MULTIDIMENSIONAL REPRESENTATION OF GEOGRAPHIC FEATURES

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ABSTRACT

A theoretical framework for representing spatial, thematic, and temporal dimensions of geographic features has been developed. This framework relies on the unifying concept of a geographic feature as a single, unique entity in the real world with multiple object representations such as raster and vector geometries, multiple resolutions and source scales, and multiple temporal sequences. The same geographic feature can be represented in the framework at one resolution as a point and at a higher resolution as an area. Similarly, linear features such as streams can be represented as single lines at a coarse resolution and as double lines and areas at higher resolutions. Changes in spatial configuration and thematic attribution through time are also supported in the framework. Although an earlier implementation of this framework used relational database technology, implementation now focuses on object-oriented approaches. The implementation logically follows the organization of category theory, with the feature forming the basic level of categorization.
An implementation for a watershed modeling application is built to test the theory. The application requires multiple feature types, such as the linear structure of the stream network embedded within the areal structure of the watershed. The multiple representations required for the watershed application include points for rain gage and stream sampling stations, which are used with digital elevation data to define polygons representing subwatersheds, vector geometry for the streams, network topology for the interstream connections and flow models, and raster geometry for the elevation surface, land cover, and soils. These requirements provide a test of the basic theoretical structure for geographic features.

INTRODUCTION

Computer-based representation of geography has advanced from initial geometric primitives of points, lines, areas, and pixels, that mimic the objects shown on maps, to systems that include multidimensional attributes and relationships of geographic phenomena and processes. Although these advances have been significant, limitations still exist, and a single multidimensional geographic theory of representation is a major research objective (UCGIS, 1999). Such a theory is needed to unify the disparate methods of representation, to provide a framework for the interchange of software and data, and to provide interoperability among systems (UCGIS, 1999; OGC, 2000). The development of a comprehensive theory is a long-term goal of the discipline and will only be accomplished in small steps by many researchers. It is the purpose of this paper not only to document one of those steps in the form of a conceptual framework that allows multiple representations of geography to exist for a single real world geographic feature but also to describe a method for implementing a part of the framework for a watershed analysis application. The following section of this paper provides the background for the framework and places it in the context of current research. The third section documents the formal concepts of the framework and provides background for implementation approaches. The fourth section describes a possible implementation for representing a watershed using raster geometry. A final section draws conclusions from the work accomplished.

BACKGROUND

Significant work toward developing a theory of geographic phenomena has been accomplished (Peuquet, 1988a; Molenaar, 1991; Mark, 1993; Usery, 1993; Tang *et al.*, 1996; Usery, 1996a; 1996b; 1996c). This theory, supported in cognitive psychology by work on category theory, in geography by work on geographic regions and spatial analysis, and in cartography by work on abstraction and generalization, provides the basis for developing a multidimensional representation of geographic phenomena (Berry, 1964; Grigg, 1965; Rosch *et al.*,1978; Lakoff and Johnson, 1980; Lakoff, 1987; Goodchild, 1987; McMaster, 1991; Nyerges, 1991).

Table 1

Dimensions, Attributes, and Relationships of Geographic Phenomena

	Space	Theme	Time
Attributes	φ,λ,Z point, line, area, surface, volume, pixel, voxel, ...	color, size, shape, ph, ...	date, duration period, ...
Relationships	topology, direction, distance, ...	topology, is_a, kind_of, part_of, ...	topology, is_a, was_a, will_be ...

Table 1 illustrates the possible attributes and relationships of a particular geographic feature (Usery, 1996a). Berry (1964) developed a conceptual framework, using equivalent elements to those in Table 1, to account for all possible types of spatial analysis. Goodchild (1987) examined spatial analysis concepts that are based on current data models and point, line, area, and grid cell objects represented in current geographic information system (GIS) software packages. Sinton (1978) argued that of the three dimensions shown in Table 1, one is fixed, a second is controlled, and the third is measured. This view is supported in GIS since most data sources are maps, and maps usually fix the time, control the theme, and vary the spatial location. These observations concerning the fundamental basis of geographic phenomena and the possible types of analytical operations lead to a set of requirements for any theory of geographic phenomena and any implementation of such a theory in terms of analytical needs.

