A SPATIOTEMPORAL DATA MODEL FOR INCORPORATING TIME IN GEOGRAPHIC INFORMATION SYSTEMS (GEN-STGIS)

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Abstract: A new object-oriented general-purpose spatiotemporal GIS data model is presented here. This model has four key benefits. First, it provides the capabilities of a standard vector-based GIS embedded in the 2-D Euclidean space. Second, it includes the two temporal dimensions, valid time and transaction time, supported by temporal databases. Third, it inherits, from the object oriented approach, the flexibility, modularity and ability to handle the complexities introduced by spatial and temporal dimensions. Fourth, it improves the geographic query capabilities of current TGIS with the introduction of the concept of bounding box while providing temporal and spatiotemporal query capabilities.

Keywords: GIS, TGIS, Temporal Geographic Information Systems, Temporal Databases, Object-Oriented Data Model.

1 Introduction

Geographic(al) Information Systems (GIS) are systems that handle geographic information [14]. To better understand and address real world problems, people use GIS technology to represent, store, and manage (i.e., insert, modify and retrieve) geographic features. The corresponding data elements (i.e., attribute and geographic) of a geographic feature describe only one of its states, which generally corresponds to the present state. Therefore, there is a real need for the new generation of GIS to incorporate the temporal data element to allow users to track the evolution of dynamic systems and analyze the past, present, and future states of geographic features [1, 3, 5, 6, 7, 13, 16, 17, 19]. The term TGIS has emerged as a descriptor for the kind of GIS that handles the attribute, the geographic and the temporal data elements of a geographic feature. For the purposes of this work, the term *spatiotemporal GIS data* is used to globally reference these three data elements.

The time dimension, in addition to the geographic or space dimension, is important for working with real world phenomena in the context of computer applications. Actually, the study of both dimensions is among the most important elements of research in many fields, particularly in the field of databases. This new field of research has been called *spatiotemporal databases* and provides the capabilities to access information about spatiotemporal objects by their location in space, and/or by their location in time as well as to examine the history of spatiotemporal objects.

The TGIS technology can be used to solve a large number of geographic problems. According to Langran in [12], potential applications are forest resource management, urban and regional management, research and development, electronic navigation chart, infrastructure management, transportation, and map and chart production. Hermosilla in [8] extends the Langran's TGIS domain of applications to cadastral management, urban ecology management, and global change management. Kemp and Groom in [11] give an example of a zoological application, and Mason, O'Conaill and Bell in [15] give three examples of environmental modeling. Joerin and Claramunt in [10] work on an application for flood risk mitigation and control. Other applications, to name a few, are founded in the areas of business, military, water utility, government, gas utility, hydrology, cartography, and geology.

At present, research dealing with the study of TGIS centers its attention on five critical areas: (a) the design of suitable spatiotemporal GIS data models; (b) the development of databases for storing spatiotemporal GIS data; (c) the development of efficient languages for querying spatiotemporal GIS data; (d) the choice of suitable visualization mechanisms for spatiotemporal GIS data; and (e) the design and implementation of a graphical user interface (GUI), dedicated to the spatiotemporal GIS data handling. Taking into account that the capabilities of TGIS depend on the data model on top of which it is implemented, this work is focused on the area of spatiotemporal GIS data models.

The objective of this paper is to propose a suitable spatiotemporal GIS data model, for representing, storing and manipulating geographic features that change over time and the relations among them. The principal aim of this data model is to capture the attribute, geographic and temporal characteristics of geographic features to overcome three of the limitations presented in the current spatiotemporal GIS data models. First, the difficulty in incorporating time into GIS has its basis in the deficiency of the data models for representing temporal data [17, 18, 21]. Second, the majority of these data models were designed to satisfy the requirements of specific-purpose applications. Third, several data models have been proposed and implemented for recording changes in geographic features, but there is not one which is universally accepted. To fulfill this objective, a new object-oriented-based spatiotemporal GIS data model, named General-purpose Spatiotemporal GIS (GEN-STGIS) data model, is presented here. It provides the capabilities of standard GIS embedded in the 2D Euclidean space, but improves their spatial query capabilities with the introduction of the concept of bounding box. Also, it provides temporal and spatiotemporal query capabilities. The temporal component is measured as a discrete variable and based on the linear model of time, where it is managed through the incorporation of the two well-accepted temporal dimensions supported by temporal databases (i.e., valid time and transaction time).

