REPRESENTING TIME IN BASE GEOGRAPHIC DATA

by

YANFEN LE

(Under the Direction of E. Lynn Usery)

ABSTRACT

This dissertation incorporates time into base geographic data, including boundary, elevation and land use/land cover. It first examines the characteristics of time in base geographic data. Although changes can be discrete, stepwise or continuous, all are simplified as discrete. Currently, there are two major spatial representations, objects and fields, but there is not an existing temporal approach that is suitable for both. Since space is represented differently in existing geographic information systems (GIS) and there are similarities between space and time, this dissertation argues time should be represented in different approaches too. Parallel to the object-field dichotomy, this dissertation introduces a feature-based temporal model for objects and suggests the layer-based approach for fields. The layer-based approach can be further classified into current-state-with-changes (CSC) and sequential snapshots. In the feature-based temporal model, a feature can have multiple temporal spaces and themes. All are functions of time, and can be simplified as constants during time intervals when changes are treated as discrete. This makes it possible to model a feature's history with several time intervals and corresponding states. In the CSC approach, discrete change in fields is modeled using the current state and a series of spatio-temporal changes. The sequential snapshots approach is recommended for fields where space is frequently fragmented through time. However, there is no strict distinction between CSC and sequential snapshots. The feature-based temporal model can be implemented in an object-relational (OR) database, which supports abstract data types. In an OR feature table, a record can model a temporal feature. Based on common spatial and temporal reference systems, a prototype temporal GIS is developed to integrate different temporal approaches. The temporal system is developed from scratch because existing GIS limits the advantages of the OR schema. The prototype temporal GIS not only integrates the three temporal approaches, but also can work with other models. In conclusion, this dissertation makes a step in moving traditional static GIS towards temporal GIS, and contributes to geographic representations in three of the nine research objectives identified by University Consortium for Geographic Information Science.

INDEX WORDS: Representation, Temporal, GIS, Base geographic data, Feature-based

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DEDICATION

This dissertation is dedicated to my husband, Wenlong Zheng, and son, Jiale Zheng.

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CHAPTER 1

INTRODUCTION

1.1 Background

Does geographic reality change gradually or rapidly, continuously or discretely? How do human activities interact with the geographic environment? Temporal information is useful in answering these geographic questions. After almost forty years of development, geographic information science (GIScience) and technology are now effective at representing spatial information, but temporal information is not well represented (Yuan *et al,* 2004; Worboys, 2005). When the environment changes, the most current information is collected, and the geographic database is updated with the new data. Usually, old data are simply deleted and can no longer be retrieved. This approach was cost efficient to most database owners when computers were expensive, slow, and had small storage space. However, temporal information is useful for better understanding dynamic geographic reality and human-environment interaction. For example, spatio-temporal information is required for geographic analysis such as urban growth, transportation analysis, and disease spreading over space and time.

Geographers not only study questions of the spatial distributions of geographic phenomena, but also why and how the spatial distributions occur and what the distribution will be in the future (Bailey and Gatrell, 1995). To answer these questions, spatial information over time has to be collected, analyzed, modeled, and predicted. For example, land use/land cover data of different years are frequently used in urban dynamics research (Yang and Lo, 2003). However, such historical information is often unavailable to the public. After a research project is finished, useful temporal data are usually not shared. Realizing the necessity of temporal information in geographic information systems (GIS), the U.S. Geological Survey (USGS, 2001) proposed to provide a temporal dimension in *The National Map—Topographic Mapping for the 21st*

Century, and spatio-temporal representation is recognized as a long-term research challenge by University Consortium for Geographic Information Science (UCGIS, 2004).

Because of the complexity of spatio-temporal data and the specific purpose of a single application, most temporal representations proposed so far are designed for spatial data in either object or field form, and usually for one particular application, such as cadastre (Al-Taha, 1992; Chen and Le, 1996), wildfire (Yuan, 1997), atmospheric study (Peuquet, 1994, 2002), boundaries (Wachowicz, 1999), transportation management (Koncz and Adams, 2002), and transportation planning (Frihida *et al*, 2002). However, the value of GIS is not working with only objects or fields for a specific application, but integrating different data for various purposes.

1.2 Base geographic data

In this dissertation, 'base geographic data' refers to geographic data such as boundaries, elevation, land use/land cover, and transportation, which are used commonly in many GIS applications. Base geographic data are major components of the National Spatial Data Infrastructure (NSDI), GIS data clearinghouses, and topographic maps. Since base geographic data are used so frequently in GIS applications, they are often collected and maintained by government agencies or organizations such as the USGS and U.S. Bureau of Census and shared as a part of NSDI to the public in the United States (NSDI, 2004).