APPROACH

Previous studies have established the need for a theory of geographic information to push geospatial technology beyond its currently limited structures (Molenaar, 1991). As a step toward generating such a theory, it has been shown that features commonly defined as mappable geographic entities fit category theory's basic level for geographic phenomena (Rosch, 1978; Mark, 1989; Usery, 1993; 1996a) and that formalization of these entities in systems design can be achieved through interaction concepts such as metaphor and object semantics (Gahegan, 1994; Molenaar, 1994). Theoretical work on human cognition indicates that the use of metaphor is an appropriate mechanism to relate geographic knowledge. For example, Couclelis and Gale (1986) found that alternative conceptions of space, including Euclidean, physical, sensorimotor, perceptual, and cognitive can be distinguished and represented as algebraic group structures. Kuhn and Frank (1991) found that interface design requires formalization of interaction concepts, one of which is metaphor. Metaphor domains are formalized by algebras, morphisms, and image-schemas. Mark (1993) explored a framework for defining geographic entity types according to category theory.

To advance from basic theoretical concepts to an implementation useful for geographic applications requires (1) a theory of sufficient completeness to support the needs of the applications, (2) a transition framework from theoretical concepts to data models, and (3) an implementation methodology from the data model. The following discussion concerns these three stages beginning with an examination of theoretical completeness, particularly with respect to the relations among features.

Theoretical Completeness

Although components of a basic theory of geographic entities or features and human understanding through metaphor and algebraic concepts are well illustrated, the theory is incomplete and the path to implementation is not clear. One of the missing parts of the theory is how one feature relates to another. These relations are extremely important and often form the basis of geographic applications. Early in the study of computer-based representation of geographic phenomena, Freeman (1975) defined 13 different spatial relationships: left of, right of, beside, above, below, behind, in front of, near, far, touching, between, inside, and outside. Peuquet (1986) refined Freeman's work and stated that all spatial relations can be defined in terms of three primitives: direction, distance, and Boolean set operations (and, or, not). She further developed some implementation methods for these set operations using a raster GIS database (Peuquet, 1988b). More recent work has focused on defining the fundamental bases of spatial relations and the operations allowed. For example, Egenhofer and

Franzosa (1991) developed an often-cited model of topological relations among point sets. Clementini *et al.* (1993) extended this work by taking into account the dimensions of the intersections. Other work has used approaches to determining qualitative relationships rather than strictly metric intersections of spatial primitives (Frank, 1991; Freska, 1991; 1992; Hernandez, 1993; Cui, *et al.*, 1993; Zimmermann, 1993). Frank (1998) attempted to simplify relation representation with formalization of spatial frames of reference. In his approach the reference frame must fix three parameters: 1) the origin of the speaker, object, etc., 2) orientation; *i.e.*, the axial frame of reference, and 3) the handedness of the coordinate system. It is interesting to note that all of this research examines only spatial relationships. The thematic and temporal relationships of Table 1 are not addressed directly and receive attention only when spatial concepts, such as topology, can be applied to the thematic or temporal dimensions (Langran, 1992).

Transition Framework

A framework is required to transfer components of any developed geographic theory to a data model. Such a framework involves the transformation from concepts as developed in the human mind to a conceptual data model and ultimately to a data structure that can be implemented on a computer system (Peuquet, 1984; Guptill *et al*., 1990). The framework shown in Figure 1 is a summary view of how information can be transferred from the real world to a knowledge representation. Details of the framework are provided in Usery (1996a). This framework begins with a set of