This paper has been organized into five sections including this one. The second section presents details of the GEN-STGIS data model. The third section explains the structure of the GEN-STGIS data model. The conclusions, contributions and future work are presented in section 4.

2 Description of the GEN-STGIS Data Model

There are two important points to consider before starting the description of the GEN-STGIS data model. First, we have taken into account that the implementation must be strictly independent of any computer platform and that the evolution of computer technology should not make it obsolete. Second, the data model must be able to represent all the various complex objects and data types required in any spatiotemporal GIS application in order to guarantee its flexibility and general-purpose base.

In the GEN-STGIS data model, geographic features are represented in 2D space and 2D time. To specify their position in space, this data model uses the 2-dimensional, or plane, Cartesian (x, y) coordinate system. It is based upon the Euclidean geometry, which is concerned with the study of points, lines, and other geometric figures that can be formed with them (i.e., polygons, polylines and arcs). A plane with the described characteristics is called an *Euclidean plane* [20].

To specify the representation of geographic features in time, the GEN-STGIS data model uses the two temporal dimensions, valid time and transaction time. According to Jensen, *valid time* is ". . . the time when the fact is true in the modeled reality;" and *transaction time* is ". . . the time when the fact is current in the database and may be retrieved" [9].

The GEN-STGIS data model is based on the linear model of time, where time is measured as a discrete variable [4]. A *discrete variable* represents a period (i.e., a fixed duration of time) which is specified by its start and end times. Therefore, *valid time* consists of a starting absolute time value, denoted VS, and an ending absolute time value, denoted VE, which represent the temporal interval, [VS, VE), during which spatiotemporal GIS data are valid in the real world. Likewise, *transaction time* consists of a starting absolute time value, denoted TS, and an ending absolute time value, denoted TE, which represent the temporal interval, [TS, TE), during which spatiotemporal GIS data remain unchangeable in the database. The main advantage of interval timestamps, at the conceptual and implementation levels, is that they allow representing information about a substantial number of units of time in a compact way [4].

The object-oriented approach used in the design of the GEN-STGIS data model ensures that it is flexible enough so that it can be used for implementing GIS with or without the temporal data element, depending upon whether the application itself requires the management of time. Another benefit of this approach is that it captures the notion of the component elements of a geographic phenomenon, as they are perceived in the real world by the users as well as by the designers. Such component elements include familiar ones in the geographic domain like geographic features; geographic categories; geographic feature states; attributes, locational and temporal properties; and geometry.

From our point of view there are three reasons that justify the selection of the object-oriented approach. First, it is important to maintain current trends for developing commercial and non-commercial software, which focus on the introduction of the object-oriented technology in databases. The second reason is that the object-oriented data model is flexible enough, so that it can be combined with the widely used vector-based data model. This will allow the design of an object-oriented spatiotemporal GIS data model that can borrow the vector-based data types (i.e., point, line and polygon) for modeling the geographic data element of a geographic feature as well as some of the vector-based standard operations and relationships. The last reason is that the ability of this approach, to represent complex objects, as well as its ability to model complex relationships, makes it a good candidate for representing the temporal dimension. Considering that the inclusion of this dimension adds more complexity in terms of data representation and the definition of temporal and spatiotemporal operations and relationships, the theoretical and practical foundations of the object-oriented technology ensure that it will provide the elements necessary to handle the complexities introduced by this dimension.

3 Modeling of Structure

The structure of the GEN-STGIS data model is described by means of a collection of class diagrams that form the object model using the diagram notation provided by the Object Modeling Technique (OMT) methodology [2]. These class diagrams are presented in figures 1, 2, and 3.

Figure 1 illustrates the class diagram for geographic phenomena, geographic categories and geographic features, where the prefix *Geo* stands for the adjective *Geographic*. In this class diagram, the *GeoPhenomenon* class represents the highest level of data abstraction and describes geographic phenomena, which are composed of one or more geographic features.