This dissertation studies time in base geographic data, not specific physical phenomena such as wildfire and storms, or personal activities on a daily schedule. On one hand, base geographic phenomena do not change/move as frequently as wildfire or personal activities do, and are usually considered static in most GIS application. On the other hand, base geographic data are commonly updated every several years because data collection and updating require extensive time and materials. For example, because there is little change in elevation, for most areas in the United States, there are only two versions of elevation data, 1979 and 1999. Census boundaries are based on the decennial collection process. For buildings, it takes several months to construct a new house and several days to destroy an existing one, so the current data collection process is not frequent enough to represent the changes in buildings. Generally speaking, base geographic data are changing, but relatively slowly.

Currently, there exist two major spatial representations, objects and fields, and one temporal representation, layers, in base geographic data. However, the traditional layer-based temporal framework is insufficient for representing temporal information, because only snapshots or changes are represented in a layer-based schema (Langran, 1992; Worboys, 1994; Hornsby and Egenhofer, 2000).

1.3 Research objectives

The primary objective of this dissertation is to incorporate time into base geographic data. Different from most spatio-temporal models proposed heretofore, the representations of time proposed in this research are not specified for a single application such as cadastre or transportation. This dissertation aims at modeling time for base geographic data, which are used commonly for many GIS applications. Of course, representations introduced in this research are not constrained to base geographic data, but may also be applied to others.

This research will not only provide a conceptual framework for time, but also study questions of how to store and manage spatio-temporal data in a computer system and how to query and visualize them in a GIS. By doing so, this research will take a step in moving the traditional static GIS towards temporal GIS. This research will contribute to the literature in three ways:

1) This dissertation will provide a representation of time in base geographic data. Since there are two major spatial representations in base geographic data, fields and objects, this research will first examine whether there is a single temporal representation suitable for both fields and objects. If not, this research will provide a different representation of time. In other words, this research will seek different temporal approaches appropriate for different data.
2) Based on the answer to the first research question, this research will study the implementation of the representation(s) introduced or chosen for base geographic data.
3) From a system view, this research will design and develop a temporal GIS, either by extending an existing system or developing one from scratch. If time in base geographic data is represented using different approaches, this dissertation will integrate different spatio-temporal models into one temporal GIS.

1.4 Study area and data sources

The study area of this dissertation is Gwinnett County, Georgia, located within the Atlanta metropolitan area (Figure 1.1). In the past thirty years, Atlanta has experienced rapid urbanization, and has been recognized as one of the fastest growing metropolitan areas in the nation (Yang and Lo, 2003). Since rapid urbanization is always accompanied with extensive changes in base geographic phenomena, Atlanta is an appropriate site for this study. This research examines Gwinnett County instead of the entire Atlanta metropolitan area because of time constraints.