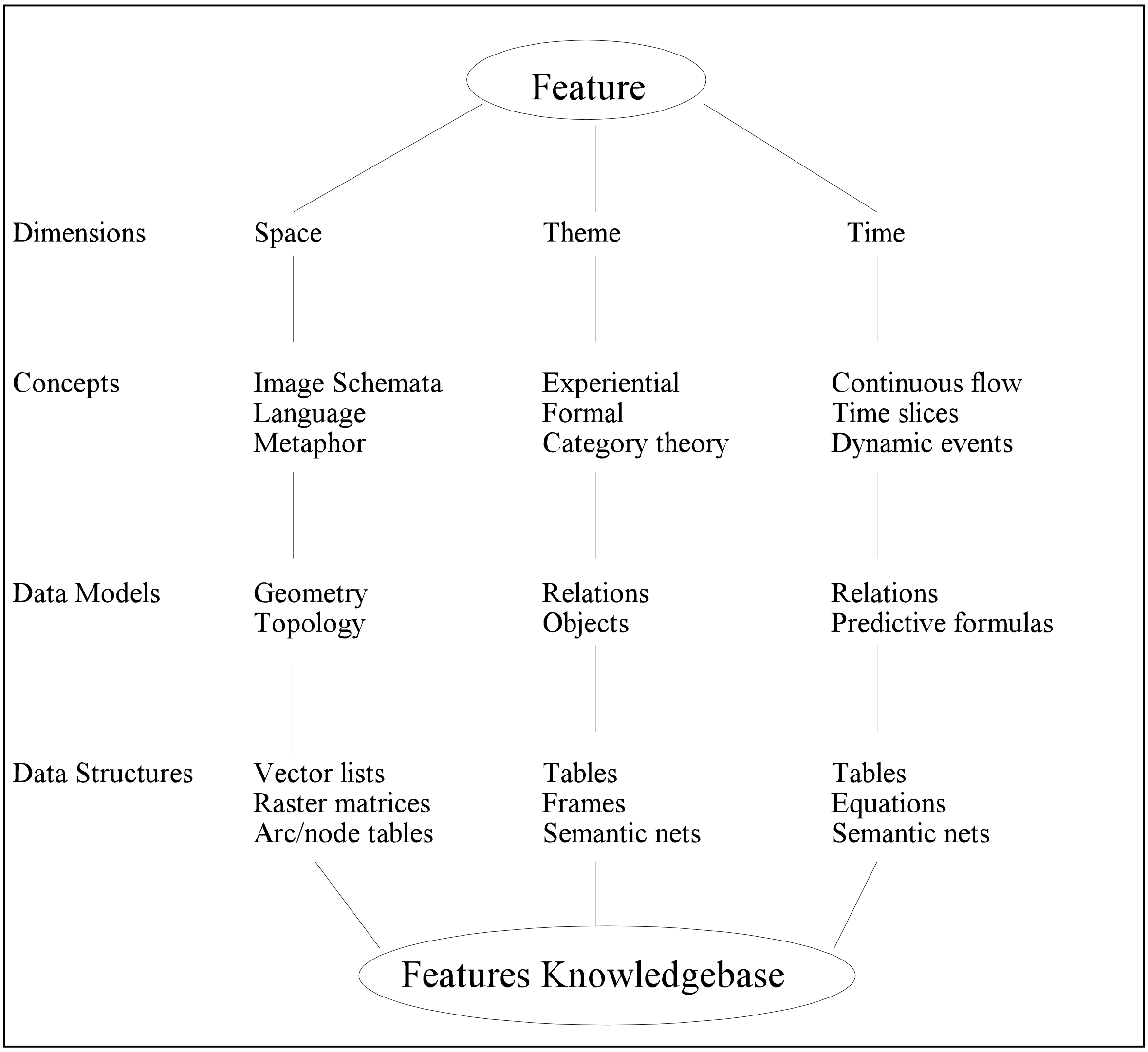

Figure 1: Conceptual framework for modeling geographic features (Adapted from Usery, 1996a).

geographically real features, poses the fundamental dimensions of each of those features as human concepts, examines each of those concepts rendering a data model, then presents data structures appropriate to the data models. Figure 1 is presented not as a comprehensive model, but as a logical method to build a transition framework. Each specific geographic feature will require its own transition framework, and all needed components for all dimensions of the transition may not be included in Figure 1.

Implementation Methodology

Automated information systems, including GIS, rely heavily on a database management system (DBMS) for support (Gallagher and Draper, 1984; Eastman, 1985). A DBMS, from an implementation perspective, attempts to model real-world phenomena within the framework of one of the three traditional data models (Tsichritzis and Lochovsky, 1982; Ullman, 1982); the hierarchical (Tsichritzis and Lochovsky, 1976), network (Taylor and Frank, 1976), and relational (Codd, 1970). Incorporating higher level constructs in the data modeling process led to the development of semantic data models (Abrial, 1974). These models provide a natural mechanism for specifying the design of a database (as represented by the conceptual schema) and capturing the data and relationships among the data. They allow the database designer to represent the objects of interest and their relationships in a manner that more closely resembles the view that the users have of these objects and relationships. For geographic phenomena, many different object models have been proposed. The current research uses the digital line graph (DLG)-F model developed by the U.S. Geological Survey (USGS, 2000) and focuses on implementing DLG-F constructs for a watershed application using an underlying raster geometry. A system design is shown in Figure 2.