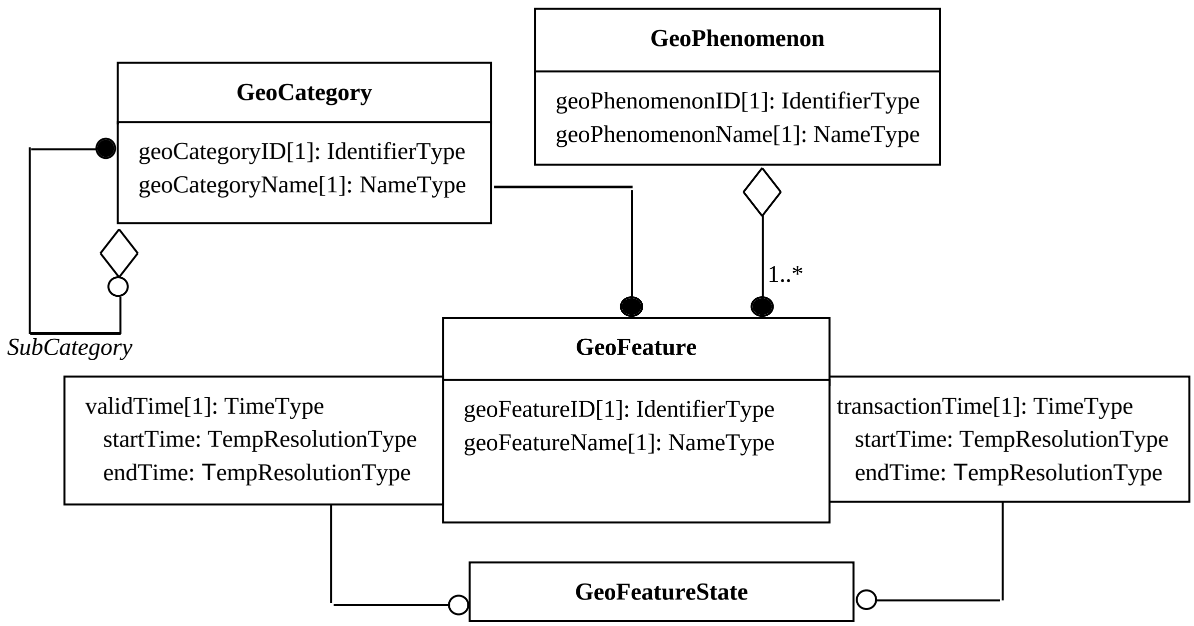

Figure 1. Class diagram for geographic phenomena, geographic categories and geographic features

The *GeoCategory* class describes geographic categories, which have multiple geographic features. Geographic categories may be structured and composed of geographic subcategories. The *GeoFeature* class represents a group of geographic features that share the same attributes, geographic and temporal representation, operations, relationships, and semantic.

A geographic feature is described through a series of states grouped in the GeoFeatureState class discussed later in this section. Each of these states corresponds to a different period represented by a temporal interval from VS to VE (i.e., valid-time interval) and a temporal interval from TS to TE (i.e., transaction-time interval). By using qualified associations, the combination of a geographic feature and a particular unit of valid time may specify a single geographic feature state. Similarly, the combination of a geographic feature and a particular unit of transaction time may specify a single geographic feature state.

The GEN-STGIS data model allows the recording of changes at any temporal resolution, which ranges from a second to a millennium. The temporal resolution is flexible enough so that the user can specify it by choosing the temporal resolution from the temporal domain set {MonthResolution, YearResolution, DateResolution, PointOfTtimeResolution}. The reader has to keep in mind that the prefix *Temp* stands for the adjective *Temporal*. Any other temporal resolution like decade, century or millennium can be derived from the YearResolution element. Also, temporal resolutions like trimester or semester can be derived from MonthResolution. This flexibility guarantees the generic temporal capability of the GEN-STGIS data model.

From the discussion above, valid-time interval, denoted V_i and transaction-time interval, denoted T_i, for i = 0, 1, 2, …, ∞, can be defined as homogeneous sets of temporal units. Following the standard definition of interval, for any two temporal units, which belong to the set, all temporal units between them belong also to the set. The valid-time interval, denoted $[VS_i, VE_i)$, is the set of all temporal units, such that

$$V_i = \{u \mid VS_i \leq u < VE_i\}.$$

Similarly, the transaction-time interval, denoted $[T_s, T_e)$, is the set of all temporal units, such that

$$T_i = \{w \mid TS_i \leq w < TE_i\}.$$

Since both valid time and transaction time are related to the same geographic feature and correspond to the same event (i.e., a change), their temporal resolutions must be the same.

