intended message? What would the components of a sound interface be for a temporal GIS? One view would be a *sonic tool box*?

Given current methods for cartographic representations (point, line, areal and volumetric symbology), how can we show temporal and spatial changes? What sort of maps can be derived from animation's? How can missing information be supplied and flagged to the user? Given sparse data samples, can a model be produced that interpolates the gaps in the data.

Investigate different kinds of time series applications and develop a taxonomy of these applications. Evaluate a variety of display techniques for time series analysis. For example, animation vs. static displays (such as dimension shifts).

How does one navigate through a temporal, spatial database? Is a flight simulation metaphor useful for this? What might the components of a Temporal Query Builder for a GIS be?

5.4.2 Researchable Questions

Many of the questions raised here are specific to the design and implementation of user interfaces for spatio-temporal information systems. In addition, many of the questions were raised specific to human representation and understanding of spatio-temporal phenomena, and formalization of these models in a temporal GIS.

- How do we present error, uncertainty, and imprecision about time and space to the user?
  - Investigate the use of various effects to show the quality and nature of the data.
  - How can missing information be supplied and flagged to the user?
- What are appropriate user interface metaphors for temporal information?
  - Are these metaphors task-dependent? Scale-dependent? Domain-dependent? Culturally dependent?
  - For spatio-temporal information, can user interface metaphors for time be combined with user interface metaphors for space, or are special interface metaphors needed for spatio-temporal information?
- Given current cartographic representation (point, line, and areal symbols), how can we show changes over time?
  - Static methods included dimension shifting (show data on a temporal axis as in a time slice map) and symbology (use lines to illustrate migration data and flow).
  - Dynamic methods include animation (providing the illusion of movement to show time variability using time for example dependent multivariate symbols and icons such as graduated symbols and histograms and time-lines) and dimension shifting (a procedural animation, for example, illumination of terrain by the sun over time using the movement of shadows to illustrate changes in a shoreline at different times).
- What are the appropriate roles for different sensory modalities (visual, auditory, tactile) for communicating temporal and spatial changes?

- Four dimensional mouse: How to navigate through a temporal-spatial database? Is a flight simulation metaphor appropriate?
- Might sound provide temporal information better than graphics? Graphics present the entire picture simultaneously (sometimes making it difficult to discover hidden patterns), where as sound presents the picture linearly—similar to text and navigation.
- Are musical sound types effective for display of qualitative and quantitative data? If so, what kinds of data and what sound types?

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Appendix A

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Appendix B:

Abstracts of Papers, NCGIA Research Initiative 10

Psychological Time and the Processing of Spatial Information
Richard A. Block

The focus of this paper, rather than on space providing a framework for time, is on how time perception might provide a framework for space perception. Important distinctions are made between position and duration, personal experiences vs. general knowledge, and prospective vs. retrospective. A contextualistic model of temporal, and by extension, spatial experience is proposed. The model looks at how several variables interact to influence duration and other kinds of temporal experiences, behaviors and judgments. The variables included personal characteristics of the experimenter, contents of time period, activities during the time period and temporal behavior. This model can be extended to space.

Morphological, Topological, and Chronological Time in Urban Development
Irene Campari

This paper proposes a view of the town development as a dynamic and continuous process manifest in actions and events provided with limited duration. The historical time becomes only a support for the analysis of the relationship between some spatio-temporal event of urban space. This approach has been fruitfully applied to geology and landscape analysis. The idea of time as sequence of actions replaces the idea of time as continuous. *Continuous* means in the present case that the processes in time have a continuous manifestation in space. Each action, provided with *duration*, interacts with physical entities and artifacts Determining the duration means finding the functional constraints limiting the actions or activities on urban space. Some of these constraints are identified with the notion of topological time. An application of those concepts to urban development is exemplified with material from and extensive case study.

Beyond the Snapshot: Changing the Approach to Change, Error, and Process
Nicholas R. Chrisman

This paper considers three issues germane to incorporating the temporal dimension into a GIS: change and error in static images of the earth (e.g., satellite images), the underlying processes, and the influences of organizational issues on the conduct of change detection studies. The goal of this discussion is to foster changes in the procedures currently used to detect change. The author contends that the snapshot and one-shot survey must be replaced with a routinely-maintained system of geographic information, which will provide access to the actual changes as they occur. Analysis of change should focus on the actual processes that produce changes.