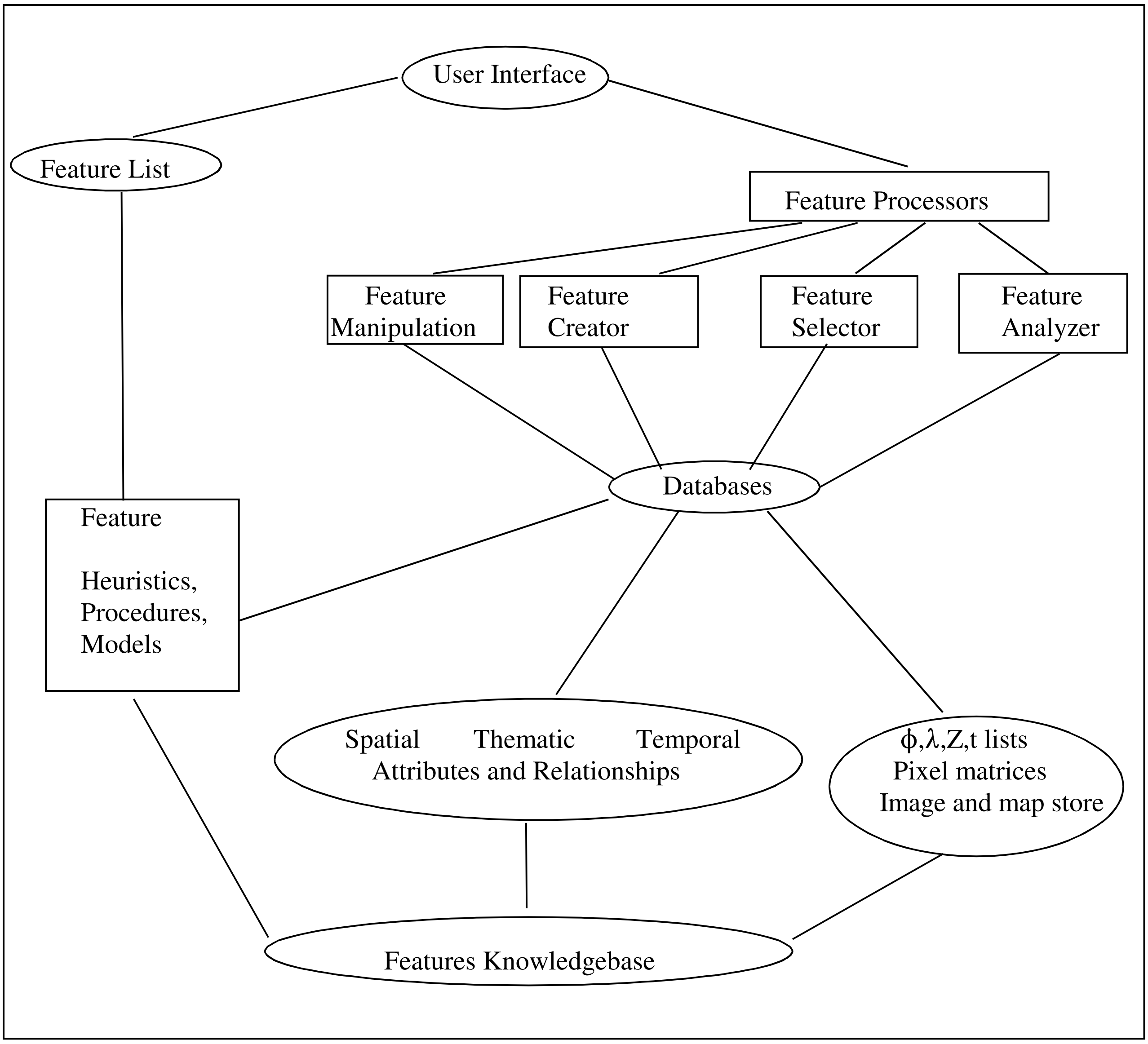

Figure 2: System design to implement geographic features with multidimensional representation.