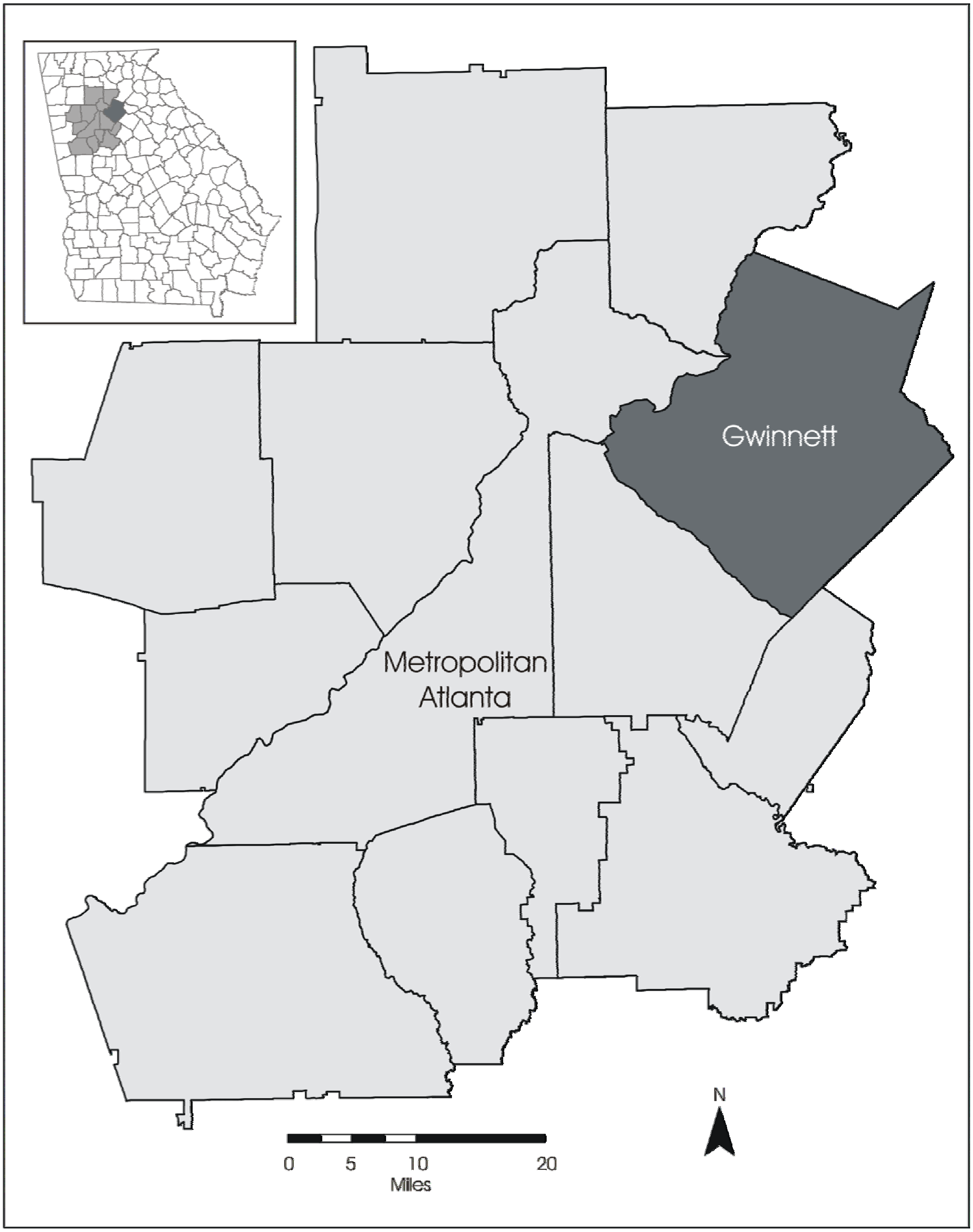


Figure 1.1 Study Area of Gwinnett County, Georgia (Le, 2005).

There are three types of data used in this research.

- Census tract: 1980, 1990 and 2000
- Land use/land cover (LULC): 1988, 1996 and 1998
- Elevation: 1979 and 1999

In Table 1.1 spatial data of census tracts are in object-form, while those of the other data types are in field-form. All datasets are of Universal Transverse Mercator (UTM) projection, which uses the Geodetic Reference System 1980 (GRS80) Spheroid, North American Datum of 1983 (NAD83) Datum, and UTM zone 16. Both LULC and elevation datasets have 30 m resolution.

Census tract data of 1980 were created by Geolytics, Inc. and the 1990 and 2000 data were by U.S. Bureau of Census. Each tract dataset was cleaned and there are no sliver polygons within any single dataset. However, overlay of different datasets shows there are some sliver polygons, some may result from change in reality while others are errors in digitizing.

Land use/land cover data of 1988, 1996 and 1998 were created by the Georgia Department of Natural Resources, USGS and University of Georgia Natural Resources Spatial Analysis Laboratory, respectively. In this research, all LULC datasets are recoded to 6 classes: urban, forest, water, wetland, agriculture, and other.

Both elevation datasets are generated by USGS, the 1979 elevation in digital elevation model (DEM) format (units: feet), and the 1999 data in National Elevation Datum (NED) format (units: meters). The 1979 DEM dataset is merged from several small images and has edge problem, while the 1999 NED dataset is interpolated using better methods and has this problem removed. Therefore, the simple difference between the DEM and NED surfaces does not represent the change. The initial difference map must be preprocessed in order to determine the change.

Table 1.1 Data sources for this research.

Data	**Spatial form**	**Year**	**Originator**	**Format**	**Geo-reference system**
Census tract	Object	1980	Geolytics, Inc.	ESRI shapefile	UTM Majority Zone (UTM, NAD83, GRS80, Zone 16)
		1990	U.S. Bureau of Census		
		2000			
LULC	Field	1988	Georgia Department of Natural Resources	ESRI Grid	UTM Majority Zone (UTM, NAD83, GRS80, Zone 16, 30 m resolution)
		1996	USGS	ERDAS Imagine	
		1998	University of Georgia Natural Resources Spatial Analysis Laboratory	GeoTiff	
Elevation	Field	1979	USGS (DEM)	ESRI Grid	
		1999	USGS (NED)	ERDAS Imagine	

1.5 Dissertation structure

This dissertation is organized into six chapters in manuscript style. Chapter 1 introduces the background, defines base geographic data, specifies three research objectives, and introduces the study area. Chapter 2 reviews the literature on spatio-temporal modeling, query and system in

GIScience and related fields including computer and cognitive science. The following three chapters are separate papers to be submitted to journals. Each manuscript chapter answers one research question. Chapter 3 proposes to represent time in base geographic data with different approaches. Chapter 4 introduces a feature-based temporal model for base geographic data in object-form, and studies its implementation and visualization in a computer system. Chapter 5 designs and develops a prototype temporal GIS to integrate different spatio-temporal data models into one system. These paper chapters are substantive to the dissertation research. Together, they achieve the research objectives. The last chapter provides conclusions.

The entire dissertation is structured as follows.