Exploring Temporal Continuity in Qualitative Spatial Calculi
A. G. Cohn, Z Cui, and D. A. Randell

This paper summarizes research aimed to evaluate, extend and implement a theory of space and time which is based upon calculus of individuals based on *connection* and is expressed in the many sorted logic LLAMA. This theory supports regions having either a spatial or temporal interpretation where the regions can be perceived to be infinite in number and any degree of connection from external contact to identity is allowed in the model. The formal theory assumes a primitive dyadic relation: C (x,y) read as "x connects with y" which is defined on regions. C is reflexive and symmetric. In terms of points incident in regions, C (x, y) holds when regions x and y share a common point. Using the relation C, a basic set of dyadic relations are defined: disconnected from (DC), part of (P), proper part of (PP), identical with (=), overlaps (O), discrete from (DR), partially overlaps (PO), externally connected with (EC), tangential part of (TP), nontangential part of (NTP), tangential proper part of (TPP), nontangential proper part of (NTPP), the identity tangential part of (TPI), and the identity nontangential part of (NTPI).

Making Space for Time: Towards a Truly Temporal Geography

Helen Couclelis

In this paper, the author proposes a modeling framework to integrate time into GIS. This framework is based on Zeigler's formal specification of discrete-time and discrete-event systems. This framework involves integrating process with spatio and temporal dimensions because space, time and process are inextricably interrelated. Space and time are treated as taxonomic frames whose definitions are constrained by the tasks, events, experiences, or phenomena they help to organize. In other words, there are as many definitions of time and space as there are phenomena, and a universal definition is unlikely. As GIS reflects a commitment to an absolute Newtonian space, the framework proposed here mirrors that commitment. Integration of time in GIS according to this framework is from a physicalist view of the world. The author discusses how discrete-time systems favor raster GIS, and how discrete-event systems favor vector GIS.

Geometric Approaches to the Nexus of Time, Space and Microprocess: Implementing a Practical Model for Mundane Socio-Spatial Systems

Pip Forer

This paper focuses on the inter-relationship and substitutability of space and time in human spatial processes. Its aim is to identify a practical means of implementing a specific range of analyses in respect of such processes, basing the temporal query part of such analyses on geometric properties rather than a data base approach. In doing this it views a geometric rather than and attribute approach.

Different Types of "Times" in GIS

Andrew U. Frank

This paper provides a brief review of the progress that has been made with the modeling of space, and is followed by a listing of several links between the modeling of space and time. Stress is put on the linkage between the process considered and space and time model used. A number of seemingly orthogonal characteristics of time models and properties of the respective processes are listed (and these are related to the corresponding spatial conceptual models). Then contrasts are made between the paradigm of reality for science and for administration, and major differences between these paradigms which strongly influence the temporal logic and the operations that are necessary for updating a model in administration are observed.

Temporal and Other Issues in Qualitative Spatial Reasoning
Christian Freksa

The focus of this paper is to explore qualitative spatial reasoning in a natural language system. The properties of physical space and time structure our knowledge about static situations and dynamic events in a fundamental way. Taking these concrete properties into account when processing knowledge about spatial and temporal situations—as well as knowledge which refers to situations and events—may result in substantial cognitive, inferential, and computational advantages. The author discusses methods under development for the direct representation and processing of spatial and temporal properties in computer systems. These methods include *direct spatial and temporal reasoning* on the basis of coarse knowledge, and a *neighborhood-based approach* to qualitative spatial reasoning which focuses on spatial aspects which actually are accessible in real problem solving situations; for example, relative orientation and distance information.

Cognitive Distance at Various Geographic Scales
Scott M. Freundschuh

The focus of this paper was to explore how people normally think about and express cognitive distance in their everyday lives. This approach was in contrast to previous studies in which subject testing occurred in unnatural experimental situations where subjects were constrained as to the kind of answers they could provide (i.e., provide distance estimate, provide time estimate). In this study, an experiment was designed to explore when, in a conversational setting, people used time vs. space to estimate distances. Subjects, who were not aware that they were being tested, were queried during a typical conversation about how far it was to other places. The results indicated an inverted U-shaped curve that suggests that time is used for intermediate distance estimates (331km - 2080km), and space is used for short (< 10km) and very long distances (8000km).

Some Operational Requirements for a Multi-Temporal 4-D GIS
N.W.J. Hazelton

This paper discusses some of the operational requirements of a multi-temporal 4-D GIS, and describes the role of the data structure and software architecture in realizing these requirements. There is assumed to be a strong dependency between the software architecture and the data structure, as in a “whole” GIS.