APPLICATION OF THE FRAMEWORK

An application in watershed and water quality modeling provides a basis for testing some of the concepts developed in the conceptual framework for multidimensional representation of geographic phenomena and processes. The ultimate goal of the application is the implementation of watershed models such as Precipitation Runoff Modelling System for water flow prediction and the Agricultural Nonpoint Source pollution model for water quality prediction. A test site was selected at the Little River watershed in southern Georgia in the United States. Traditional datasets, including layers for hydrography, soils, land cover, elevation, and precipitation have been developed for Little River. The watershed boundary is defined and all layers have been clipped to the boundary. Conventional raster and vector processing of these data to generate parameters for the water models are also under way.

Using the concept that each unique geographic entity may be represented as a number of digital object representations, several features were selected for modeling (Table 2). The approach here is to use an underlying raster geometry; thus, each feature listed in Table 2 has a raster model based on the necessary pixel description. A list of possible raster pixel descriptions is provided in Usery (1994). Attributes and relationships are modeled as in DLG-F.

Table 2

Example Watershed Features Modeled from Raster Geometry

Entity	Object	Attributes	Relationships
Gaging station	Pixel	Table of heights	Subwatershed area
Sampling station	Pixel	Table of water quality values	Subwatershed area
Stream	Line of pixels	Name Table of flow	Connects to: streams Flow from: flowplanes
Flowplane	Pixel aggregation	Slope (avg)	Flows to: stream
Subwatershed	Pixel Aggregation	Area	Composed of: flowplanes Contains: stream Part of: subwatershed

The fundamental basis of the representation is the constant of the geographic feature. Each feature in Table 2 exists as an entity in the real world and as multiple objects in the digital representation. This one-to-many relationship allows multiple spatial, thematic, and temporal representations to exist for the same feature. The implementation of a process model for the sediment flow and water quality through the basin over time requires dynamic temporal representation from the theoretical framework

CONCLUSIONS

A conceptual framework has been developed for the multidimensional representation of geographic phenomena and processes. The framework relies on theories from cognitive psychology, geography, and cartography. It can support multiple representations of single geographic entities. The geographic feature in the real world forms a single unique individual that can be represented as multiple digital objects of varying spatial, thematic, and temporal dimensions. Implementation of the framework requires a transition from conceptual modeling to a data model and ultimately to a data structure. From this framework, an implementation method with a specific underlying geometry, theme, and time must be developed. Specific examples for watershed modeling include sampling stations, streams, flowplanes, and subwatersheds.

REFERENCES

Abrial, J.R., 1974. "Data Semantics," In *Data Base Management*, Klimbie, J.W. and K.L. Koffeman, (eds.) North Holland, Amsterdam, pp. 1-59.

Berry, B.J.L., 1964. Approaches to Spatial Analysis: A Regional Synthesis. *Annals of the Association of American Geographers*, 54, 2-11.

Clementini, E., P. DiFelice, and P. van Oostterom, 1993. "A Small Set of Formal Topological Relationships Suitable for End-User Interaction," In Abel, D. and B.C. Ooi, 1993. *Advances in Spatial Databases, 3rd International Symposium, SSD '93*, Singapore, pp. 277-296.

Codd, E.F., 1970. "A Relational Model for Large Shared Data Banks," *CACM*, vol. 13:6, pp. 377-387.

Couclelis, H. and N. Gale, 1986. "Space and Spaces," *Geografiska Annaler*, 68B-1, pp. 1-12.

Cui, Z., A.G. Cohn, and D.A. Randall, 1993. "Qualitative and Topological Relationships in Spatial Databases," In Abel, D. and B.C. Ooi, 1993. *Advances in Spatial Databases, 3rd International Symposium, SSD '93*, Singapore, pp. 296-315.

Eastman, C. M., 1985. "Database Management Systems," *Annual Review of Information Science and Technology*, vol. 20, pp. 91-115, Knowledge Industry Publications, Inc., White Plains, NY, (M. Williams, ed.)

Egenhofer, M. and R. Franzosa, 1991. "Point-Set Topological Spatial Relations," *International Journal of Geographical Information Systems,* Vol. 5, No. 2, pp. 161-174.