- *Chapter 1: Introduction*
- *Chapter 2: Literature Review*
- *Chapter 3: Representing Time in Base Geographic Data with Different Approaches*
- *Chapter 4: A Feature-based Temporal Model for Base Geographic Data in Object-form*
- *Chapter 5: A Prototype Temporal GIS for Multiple Spatio-Temporal Representations*
- *Chapter 6: Conclusions*

CHAPTER 2

LITERATURE REVIEW

This chapter provides a review of the literature related to this dissertation. It first briefly introduces the body of literature on spatio-temporal models. Next, this chapter examines the characteristics of time and spatio-temporal changes. This is followed by reviews on spatio-temporal data modeling in GIScience and related fields, including cognitive and computer science. Finally, it ends with a summarization.

2.1 Introduction

Space, theme, and time are identified as three basic characteristics of geographic features (Berry, 1964). Of these three dimensions, one is fixed, a second is controlled, and the third is measured (Sinton, 1978). In traditional GIS, which is rooted in cartography, usually the time is fixed, the theme is controlled, and the space varies (Usery, 1996; Galton, 2001). These types of GIS work well in describing a single state, such as the current state, of a geographic area and the spatial distribution of phenomena. However, the geographic environment is changing. GIS databases, which model the real world in the computer information systems, should also evolve with the changing world. After almost forty years of development, GISscience and technology are now good at representing space, but not time. Time, as well as space and theme, is required to be represented in GIS by many applications.

The pioneering work on time in geography began in the 1970s (Hägerstrand, 1970; Thrift, 1977). Thereafter, little was done until the publication of several PhD theses in the last decade (Hazelton, 1991; Kelmelis, 1991; Wachowicz, 1999). Langran's (1992) *Time in Geographic Information Systems* is regarded as a landmark in temporal GIS (Al-Taha, 1992; Peuquet, 2002). Among all spatio-temporal representations, the traditional layer-based framework is the only one supported by existing GIS. However, previous research shows that it is insufficient for representing temporal information, because only snapshots or changes are represented in a layer-based schema (Langran, 1992; Peuquet and Duan, 1995).

Among the various spatio-temporal approaches proposed previously, many early temporal GIS models were designed for cadastre (Hunter and Williamson, 1990; Al-Taha, 1992; Chen and Le, 1996). This occurred mainly because the spatio-temporal changes of land information are relatively simple to represent, and necessary for cadastral databases. Recently, temporal GIS approaches have tried to model continuous processes, including wildfire (Yuan, 1997) and environmental health (Mark *et al,* 2003). Temporal GIS is also gaining more attention in transportation agencies when the focus is moving from construction phrases to facilities management (Koncz and Adams, 2002).

Because of the large volume of spatio-temporal data and the specific purpose of a single application, most temporal GIS proposed so far are designed for one particular application, such as cadastre (Al-Taha, 1992; Chen and Le; 1996), wildfire (Yuan, 1997), atmosphere (Peuquet, 1994, 2002), public boundaries (Wachowicz, 1999), and transportation (Koncz and Adams, 2002). However, few temporal GIS models can provide the spatio-temporal information for base geographic data, which are commonly used in most GIS applications. Because of the difficulties in representing time, spatio-temporal modeling and analysis were recognized as one of the ten long-term research challenges by University Consortium for Geographic Information Science (UCGIS, 2004).

The concept of representation can be explained at three levels: data models, formalization, and visualization (Yuan *et al,* 2004). A data model conceptualizes the real world in a computer information system (Goodchild, 1987), and constrains that which can be formalized and visualized (Yuan *et al,* 2004). This research first examines representations at the data model level, then at the formalization and visualization levels. Balley *et al* (2004) and Hangouët (2004) discussed multiple-representation, which models a single feature in various ways depending on differences in viewpoint and resolution (Balley *et al,* 2004). This dissertation is not concerned with representation of a single feature in different models, but optimal representation of time for base geographic data in both field and object form.

2.2 Time and spatio-temporal changes

This section discusses time and the characteristics of spatio-temporal changes. The way people think about time in the real world is important to the way that time is represented in the computer system. There exist different concepts of time. These concepts pose requirements for the representation of time in base geographic data.

2.2.1. Time

- Absolute vs. relative time

In Newton's absolute view, time is composed of instants and exists independently of the frame of time. In Leibniz's relative view, objects are located relative to each other instead of a single dimensional time axis. The absolute view predominated until the adoption of Einstein's relativity theory at the beginning of this century (Kern, 1983). Leibniz's relative view is not contradictory but complementary to Newton's absolute view. Peuquet (1994) argued that absolute time is objective and relative is subjective.

- Linear vs. cyclical time

Gould (1987, p.10) discussed the dichotomy: "linear and cyclical time, or time's arrow and time's cycle". Linear time, the primary metaphor of history, views history as an unalterable sequence of unrepeatable events and looks at time as a straight directional line stretched from past through present and to future. Cyclical time means "time has no direction and events are parts of repeating cycles" (p.10-11). Gould (1987) recognizes that "the dichotomy is oversimplified and both of them are needed" (p.13). Therefore, "it is possible to define four metaphors of time: linear (past, present, and future), cyclical (season, day/night, etc.), branching (inter-entity time dependencies), and multi-dimensional time (world time, survey time, valid time, display time) " (Claramunt and Thériault, 1995, p. 25). Similarly, Worboys (1998) identified three types of temporal topology: linear, branching, and periodical (Figure 2.1). Cyclical is one example of relative time, while linear is absolute in nature.