Process Dynamics, Temporal Extent, and Causal Propagation as the Basis for Linking Space and Time
John A. Kelmelis

In this paper, the author points out the increasing demand for GIS to understand dynamic geographic phenomena, therefore, the need to incorporate the variables necessary to model processes into geographic data and information. Example’s of dynamic phenomena are climate change, climate variability, disaster propagation, and environmental epidemiology. Key to modeling these dynamic phenomena is understanding that the process dynamics can vary significantly from process to process (i.e., from phenomena to phenomena). A relationship exists between the temporal extent of an event and the event’s sustained causal propagation and the intensity of its effects. A function ($E_s = f(E_t, t_e, V_{cp}, A)$) that links the spatial and temporal extent of processes is illustrated. This function provides a systematic framework for linking space and time in geographic and process modeling. The author suggests that such a linkage will help in cause and effect analysis, predictive modeling, and process and spatio-temporal feature boundary identification. Use of this function will make inclusion of some dynamic processes in GIS more effective.

Spatio-Temporal Reasoning in Atmospheric Science Databases

Siu-Wah Lau, Richard R. Muntz, Eddie C. Shek, Carlo Zaniolo, and Son K. Dao

In this paper, the authors characterize the need for performing spatio-temporal analysis and queries on very large databases as ubiquitous in diverse applications ranging from earth and space sciences to resource exploration, selective marketing and sales analysis. They report on a project with atmospheric scientists designed to develop systems and techniques for detecting and tracking evolving physical phenomena on massive data sets produced by combined atmospheric and ocean global models. Toward these goals, the authors propose spatial extensions to LDL++, a system that supports rule-based reasoning and expert application development for databases, and Event Pattern Language (EPL), which is designed to detect sequences of temporal events. The integration of these systems provides a computing environment where complex queries and reasoning on spatial and temporal data to be easily expressed and efficiently supported. The authors also discuss the problem of indexing such databases for efficient query processing and describe the use of EPL to provide intelligent active indexing capabilities.

A New Framework for Understanding the Acquisition of Spatial Knowledge in Large-Scale Environments

Daniel R. Montello

In this paper, the author argues for a modification of the simplistic landmark/route/survey distinction (which he termed the dominant framework) of spatial knowledge, and offers a new framework comprised of five major tenets. The first is that there is no stage at which only pure landmark or route knowledge that contains no metric information about distance and direction exists. Metric configurational knowledge begins to be acquired on first exposure to a novel place. The second tenet suggests that with increasing familiarity and exposure to places, there is a relatively continuous increase in the quantity [quantitative rather than qualitative shift], accuracy, and completeness of spatial knowledge. The third tenet indicates that the integration of knowledge about separately-learned places into more complex hierarchically-organized knowledge structures represents a significant and relatively sophisticated step in the microgenesis of spatial knowledge. The fourth tenet suggests that individuals with equal levels of exposure to an environment will differ in the extent and accuracy of their spatial knowledge. The final tenet indicates that linguistic systems for storing spatial knowledge provide for the existence of relatively pure topological knowledge, or at least non-metric knowledge. However, such non-metric knowledge exists in addition to metric spatial knowledge, not as a necessary precursor or intrinsic part of it.

Longitudinal Analysis of Migration and Mobility Behavior: Investigations of Spatial Choices in an Explicitly Temporal Context

John Odland

This paper is a review and analysis for longitudinal modeling of spatial behavior, with an emphasis on the ways that adoption of an explicitly temporal context transforms problems and procedures in this area of research. This is a relatively new research area in which traditional questions about spatial decision making, especially migration and mobility behavior, are being placed in an explicitly temporal context: that of continuous locational histories for individuals. The emphasis in the paper is on the ways that adoption of an explicitly temporal framework for analyses of spatial behavior mandates some very basic changes in the definition of research problems, the formulation of hypotheses, and the application of statistical methods to problems of estimation and hypothesis testing.

Seeing Time

Guiseppe Papagno

In this paper, the author asserts that we need space to talk about time, and vise-versa. Looking at the effects of man on the landscape over time is one way to model changes in space over time. A dynamic conceptual model composed of the three elements material, activity and function is proposed to define geographic features (objects). All objects have a material structure, transmit an activity of relationship in space, and exert a function which justifies the existence in time of a material and of an activity for itself in its environment. This model is illustrated with an example of the Visdende Valley which is a remote valley in Northern Italy. Policies concerning the forbidden harvesting of lumber in the Valley that date back several centuries can be used to explain why even though the tress are certainly “ripe for cutting,” they remain untouched. In the seventeenth century, general exploitation of the trees was prohibited to preserve the trees for use in constructing ships of the Arsenale.

Path, Points, and Proforms

Háj Ross

This paper focuses on motion in general, and on syntactic and semantic structures expressing paths of movement, in particular. A model is proposed wherein the description of a moving object’s path can be composed of the eight elements of source (from), trajectory (physical route), direction, distance, speed, totality (from A to B), goal (destination) and mode (method of transport). The author addresses a number of conceptual organizational issues concerning these elements such as, “Are all eight of these elements on the same level of the hierarchy of phrase structure?” Several possible organizational structures are proposed and supported with examples from the literature.