Frank, A.U., 1991. "Qualitative Spatial Reasoning about Cardinal Directions," *Proceedings, Auto-Carto 10*, Baltimore, pp. 148-167.

Frank, A., 1998. "Formal Models for Cognition   Taxonomy of Spatial Location Description and Frames of Reference," In Wender, K.F. (ed), 1998. *Spatial Cognition*, Springer-Verlag, Berlin, pp. 293-312.

Freeman, J., 1975. "The Modelling of Spatial Relations, " *Computer Graphics and Image Processing*, Vol. 4, pp. 156-171.

Freska, C., 1991. "Qualitative Spatial Reasoning," In Mark, D.M. and A.U. Frank, (eds), 1991. *Cognitive and Linguistic Aspects of Geographic Space*, Kluwer Academic Publishers, Netherlands, pp. 361-372.

Freska, C., 1992. "Using Orientation Information for Qualitative Spatial Reasoning," In Frank, A.U., I. Compari, and U. Formentini (eds), *Theories and Methods of Spatio-Temporal Reasoning,* Springer-Verlag, Berlin, pp. 162-178.

Gahegan, M., 1994. "Formal Semantics for the Integration of Image Data into Geographic Information Systems," In Molenaar, M. and S. DeHoop (eds), 1994. *Advanced Geographic Data Modelling,* Netherlands Geodetic Commission, Delft, pp. 19-39.

Gallagher, L. J. and J. M. Draper, 1984. "Guide on Data Models in the Selection and Use of Database Management Systems," NBS Special Publication, National Bureau of Standards. (Publication Number: 500-108)

Goodchild, M.F., 1987. A Spatial Analytical Perspective on Geographic Information Systems. *International Journal of Geographical Information Systems*, 1/4, 327-334.

Grigg, D., 1965. The Logic of Regional Systems. *Annals of the Association of American Geographers*, 55, 465-491.

Guptill, S.C., K.J. Boyko, M.A. Domaratz, R.G. Fegeas, H.J. Rossmeissl, and E.L. Usery, 1990. *An Enhanced Digital Line Graph Design*, U.S. Geological Survey Circular 1048, Reston, Virginia.

Hernandez, D., 1993. "Maintaining Qualitative Spatial knowledge," In Frank, A. and I. Compari, (eds), 1993. *Spatial Information Theory: A Theoretical Basis for GIS*, European Conference, COSIT '93, Mariana Marina, Elba Island, Italy. Springer-Verlag, Berlin, pp. 36-53.

Kuhn, W. and A.U. Frank, 1991. "A Formalization of Metaphors and Image-Schemas in User Interfaces," In Mark, D.M. and A.U. Frank, (eds), 1991. *Cognitive and Linguistic Aspects of Geographic Space*, Kluwer Academic Publishers, Netherlands, pp. 419-434.

Lakoff, G., 1987. *Women, Fire, and Dangerous Things: What Categories Reveal about the Mind* (Chicago: University of Chicago Press).

Lakoff, G. and M. Johnson, 1980. *Metaphors We Live By* (Chicago: Chicago University Press).

Langran, G., 1992. *Time in Geographic Information Systems* (Basingstoke, England: Taylor and Francis).

Mark, D.M., 1989. "Cognitive Image-Schemata for Geographic Information: Relations to User Views and GIS Interfaces," *Proceedings, GIS/LIS '89*, Orlando, Florida, pp. 551-560.

Mark, D.M., 1993. "Toward a Theoretical Framework for Geographic Entity Types," In Frank, A. and I. Compari, (eds.), 1993. *Spatial Information Theory: A Theoretical Basis for GIS*, European Conference, COSIT '93, Mariana Marina, Elba Island, Italy. Springer-Verlag, Berlin, pp. 270-283.

McMaster, R.B., 1991. Conceptual Frameworks for Geographical Knowledge. In Buttenfield, B.P. and R.B. McMaster, (eds), *Map Generalization: Making Decisions for Knowledge Representation* (London: Longman Scientific Publications) 21-39.

Molenaar, M., 1991. "Status and Problems of Geographical Information Systems: The Necessity of a Geoinformation Theory," *ISPRS Journal of Photogrammetry and Remote Sensing*, Vol. 46, pp. 85-103.