When modeling a geographic phenomenon, the initial state of all its geographic features will be completely stored at the transaction time T_0. A new state, which is timestamped with the corresponding transaction time, will be generated each time changes over space, time and/or the attributes need to be made to an individual geographic feature. This new state will contain only those elements (i.e., attribute, geographic and/or temporal) of the geographic feature that have changed. In this way, it can be easy to trace and compare changes of each geographic feature over time. A second reason for storing only the changes is that the simple fact of adding the temporal dimension notably increases the amount of data that need to be stored. Therefore, to minimize this problem, the recording of changes minimizes the duplication of data.

Figure 2 corresponds to the class diagram that describes the *GeoFeatureState* class, which is the assembly part of an aggregation association. Its parts are the attribute, the geographic and the temporal data elements of a geographic feature state that correspond to a specific period, represented by its valid-time and transaction-time interval. Each object of this composite class is unambiguously identified.

Since only those elements of a geographic feature that change are stored, a geographic feature state may consist of zero or more objects of the AttributeData class, zero or one object of the GeoData class and zero or one object of the TempData class. For the same reason, almost all the attributes of these three classes are optional.

The *AttributeData* class describes the characteristics of the attribute data element of a geographic feature state. The *TempData* class describes the characteristics of the temporal data element of a geographic feature.

The *GeoData* class describes the characteristics of the geographic data element of geographic features. A GeoData object, in turn, may comprise several geometric objects for representing the spatial or geometric structure (i.e., shape) of a geographic feature and a box bounding this set of geometric objects. Both geometric objects and bounding boxes are grouped into the GeometricData class discussed below.