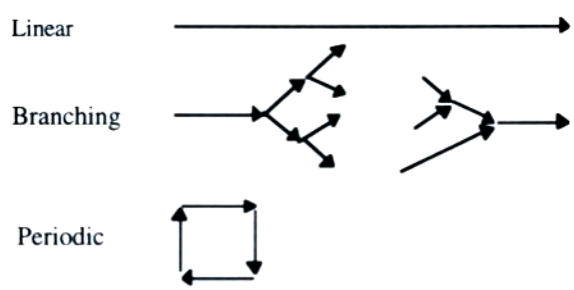


Figure 2.1 Linear, branching and periodic times (Worboys, 1998).

- Discrete vs. continuous time

Time, as an independent variable, can be measured continuously or discretely. Theoretically, it is possible to measure continuous time at an arbitrary level of precision (Frank, 1998; Worboys, 1998). Discrete time is measured at certain instants or intervals, while continuous time is measured always. Continuous time is appropriate for continuously changing phenomena, which have an underlying model assuming interpolation of any time point from measurements at other time points (Peuquet, 1994). For example, the Weather Channel uses a continuous time variable to show weather prediction based on weather condition at certain previous times. Discrete time is appropriate for phenomena that evolve only at a particular time instead of all the time. For example, land ownership in a cadastral database uses discrete time. Peuquet (1994) argued that time is continuous in nature and is broken into discrete units for the purpose of measurements. These discrete units are also called temporal granularity.

- World vs. database time

The fourth metaphor of time, multidimensional time, is further investigated (Jensen *et al*, 1995; Date *et al*, 2003). World and database time are considered as two dimensions (Langran, 1992; Jensen *et al*, 1995; Worboys, 1998). Other dimensions of time include display time, survey time, etc. World time means a fact is true in the real world, while database time indicates a specific phenomenon is recorded in the database. In temporal database management systems, world and database time are also called valid and transaction time, respectively (Jensen *et al*, 1995; Date *et al*, 2003). Jensen *et al* (1996) argued that world time was needed if changes to the past were important, while database time was required if rollback to a previous database state was necessary. A data model that supports both world and database time is called bitemporal (Jensen *et al*, 1995; Jensen and Snodgrass, 1996; Worboys, 1998).

- Point vs. interval time

Point time is an instant or a single point in the time dimension, while time interval is a period of time with a starting and an ending point in the time dimension. Point time is also termed an instant (Snodgrass, 2000). The concepts of point and interval time are similar to those of a point and an interval in space. Actually, many terms used in time are comparable to those in space (Peuquet, 1994).

- Four modes of temporal explanation

Harvey (1969) analyzed four modes of temporal explanation. To Harvey, narrative mode is the weakest, but is also the best when there is little historical data. Explanation by reference to time treats time as an independent variable rather than a parameter. Explanation by reference to hypothesized process, which assumes a specific mechanism and an artificial time scale, encounters some conceptual difficulties. Explanation by reference to an actual process is a scientific approach, although it is inferior in human geography.

- Temporal granularity

Temporal granularity is the unit of measurement in the time dimension (Dyreson *et al*, 1995). For example, the temporal granularity of birthday is a day, while that of a flight schedule is minutes. Dyreson *et al* (1995) stated that the mixture of different temporal granularities in a single database is common but causes problems. In temporal database management systems, a chronon is defined as the shortest duration of time, just as a cell is the smallest and non-decomposable space (Jensen *et al*, 1995). Temporal granularity is related with temporal resolution and temporal scale.

2.2.2. Spatio-temporal changes

Spatio-temporal changes occur in space over time. Claramunt and Thériault (1995, p.25) studied the evolution of entities over space and time, and identified "three main types of spatio-temporal processes: change of a single feature, functional relations between entities, and evolution involving several entities". Wang and Cheng (2001) distinguished three types of spatio-temporal change: a) discrete, b) stepwise, and c) continuous (Figure 2.2).

Peuquet (1999) argued that temporal duration, frequency, and pattern are important temporal characteristics. She identified four types of spatio-temporal changes: continuous, majorative, sporadic, and unique, and defined four temporal distribution patterns: steady, oscillating, random, and chaotic. A continuous change takes place throughout the time interval. A majorative change occurs during most of the time. A sporadic change happens only some of the time. A unique change occurs only once during the time interval. In Peuquet's (1994) view, the four temporal distribution patterns: steady-state, oscillating, random, and chaotic, are parallel to the four spatial distribution patterns: regular, clustered, random, and chaotic.