Molenaar, M., 1994. "A Syntax for the Representation of Fuzzy Spatial Objects," In Molenaar, M. and S. DeHoop (eds), 1994. *Advanced Geographic Data Modelling,* Netherlands Geodetic Commission, Delft, pp. 155-169.

Nyerges, T.L., 1991. "Representing Geographical Meaning," In Buttenfield, B.P. and R.B. McMaster, (eds), *Map Generalization: Making Decisions for Knowledge Representation* (London: Longman Scientific Publications) 59-85.

OGC, 2000. Open GIS Consortium. http://www.opengis.org.

Peuquet, D.J., 1984. A Conceptual Framework and Comparison of Spatial Data Models. *Cartographica*, 21/4, pp. 66-113.

Peuquet, D.J., 1986. The Use of Spatial Relationships to Aid Spatial Database Retrieval, *Proceedings, Second International Symposium on Spatial Data Handling*, Seattle, pp. 459-471.

Peuquet, D.J., 1988a. Representations of Geographic Space: Toward a Conceptual Synthesis. *Annals of the Association of American Geographers*, 78/3, pp. 375-394.

Peuquet, D.J., 1988b. Toward the Definition and Use of Complex Spatial Relationships, *Proceedings, Third International Symposium on Spatial Data Handling*, Sydney, pp. 211-223.

Rosch, E., 1978. Principles of Categorization. In E. Rosch and B.B. Lloyd, (eds), *Cognition and Categorization* (New York: Halstead Press) 27-48.

Sinton, D., 1978. The Inherent Structure of Information as a Constraint to Analysis: Mapped Thematic Data as a Case Study. In G. Dutton, (ed.), *Harvard Papers on Geographic Information Systems, Volume 6* (Reading MA: Addison Wesley).

Tang, A.Y.S., T. Adams, and E.L. Usery, 1996. "A Spatial Data Structure Design for a Feature-Based GIS," *International Journal of Geographical Information Systems*, Vol. 10, No. 5, pp. 643-659.

Taylor, R.W. and R.L. Frank, 1976. "CODASYL Database Management Systems," *Computing Surveys*, Vol. 8:1, pp. 67-104.

Tsichritzis, D. and F. Lochovsky, 1976. "Hierarchical Database Management: A Survey," *Computing Surveys*, vol. 8:1, pp. 105-124.
Tsichritzis, D. and F. Lochovsky, 1982. *Data Models*, Prentice Hall, Englewood Cliffs, N.J.

UCGIS, 1999. University Consortium for Geographic Information Science Research Priorities, http://www.geog.umn.edu/umucgis/research_priorities/.

Ullman, J.D., 1982. *Principles of Database Systems, 2nd Edition*, Computer Science Press, Rockville, Maryland.

Usery, E.L., 1993. "Category Theory and the Structure of Features in Geographic Information Systems," *Cartography and Geographic Information Systems*, Vol. 20, No. 1, pp 5-12.

Usery, E.L., 1994. "Implementation Constructs for Raster Features," *Proceedings, American Society for Photogrammetry and Remote Sensing Annual Convention*, Reno, Nevada, pp. 661-670.

Usery, E.L., 1996a. "A Feature-Based Geographic Information System Model," *Photogrammetric Engineering and Remote Sensing*, Vol. 62, No. 7, pp. 833-838.

Usery, E.L., 1996b. "A Conceptual Framework and Fuzzy Set Implementation for Geographic Features," In Burrough, P. A. and A.U. Frank, (eds.), 1996. *Geographic Objects with Indeterminate Boundaries*," Taylor and Francis, London, pp. 71-85.

Usery, E.L., 1996c. Membership Functions for Fuzzy Set Representation of Geographic Features," Proceedings, International Society for Photogrammetry and Remote Sensing International Congress, *International Archives of Photogrammetry, Volume XXXI, Part B4*, Vienna, Austria, p. 881-883.

USGS, 2000. "DLG-F," Internal Document, U.S. Geological Survey, Reston, VA.

Zimmermann, K., 1993. "Enhancing Qualitative Spatial Reasoning Combining Orientation and Distance," In Frank, A. and I. Compari, (eds), 1993. *Spatial Information Theory: A Theoretical Basis for GIS*, European Conference, COSIT '93, Mariana Marina, Elba Island, Italy. Springer-Verlag, Berlin, pp. 69-76.