A Feature-Based Geographic Information System Model

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Abstract

A conceptual model for structuring features in a geographic information system (GIS) is presented. The model includes spatial, thematic, and temporal dimensions and structures attributes and relationships for each dimension to build a feature-based GIS. The model is grounded in an entity-based view of geographic phenomena and requires representation of geographic entities as feature objects in GIS. The model is built on concepts from region theory in geography, category theory in cognitive psychology, and data modeling theories, including abstraction and generalization concepts in cartography and GIS. The feature construct provides direct access to spatial, thematic, and temporal attributes and relationships and thus supports multiple representations and multiple geometries, such as raster and vector. The rich structure has potential application for spatial analysis and sophisticated geographic process models. Resolution and application dependencies of feature-based systems are discussed with tools to aid in feature determination. Example features are included with parts of the model explicated for these examples.

Introduction

The development of geographic information systems (GIS) has advanced to the point that alternative approaches for modeling geographic phenomena can now be implemented. The conventional map framework based on layers of geography appears inadequate to handle sophisticated geographic process models and spatial analysis approaches (Goodchild, 1987; Goodchild, 1991; Nyerges, 1991). Few would argue the need to develop better interfaces to GIS in which users are able to name geographic entities and perform analyses on those named entities. The difficulty occurs in whether the underlying data model need reflect these entities directly or whether, through sophisticated data processing, these entities can be presented to the user through conventional layer-based models. This paper is developed from the assumption that the user's perception of geographic reality is one of geographic entities such as roads, buildings, hills, and ethnic immigration areas rather than one of layers of data, and that it is desirable for the data model to directly reflect this perception. Given this assumption, the design for an object-based model in which objects are a direct representation of the geographic features rather than of geometric elements such as point, line, and area is developed. This design is referred to as a feature-based geographic information system (FBGIS) because the term "feature" encompasses both the geographical entity and its object representation (NCDCDS, 1988).

In order to model geographic phenomena from reality, some subset of that reality, i.e., an idea of geographic reality, must be developed which reflects a particular application context and resolution of representation. For example, a trafficability application in terrain analysis requires terrain data modeled as hills, valleys, and other features. One may refer to the spatial analysis literature and find that an infinite complex of geographic entities with infinite attributes must exist; therefore, any given spatial analysis must work with a subset of these infinities (Berry, 1964). The basic characteristics of geographic phenomena have been enumerated by various researchers and consist of space (location), theme (classification or attribute), and time (Berry, 1964; Dangermond, 1983; Nyerges, 1991). Sinton (1978) argued that, of these three dimensions, one is fixed, a second is controlled, and the third is measured. This view is supported in GIS because most data sources are maps, and maps usually fix the time, control the theme, and vary the spatial location.

Table I. Dimensions, Attributes, and Relationships of the FBGIS Conceptual Model

	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 ...

In order to specify an idea of geographic reality, one must include spatial, thematic, and temporal attributes and relationships. The model of geographic phenomena describes the basic dimensions of any geographic entity (Table 1). Thus, if one describes spatial, thematic, and temporal dimensions for a geographical entity such as a road, one has described an object and thus a feature. A feature is similar to the region concept in geographic research (Grigg, 1965; NCDCDS, 1988; Usery, 1993). For a constrained definition and implementation of regions in GIS, see van Roessel and Pullar (1994).

Representation of geographic phenomena in GIS using the layered model focuses on database management and query (Peuquet, 1988; Rhind *et al.*, 1991). This representation structures the locational attributes as basic geometric objects such as points, lines, areas, and pixels (Burrough, 1986; Goodchild, 1987; Goodchild, 1991). Spatial relationships are structured using planar topology with only attribute repre-