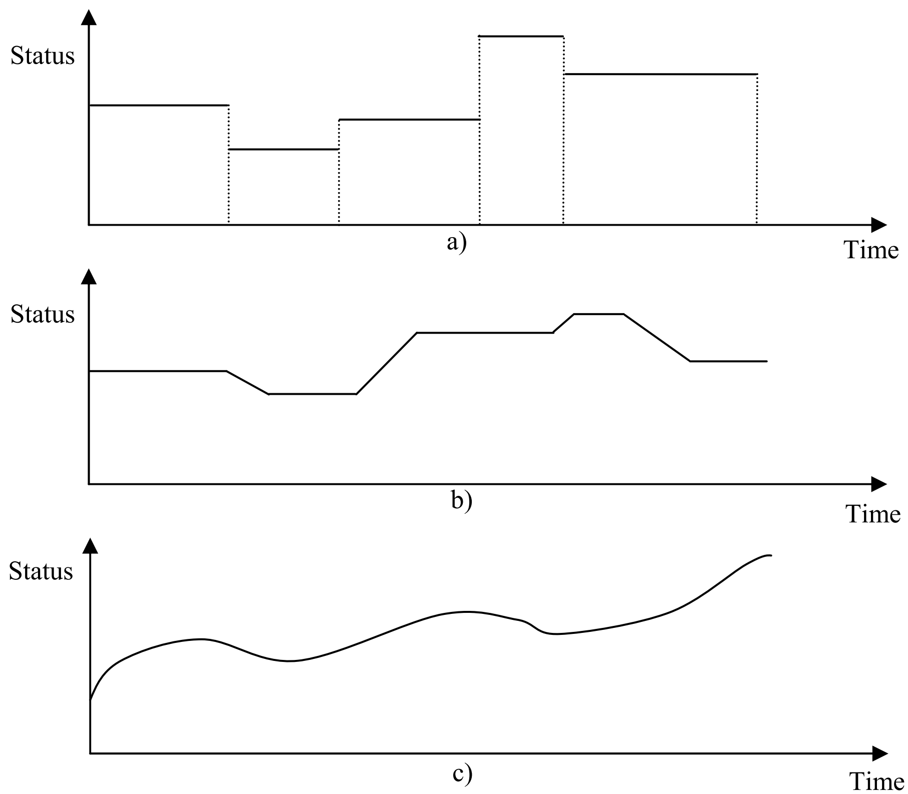


Figure 2.2 a) Discrete, b) stepwise and c) continuous spatio-temporal changes.

2.3 Time in GIScience

2.3.1 Spatio-temporal modeling

Among the large body of literature in temporal GIS, the majority is on spatio-temporal data models. A data model is a simplified representation of the real world in the computer information system (Goodchild, 1987). The closer a spatio-temporal data model is to our own concepts of space and time, the easier and faster spatio-temporal knowledge will be represented. Therefore, the design of a data model is important to the success of information systems.

Time has been studied in GIScience since 1970. Hägerstand (1970) developed the concept of time geography and proposed to represent time using space-time paths. Thrift (1977) proposed time as an additional dimension to space. Langran (1992) described four temporal GIS models: the space-time cube, sequential snapshots, a base state with amendments, and the space-time composite. Later research proposed various approaches to modeling time in GIS, including event-based (Claramunt and Thériault, 1995; Peuquet and Duan, 1995; Chen and Jiang, 1998), process-based (Yuan, 1997), feature-based (Usery, 1996), time-based (Peuquet, 1999), activity-based (Wang and Cheng, 2001), object-oriented (Wachowicz, 1999), identity-based (Hornsby and Egenhofer, 2000), integrated (Peuquet, 1994; Koncz and Adams, 2002), and event-oriented (Worboys, 2005) approaches. Some of these approaches are similar in concept.

2.3.1.1 Space-time cube and space-time paths

A space-time cube is a 3-D cube representing 2-D space and 1-D time. The 2-D space progresses along the time dimension. This view is the same as Thrift's (1977)'s idea, which treats time as an additional dimension to space. Time is linear and continuous in the space-time cube. The space-time cube is suitable for the fields with continuous spatio-temporal change (Ohsawa and Kim, 1999). The space-time cube is easy to conceive from the perspective of static GIS data model. However, Langran (1992) argued the space-time cube was difficult to implement because of philosophical and conceptual difficulties and the status of computer technologies.

Langran (1992) defined the space-time cube using Hägerstrand's (1970) space-time paths. Each object has a 3-D trajectory or a space-time path in the space-time cube. The history of an object can be accessed by tracing its trajectory. In my opinion, a space-time path is an identifiable entity in the space-time cube or hyperspace, as an object is in the space; so space-time paths are only one representation of a space-time cube. In addition to objects, there are fields in spatial representation. Since there exist similarities between space and space-time (Galton, 2003), there should exist another view in space-time cube, which represents the space-time cube as continuous fields. For example, temporal information of the atmosphere or temperature is continuous in the space-time cubes, and the field representation fits better than space-time paths.