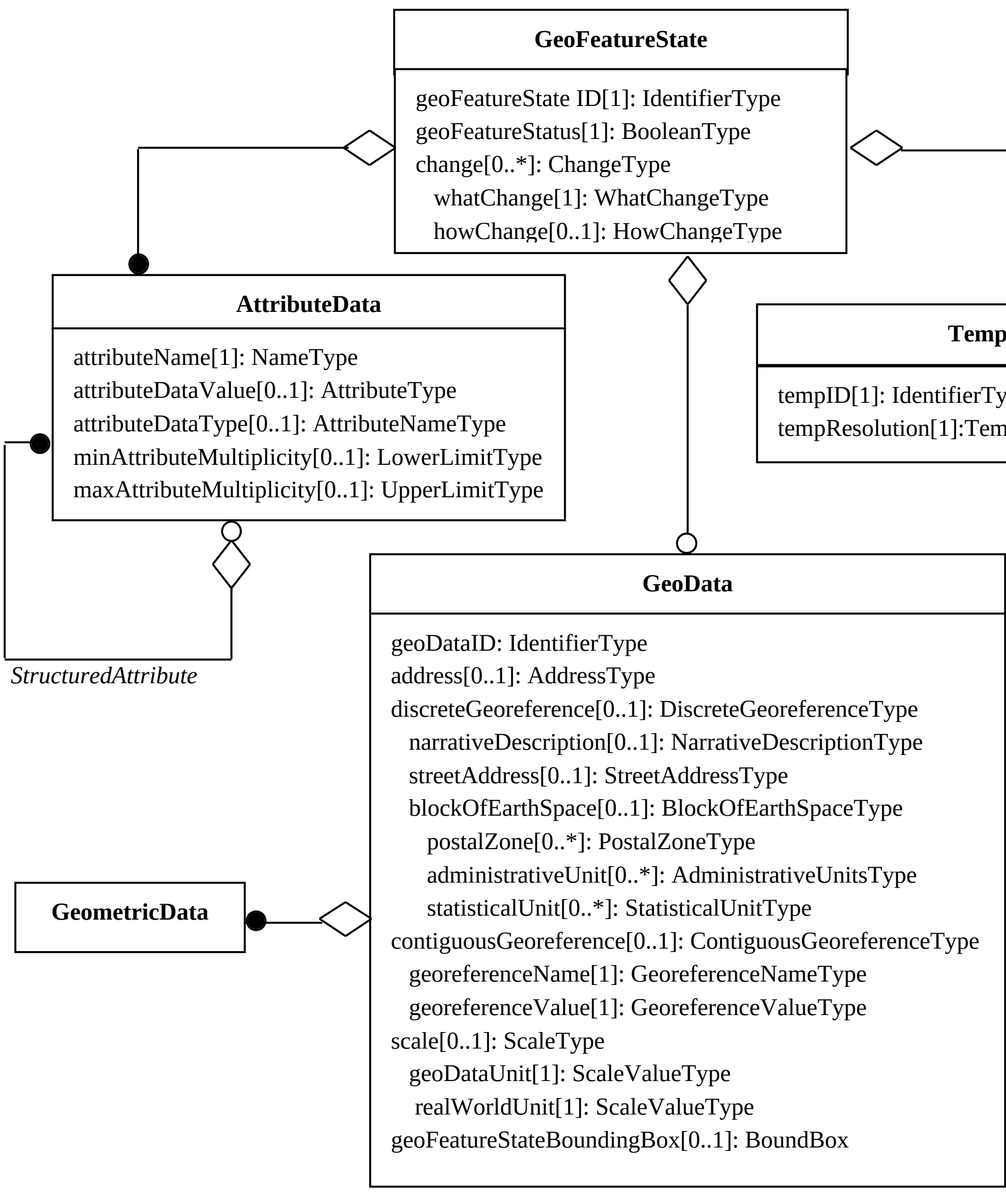

Figure 2. Class diagram for geographic feature states

Figure 3 corresponds to the class diagram for geometric objects. Since they are used to represent the spatial structure geographic features, they will be grouped into the *GeometricData* superclass.

The GEN-STGIS data model provides six basic types of geographic classes: Point, Line, Polyline, Polygon, BoundBox, and ArcOrOval, representing the lowest level of data abstraction. These classes allow modeling of the spatial structure of geographic features in the 2D, Cartesian coordinate system as well as the required operations and relationships. However, the modularity offered by the object-oriented approach allows the introduction of new classes and new data types, which need not be geographic ones.