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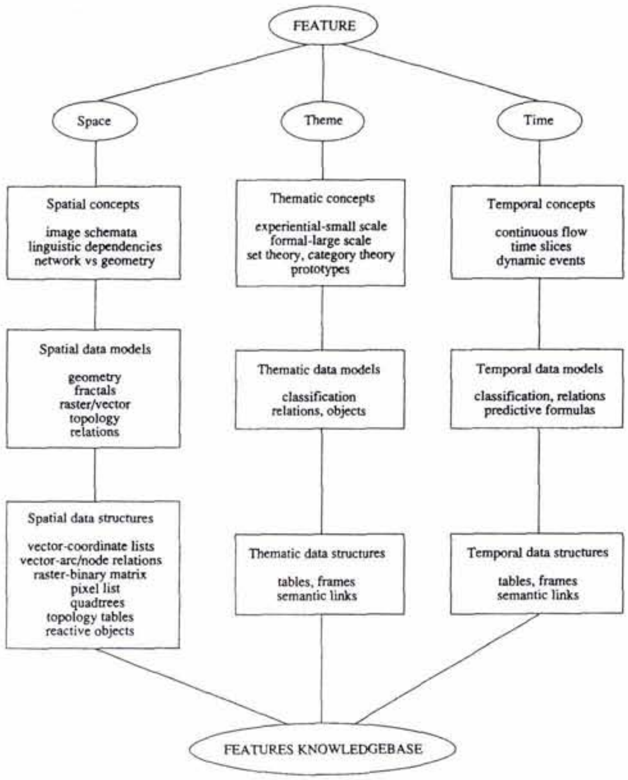

Figure 1. Dimensional concepts, models, and structures of a feature-based GIS.

sentation for the third or higher dimensions. The thematic attributes are attached to the basic geometric objects. Thematic relationships are not contained in the layered model except in those cases in which the relationships are intrinsic to the layer. For example, "a church is a building" is a thematic relationship which is usually represented in the layered model by including churches in a layer called buildings. Other thematic relationships, often hierarchical in structure, are not generally represented in the layered model. These include thematic disjunctive relationships such as "the park is a part of the city" when the park is not a part of the corporate limits of the city. Spatial disjunction — for example, separated parts of the corporate limits of a city — is supported in layered systems with planar graph enforcement through multiple rings, but thematic disjunction requires hierarchy based on thematic relations. Additional difficulties arise with planar graph layered models in handling three-dimensional relationships such as the relation between two roads as overpassing/underpassing and with dynamic temporal features such as a moving oil spill. Temporal classification is accomplished as static time slices and temporal relationships as comparisons of multiple time slices.

The FBGIS model focuses on spatial entity modeling and explicitly contains thematic attributes and relationships for three- and higher-dimensional data and temporal phenomena. Because the definition of feature reflects both actual geographical entities and their object representations, a feature must include the three dimensions of any geographic phenomenon — space, theme, and time — as shown in Table 1. A feature specified only by spatial location is incomplete; both theme and time are required as a part of the representation (object) and, while these may be fixed attributes of the feature, they are always present for actual geographical entities. Thus, the FBGIS model includes explicit thematic and temporal dimensions for each feature as well as the spatial location. Furthermore, because these dimensions can be described by their inherent characteristics and/or by their association with other characteristics, both attributes and relationships of each of the dimensions are required to specify a feature.

While the FBGIS approach, similar to the geographical matrix (Berry, 1964), can model an infinite number of attributes and relationships directly, the practical problem of determination and implementation of the appropriate set of features for a given application and resolution requires a subset of these infinities. One guide to that subset problem can be taken from cartography, in which maps have always been produced for specific applications and at specific resolutions or scales. From the work in cartography, the most relevant research concerns conceptual models and theories of generalization of geographic phenomena (McMaster, 1991; Nyerges, 1991).

The communication model of cartography, which dominated research in that discipline in the 1970s, recognizes the importance of the map user on map design and generalization processes (Kolacny, 1969; Ratajski, 1973; Morrison, 1976). It is critical that FBGIS be designed with that same understanding of the user.

The transformational view of cartography also provides concepts to FBGIS development and application (Tobler, 1979; Moellering, 1991). This view supports many of the analytical operations, such as coordinate transformation, thematic overlay, spatial buffering, and network analysis, which are necessary to structure features in forms appropriate for scientific study and analysis.