A Representation Framework for Route Planning in Space and Time

Stephen Smyth

This paper describes a conceptual development of a research environment for future Geographic Information Systems (GIS). This environment separates *architecture* from *representation*. Many useful spatial and geographic applications require a combination of spatial and temporal representations, version management, inference mechanisms, user interface management, and communications. If there were a framework for integrating applications consisting of standardized interfaces to a spatial-temporal representation, to an inference mechanism, to a user interface, and to communication services, then a second, orthogonal structure might formalize the relationship between abstract representational theories and the concrete concerns of software engineering. Spatial representation in such an environment should encompass the usual elements of surveying and cartography, as well as the mathematical details of capturing form and relationships in a Euclidean three-space. Temporal representation should allow for time recording and naming conventions as they exist in a multicultural world, with alternative calendars. Versioning should allow for alternative views of reality.

Temporal Dynamics and Geographical Information Systems
Stephen D. Stead

In this paper, the author contends that the real world operates along a time line, which is a single ordered line upon which the temporal extent of data values are plotted. The domain of this research focuses on systems to deal with modeling time in archeological. An alternative method to the standard time-slicing technique which stores snapshots of the landscape which are used as interpretive back-cloths is proposed. This alternative model is to represent known data elements in four dimensions (x, y, z, and t) rather than the conventional three dimensions. From these, real world processes can be modeled. An object-oriented approach is used to model geographical features (objects).

Present and Future Diurnal Circulation of Population in a Large City
Frederick P. Stutz, Robert Parrott, and Paul Kavanaugh

This paper reports a study in which travel diaries were administered to 2754 households in San Diego by the San Diego Association of Governments (SANDAG) on day in 1986. These surveys are used to document population shifts throughout the 24-hour day and for documenting the maximum population for each census tract. To develop the formula for estimating populations in time and space, factors of trips by time of day and type of trip (e.g., home-to-work and home-to-shop) were elucidated from the travel behavior survey. These factors were then applied to the daily trip productions and trip attractions obtained from the standard trip generation models used by the California Department of Transportation (CALTRANS). The population data input to produce the 1986 estimates is also available to generate daytime population estimates for 1995, 2000, 2010. Such time-space charting is absolutely essential if urban areas are to be prepared to first, meet the service demands of a mobile urban population, and second, to manage evacuation procedures for earthquakes, flooding, or nuclear attack.

Acquiring and Updating Spatial Knowledge from Language
Barbara Tversky

In this paper, the authors discuss the results of several experiments designed to assess spatial knowledge acquired from narrative. In the first experiment, subjects read route or survey descriptions of naturalistic environments, after which they answered verbatim or inference questions that required either route or survey knowledge to answer. Verbatim statements were verified faster than responses to inference questions, but there were no differences in responses to inference questions dependent on the route/survey distinction. This suggests a single representational schema, regardless of how spatial information is acquired. In a second experiment, Tversky (with Franklin and Bryant) explored spatial knowledge acquisition from small scale scenes described in narrative where objects in the scenes were described in terms of up/down, front/back, and left/right of a protagonist. Results supported the spatial framework model which purports that space is conceptualized in terms of three axes corresponding to bodily position.

The Representation of Spatio-Temporal Variation in GIS and Cartographic Displays: The Case for Sonification and Auditory Data Representation

Christopher R. Weber

This paper reviews the relatively brief literature on Auditory Data Representation (ADR) and the strengths of this medium to enhance visual depictions of spatio-temporal change. The focus of this paper was the application of ADR in cartographic representations. Preliminary work by the authors to measure subject association of complex harmonic intervals with various adjective pairs which might describe continua of cartographic conditions or variables indicated that the time-dependent variables of *constant-variable* and *static-wavering* scored most highly for subject ranking by relative consonance (which is determined by the constructive and destructive wave interference between two frequencies).

A Generic Model for Spatio-Bitemporal Geographic Information

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This paper describes work in progress on the construction of a generic object model for a GIS which handles objects with both references to embeddings in two orthogonal spatial dimensions and two orthogonal temporal dimensions. An embedding in 2D Euclidean space is assumed for spatial references, and the two orthogonal dimensions of real (or event or valid) time and transaction or database time are used to handle temporal information. Bitemporal elements are used to extend purely spatial theory to include temporal referencing. Bitemporal objects (ST-complexes) capable of representing simultaneously the structure of the components of an information system which may vary in two spatial and two temporal dimensions are employed.