With advancement in computer technology including object-oriented programming, the space-time cube has evolved into other approaches including object-orientation (Wachowiz, 1999) and activity-based (Wang and Cheng, 2001). Recently, space-time paths are studied to model a person's location on a daily schedule (Kwan *et al*, 2003). Space-time paths can represent personal locations well because the spatial dimension of a person's location is a point, which is very easy to represent compared to a line or polygon. In a space-time cube, a point only moves or changes location and there is no change in shape. For a line or polygon, it can not only move together, but also change point-by-point. In other words, a line or polygon can change shape in the space-time cube because each point of the line or polygon can move in different direction at different speed. For example, it is difficult to represent a storm or a wildfire with a space-time path. Therefore, personal location is a simple case of the space-time cube.

2.3.1.2 Sequential snapshots

Sequential snapshots are the only spatio-temporal approach currently supported by commercial GIS (Peuquet, 1999). This approach uses a temporal series of spatially registered snapshots $\{S_i\}$

to represent the spatial-temporal progress (Figure 2.3). Each snapshot models one status of the real world at that specific time. Discrete and point time are employed in this approach. The temporal distances between any two consecutive times, t_i and t_{i+1}, may be different. Snapshots are also viewed as a series of time-slices from the space-time cube (Langran, 1992). This approach can be employed for both field and object data. Since all snapshots are spatially registered and history is tracked by location, this method is also called a location-based approach.

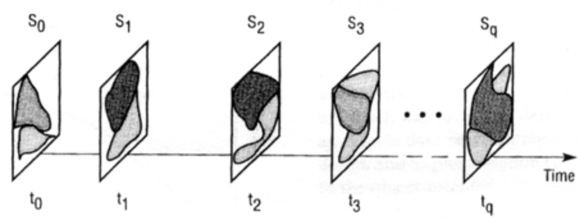
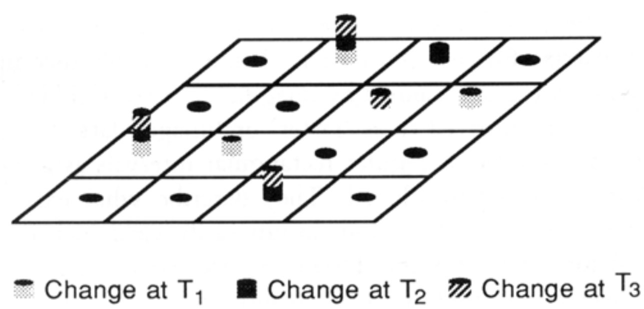


Figure 2.3 Sequential snapshots (Peuquet and Duan, 1995).

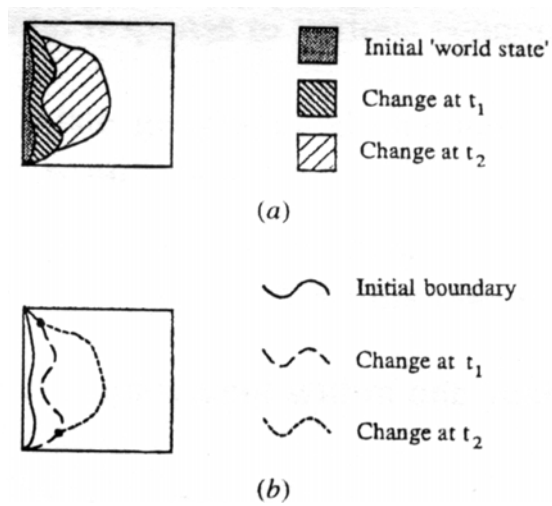
This approach is conceptually straightforward (Peuquet, 1999). For each time t_i, it is easy to retrieve the status of the real world at any spatial location. However, we cannot tell for sure the status of the real world between t_i and t_{i+1}. Furthermore, the accumulated changes between t_i and t_{i+1} are not explicitly modeled. Langran (1992) argued that snapshots are the temporal equivalence of spaghetti in space. This approach can only model accumulated changes between any consecutive times, t_i and t_{i+1}, by comparison between these two snapshots based on location. The comparison procedure is time consuming and might be trapped by errors because of improbable changes. Also, data volume increases quickly since each snapshot records the whole area whenever change takes place at that location. This brings about redundancy in a database.

2.3.1.3 Base state with amendments

Base state with amendments (Figure 2.4) is an alternative to the sequential snapshots approach. It starts with the original snapshot at the time of beginning, t_0, as base status and only records changes of events under observation between any two consecutive times. This change-only, time- or event-based temporal approach modeled change instead of world status (Langran, 1992). Same types of time concepts, point and discrete time, are used in this approach as they are in snapshots approach. This approach can be used for both raster data and vector data.



A) for fields (Langran, 1992)



B) for objects (Peuquet and Duan, 1995)

Figure 2.4 Base state with amendments

This approach is better than the snapshots approach because it models changes instead of world status and has minimal redundancy (Langran, 1992). Accumulated changes between two point times are easy to access. World status can be retrieved by amending changes to the base status. This approach is better for location-based queries (Peuquet and Duan, 1995).

Ohsawa and Kim (1999) argued the current data are the most frequently used and need to be accessed efficiently, so it should be more meaningful to take the snapshot at the current or latest time t_n rather than the beginning time t_0 as the base state.