Because maps are designed to serve specific purposes, a base of knowledge has been developed to guide which features are appropriate for those purposes. FBGIS can use this knowledge as a starting point to guide the types of features to be structured in databases and knowledge bases and to provide users with the tools to generate new features which do not exist. The digital line graph-enhanced (DLG-E) of the U.S. Geological Survey (USGS) is a feature-based dataset built from this approach (Guptill *et al.*, 1990).

In the next section of this paper, the concepts of an FBGIS are explored in the context of data model theories. The third section further develops the model and provides three examples: a road, a hill, and an oil spill. The fourth section briefly explores some of the potential tools for feature determination. A concluding section discusses the potential of this model.

FBGIS and Data Model Theories

Table 1 captures the essence of the FBGIS model, but the model must be examined in the context of representing geographic phenomena in a way which provides capabilities for producing geographic information useful for spatial decision making. A framework for implementation of the model can be established, and through this framework the logical parts of the model can be explored and implemented.

Using the geographic data modeling concepts developed by Peuquet (1984), Guptill *et al.* (1990), and Nyerges (1991), one may establish abstraction levels from the real world to the computer implementation, including ideas about reality, data model, data structure, and file structure. For the FBGIS model, an implementation framework which addresses each part of the spatial, thematic, and temporal aspects of features is proposed (Figure 1). The spatial feature aspects can be viewed as consisting of three abstraction levels: spatial concepts, spatial data models, and spatial data structures (Egenhofer and Herring, 1991). Spatial concepts are used to organize and structure human perception and cognition of space.

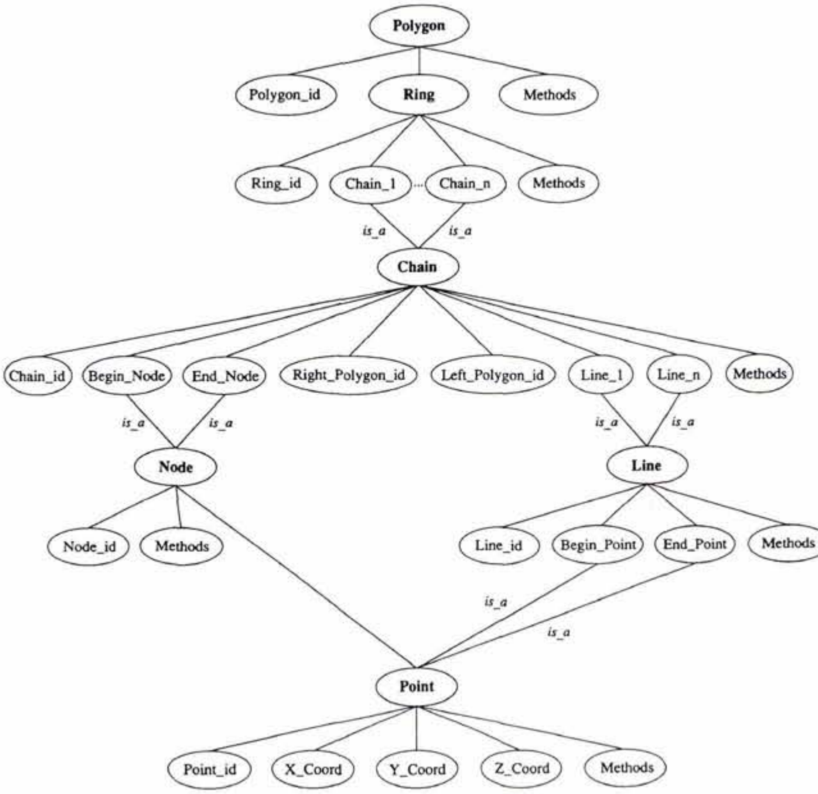

Figure 2. Spatial dimensions of vector data in an FBGIS. This is an object-oriented implementation of vector geometry and topology based on the work of Tang (1992).

For example, one might use a traditional Euclidean geometry model to move about a room but a spatial network concept to navigate through a city. These spatial concepts are intuitively used and based on image schemata which relate to linguistic terms (Talmy, 1983; Herskovits, 1986; Johnson, 1987; Mark, 1989; Frank and Mark, 1991).