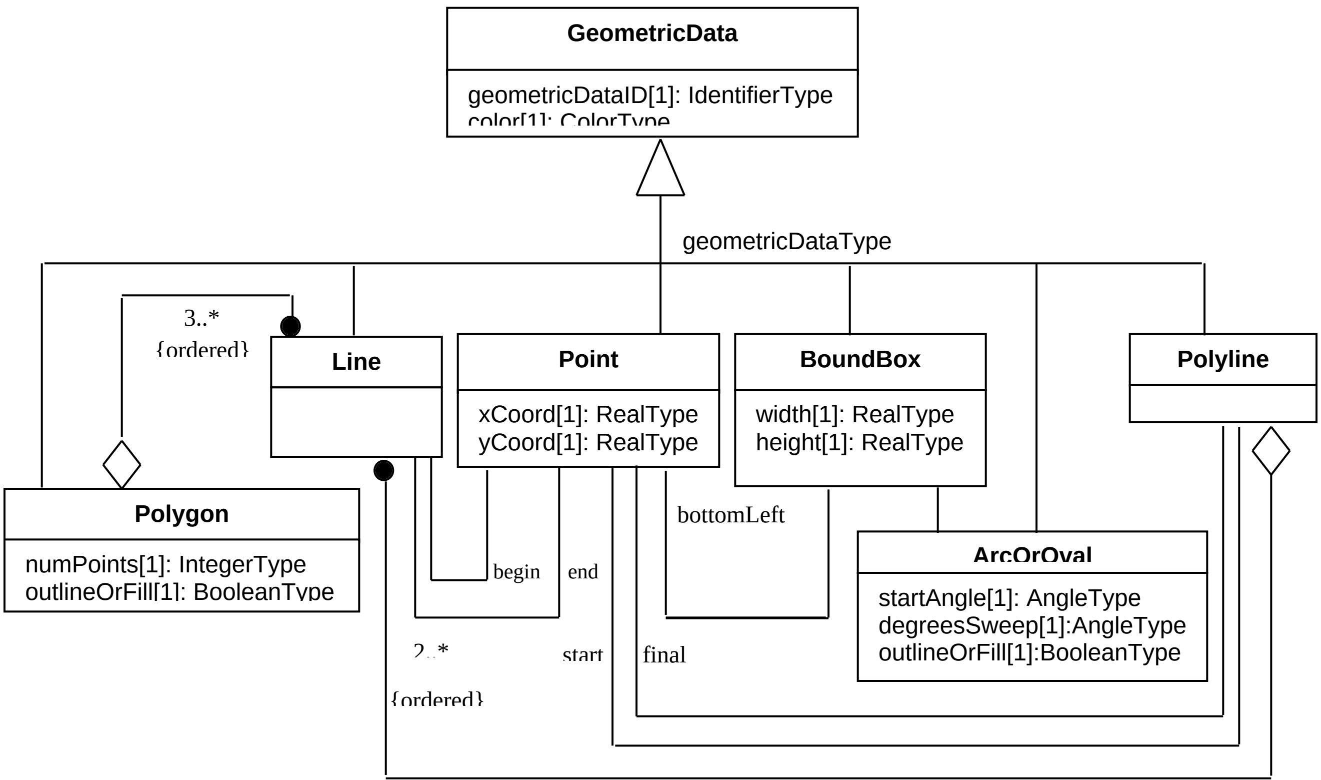

Figure 3. Class diagram for geometric data

The behavior of the objects previously defined in the structural model corresponds to the definition of each operation that can be applied to or by objects in a class and relationships between the objects of the classes or else the interaction between them. The operations and relationships will be modeled as unary and binary application independent operations that can be carried out on such objects. This uniform way for defining operations simplifies the behavioral modeling and provides more flexibility. These operations have been classified into three main classes: geographic, temporal and geo-temporal, each of which will be explained in a future paper.

4 Conclusions, Contributions and Future Work

The necessity of spatiotemporal GIS data models and the benefits of the object-oriented approach for spatiotemporal GIS data modeling are properly justified in this work.

To address the needs of spatiotemporal GIS, a combination of vector-based spatiotemporal GIS data models, object-oriented data models and temporal databases was created. This new GEN-STGIS data model satisfies one of the principal requirements of spatiotemporal GIS applications. It provides a significant advance in the field of TGIS by providing a reasonable 2D spatial and 2D temporal representation of geographic features.

The GEN-STGIS data model enables any system to function as a GIS when working with the current state as well as a TGIS when working with the states defined by the valid-time or transaction-time intervals, it provides a broad framework for developing GIS and TGIS applications theoretically in any domain.

This work has proved that the object-oriented approach, for data modeling, can be used to build the next generation of TGIS because of its flexibility, its modularity and its ability to handle the complexities introduced by spatial and temporal dimensions. In addition, the use of the OMT methodology was useful for describing the GEN-STGIS data model at a suitable level of detail.
Throughout this work, the emphasis has been on the particular aspects of the design process that comprise the modeling of the structure of the GEN-STGIS data model (i.e., the definition of classes, associations, generalizations, aggregations, and constraints). In practice, the study of its behavior (i.e., the definition of operations and relationships) is required in order to complete the design process. Also, implementation and validation phases are required in order to complete the development of a TGIS. Success in these phases requires the development of a suitable GUI to implement visualization operations for spatiotemporal GIS data handling that helps the users to better formulate and understand the results of queries.

Summarizing, the contributions of this work are:

- The development of a totally new object-oriented spatiotemporal GIS data model that removes some of the limitations of current spatiotemporal GIS data models and can be usefully used as a framework for developing spatiotemporal GIS applications.
- The demonstration of the usefulness of manipulating temporal data as a function of two different dimensions of time, valid-time and transaction time in the context of GIS.
- The demonstration that the combination of object-oriented spatiotemporal GIS data models with temporal databases can contribute in the development of spatiotemporal GIS applications.
- The demonstration that inclusion of time in GIS is not an unattainable ideal.

Much research needs to be done to deal with the complexities of TGIS before any complete version will be available and accepted by the GIS community. Some problems, like the requirement of sophisticated hardware and software due to the storage requirements and the manipulation of immense amounts of data, need to be solved. The GEN-STGIS data model offers a framework to describe 2D spatiotemporal GIS data. The further capacity to manipulate this kind of data in 3D would be the most immediate extension of this work. Since the data model is defined in terms of temporal discrete variables, future important research should further explore the use of temporal continuous variables.

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