Formalization of the spatial concepts leads to spatial data models. The most frequent formalization of space for geographic phenomena is based on the Euclidean metric although other space models, such as the taxicab metric, may be more appropriate for specific analytical purposes (Atkin, 1981; Gatrell, 1983; Gatrell, 1991). Often, the spatial data model is used to refer to the combination of spatial and nonspatial or thematic parts of geography (for example, see Morehouse (1989) and Egenhofer and Herring (1991)), but in the proposed FBGIS model a clear separation of space, theme, and time is used because all three are required dimensions of a feature. This separation allows each dimension of a geographic phenomenon to be modeled with appropriate concepts, structures, and implementation mechanisms, yet to be viewed as component parts of a holistic description of features.

The formalization includes the basic elements of the spatial concepts such as the point, line, area, volume, pixel, and volume element or voxel objects (see Table 1). Attributes of these objects, such as location in some spatial reference system (Euclidean or otherwise), and their interrelations, such as topology, are formalized through axioms and rules. For the FBGIS framework, specific formalizations building from existing vector-based topological systems (Figure 2) (Tang, 1991) and raster-based object systems (Table 2) (Usery, 1994)

Table 2. Possible Representations of Features from Raster Data

Feature	Pixel Configuration(s)	Representation Method(s)
Road	Line of pixels	Chain code, piecewise linear function
Railroad	Line of pixels	Chain code, polynomial, piece-wise linear function
Building	Single pixel, Multiple contiguous pixels	Point (x,y), defined set, or medial axis transformation
Hill	Multiple contiguous pixels	Fuzzy set
Valley	Multiple contiguous pixels	Fuzzy set around piecewise linear function
Stream	Line of pixels	Chain code, piecewise linear function
Lake	Multiple contiguous pixels	Ring of pixels, piecewise linear function with closing
Boundary	Line of pixels	Linear function, polynomials
City	Complex pixel aggregation	Ring of pixels, defined set
Township	Multiple contiguous pixels	Linear functions defining set
Land use	Multiple contiguous pixels	Seed pixel plus probability distribution

Table 3. Example Specification of Attributes and Relationshipos for a Road Feature

Space: Euclidean	Theme	Time
Type: line	Name: Hwy PD	Date of Const: May, 1982
Location:	No. Lanes: 2	Date of Last Maint: 1989
ϕ, λ, Z ...		
ϕ, λ, Z	Width: 10 m	
Network Topology	Part of: WI state highway system	Pavement wear: 0.5 cm/yr
Node, area, line lists		

are used. An object-oriented implementation of the Spatial Data Transfer Standard (SDTS) spatial model of features is given by Barnett and Carlis (1994). The implementation of the spatial model in a computer system requires development of spatial data structures which can accept the dimensions of the spatial data model.

In the FBGIS framework, the thematic concepts are placed at an equal level with spatial concepts in contrast to layer-based systems which assume a space dominant model (Figure 1). This distinction, in which a feature requires spatial, thematic, and temporal dimensions in order to exist at equal levels, is perhaps the most fundamental difference between the FBGIS model and layer-based models. Much of the research in GIS has focused on development of databases for representing the spatial conceptual model, and only recently have thematic conceptual models been explored (Nyerges, 1991). Thematic concepts include basic theories concerning categorization of phenomena which have impacts on which attributes define the spatial objects and lead to the formation of features. Basic research in cognition has led to category theory and the concept of prototypes which offer a basis in experiential models (Rosch, 1978; Lakoff and Johnson, 1980; Lakoff, 1987). Mark and Frank (1990) have used this research as a basis to differentiate small areal spaces and large geographic spaces as experiential and formal models, respectively. Usery (1993) has used category theory as one basis for structuring features in a GIS.

Thematic concepts have traditionally been explored through set theory. Perhaps the best example which uses set theoretical constructs to structure thematic groupings of geographic phenomena is multispectral classification of remotely sensed data into land-cover categories. Almost all current GIS are built on the concepts of set theory (Gatrell, 1983; Gatrell, 1991) with the table of the relational data model being the formal model often used for the thematic attributes and relationships (Codd, 1970).

The FBGIS thematic data model includes relational and object-oriented approaches. The relational approach is much like current attempts. It relies on the ability to construct features as collections (sets) of thematic attributes through which features may be related. The object-oriented approach to thematic concepts is detailed by Mark (1991) in an examination of phenomenon-based (feature-based) approaches to generalization. In the object-oriented approach, objects are constructed based on either sets or category-theory concepts of prototypes. A prototype is the most typical representative member of the category (feature) and other objects become members if they are more similar to the selected prototype than they are to other prototypes (Rosch, 1978; Lakoff, 1987; Usery, 1993). Usery (1994) has suggested fuzzy sets as possible techniques to describe prototype features such as hills.

Temporal concepts are the least researched aspect of geographic phenomena. Only recently through the work of a few researchers such as Langran and Chrisman (1988), Langran (1989), Langran (1992), and Greve *et al.* (1993) has progress occurred in temporal database development and implementation. Similar to the other feature dimensions, temporal concepts involve human perception and schemata of the mind. In general, the human view of time as continuous flow from birth to death dictates temporal organization. For example, the traditional view of each spatial representation as a snapshot in time accounts for our ideas of change detection in geographic phenomena. Change over time becomes the differences between two of these snapshots each at a specific instant of time. These time slices are inadequate to handle dynamic features such as oil spills. The change over time must be modeled in a continuous fashion to capture the geographic phenomena. To accomplish this, a temporal model is incorporated in the FBGIS. The temporal model is not a static attribute in a relational database but an object-oriented predictive function which models change in spatial configuration and thematic attributes and relationships over time. This modeling construct allows dynamic geographic entities to be included in the FBGIS, with static entities temporally modeled with traditional time-slice techniques such as time-stamp attributes.

Feature Examples

The description of the conceptual dimensions of a feature requires examples for which each of the dimensions is developed. Features are constructed recognizing the constraints of application and resolution dependencies. To develop the example, assume the application is to provide a base set of features for use in other spatial analysis problems. This is similar to the provision of a basic set of features on a topographic map. Also assume that a resolution appropriate for use in local and regional studies is selected; that is, for a given feature no spatial characteristics can be defined to a precision higher than 0.5 m. As a specific case, assume a road is the feature of interest. To understand the resolution dependency, at higher resolutions, 0.5 mm for example, one no longer examines the feature, road, but features such as the particles of asphalt or concrete of which the road is composed. At some high and low resolutions, geographic features yield to features of interest to other disciplines such as chemistry, physics, biology, or astronomy. Essentially, the resolution limits of geographic phenomena represent the realm of human-sized objects, that is, from the size of man to the size of the Earth. It is within this resolution range that the FBGIS model is cast.

Table 3 places a road into the modeling framework of a feature using the spatial, thematic, and temporal concepts. Assuming a Euclidean geometric model, spatially, the road possesses attributes of type = line (or type = area if resolution is sufficiently high), location = ϕ, λ, Z ... ϕ, λ, Z positional coordinates; and relationships of network topology (see Table 3 and also Table 1). The thematic attributes include name of the road, route number, number of lanes, width, and others; thematic relationships include part of = transportation network, overpasses = another road. The temporal attributes include time stamps for date of construction, date of last maintenance; temporal relationships include pavement wear per year. The level of detail of these attributes and relationships is determined by application needs.

Attributes and relationships for a hill are shown in Table 4. Again assuming Euclidean geometry, the spatial attributes are type = volume, location = ϕ, λ, Z ... ϕ, λ, Z positional coordinates forming a convex hull; and relationships of three-dimensional topology (Tsai, 1994). Note that, in this example, a raster geometry is also specified by use of a fuzzy set function. The thematic attributes include name and relative relief. Thematic relationships include two "part _ of" relations to larger geomorphic structures. The temporal attributes include time of origin, and a temporal relationship is given for the rate of erosion.

TABLE 4. EXAMPLE SPECIFICATION OF ATTRIBUTES AND RELATIONSHIPS FOR A HILL FEATURE

Space: Euclidean	Theme	Time
Type: volume	Name: Blue Mounds (west)	Date: 10,000 BC
Location:	Relative relief: 200 m	
$\phi, \lambda, Z \ldots$ ϕ, λ, Z		
Volume Topology	Part of: Blue Mounds	Erosion: 0.5 cm/yr
Node, line, area, volume lists	Part of: Wisconsin Driftless	

TABLE 5. EXAMPLE SPECIFICATION OF ATTRIBUTES AND RELATIONSHIPS FOR AN OIL SPILL FEATURE

Space: Euclidean	Theme	Time
Type: volume	Type: Crude Oil Size: 5,000,000 m^3	Date: 5/34/87 Cleanup: 5/4/87
Location:		
ϕ, λ, Z ϕ, λ, Z		
Volume Topology	Outflow From: Tanker	Rate of Size Change:
Node, line, area, volume lists	Features in Path: Alaska coast	1,000 m^3 per day
Direction: NW		Movement: 3 km/hr

Table 5 places an oil spill in the modeling framework. With Euclidean geometry, the spatial attributes are type = volume, location = $\phi, \lambda, Z \ldots \phi, \lambda, Z$ positional coordinates forming a convex hull; and relationships of three-dimensional topology. The thematic attributes include size, shape, oil characteristics, and others; thematic relationships include outflow from source and impact on other features. The temporal attributes include time and date spill occurred, time and date of modifying operations such as cleanup, and others; temporal relationships include rate of change of size, speed, and direction of movement with respect to the water and other features.

The dependencies which become obvious in an attempt to explicate the complete set of attributes and relationships for a specific feature dictate a need for users to have tools to develop features as needed from basic geographic data. These features, once developed, may be stored if desired or used only as the application requires. The feature development tools must be implementations of the basic modeling concepts which spatial analysts use to construct features. As such, the tools require both simple techniques such as counting and summation and sophisticated methods for modeling human cognition. Examples of these tools are developed in the next section.

Feature Determination

The concept of FBGIS requires some method of determining features which are appropriate for inclusion in the knowledge and databases which support user applications. That determination is usually dependent on the particular application and has traditionally been performed in spatial analysis studies through the experience of the analyst. While FBGIS approaches cannot replace the analyst and judicious selection of geographic entities for a particular study, these systems can aid the user in development of such features. As a starting point, a set of base features which have been automatically developed from the system databases will exist in the features knowledge base. The assumption is that a base set of geographic data roughly corresponding to the digital equivalent of large-scale topographic maps for the study area already exists in the FBGIS databases. For example, DLG-E is one such database currently being developed. From these databases a set of universal features are determined and placed in the knowledge bases. It is the user application which will determine needs beyond this basic set.

The variety of applications requires a dynamic feature determination system capable of learning. For example, in a terrain analysis application, a user may want to build features which determine the trafficability of a surface by particular types of vehicles. The FBGIS can provide the base set of terrain features to the user for review. If this is insufficient, then the user can specify requirements including spatial, thematic, and temporal attributes and relationships, for features to be added to the system. Assuming appropriate data exist in the databases, these new features can be generated and added to the set of system features. The next user requesting features for a similar application will be shown the base set plus the new features defined by this application.

The actual methods of feature determination from databases require a combination of database retrieval and data processing routines, such as those contained in a relational database management system, and standard spatial processing tools such as overlay and spatial buffering. These database and spatial tools must be tightly interfaced to a set of statistical and analytical processing tools such as multispectral classification, factor analysis, multidimensional scaling, and q-analysis. Data reduction and presentation of the results to the user for final confirmation of the feature's correctness are prerequisite tasks.

Conclusions

A conceptual modeling framework for a feature-based approach to GIS has been presented. The model explicitly includes spatial, temporal, and thematic dimensions and is firmly grounded in region theory from geography, category theory from cognitive psychology, and data modeling theories developed in cartography and GIS. This model holds potential for effectively representing geographic entities. The model is not constrained to map and layered representations of geography and can represent three- and higher-dimensional entities and temporal events. Multiple spatial representations, such as raster and vector geometries, of geographic phenomena are directly supported by the model.

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