2.3.1.4 Space-time composite

The space-time composite was originally proposed by Chrisman and further explored by Langran and Chrisman (Langran, 1992). This approach begins with a base map, and decomposes the base map using the overlay method when the real world evolves. As the time passes, the space-time composite is fragmented little by little.

Langran (1992) argued that this approach used an atemporal method to deal with the temporal problem. Changes are implicitly represented in this approach. The space-time composite is conceptually straightforward. To access world status, all fragments valid at that point in time are retrieved, and then common boundaries between these fragments are resolved by rebuilding spatial topology. The problem with this approach is the fragmentation. The updating process is relatively more time consuming than other methods.

2.3.1.5 Event- or time-based approaches

Events are things, conditions, processes, or objects that exist (Claramunt and Thériault, 1995). Several event-based approaches have been proposed by Claramunt and Thériault (1995), Chen and Le (1996), Peuquet and Duan (1995), and Chen and Jiang (1998). Among these approaches, some are different in essence, while others are similar. The common idea behind these four approaches is explicitly presenting the temporal successive relationships using backward and forward pointers in the database.

Claramunt and Thériault (1995) presented an event-oriented approach for vector data using extended versioning (Figure 2.5). To them, ordered events are more useful than precisely dated events, and versioning is a mechanism to organizing the history in order. The extended versioning is good at describing the history involving several entities. Temporal successive relationships are explicitly recorded using extended versioning in this approach. Using a different versioning mechanism, Chen and Le (1996) proposed another approach for land information systems. Conceptually, these two approaches are similar. With them, the history of features can be tracked by following the backward or forward pointers, and the world status at a given time can be accessed by retrieving features valid at that time.

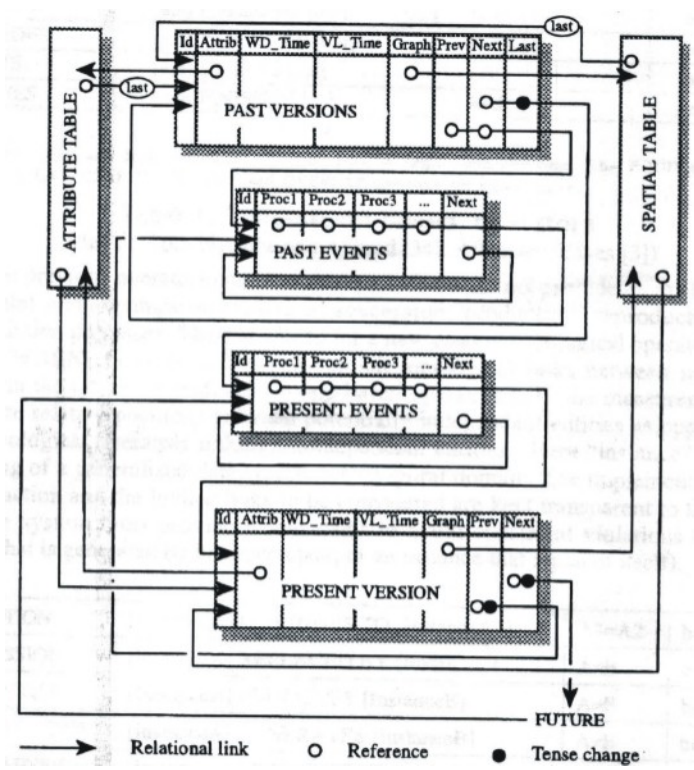


Figure 2.5 Extended version management (Claramunt and Thériault, 1995).

Peuquet and Duan (1995) developed an event-based spatio-temporal data model for raster data (Figure 2.6). They also called their approach a time-based data model. Actually, the snapshots and base state with amendments approach are all based on time. Conceptually, this model is an implementation of base state with amendments. The original framework of base state with amendments is implemented by explicitly representing the temporal successive relationships using backward and forward pointers, and the amendments are realized by change components. This agrees with the opinion that explicitly ordered events are better than implicitly dated versions (Claramunt and Thériault, 1995; Wachowicz, 1999). This framework is implemented in the temporal GIS data management system called TEMPEST, which is applied in the Apoala project and is claimed to have extremely fast access to data (GeoVISTA, 2003).

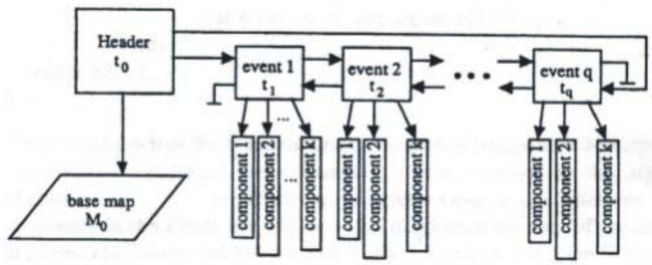


Figure 2.6 Event-based spatio-temporal data model (Peuquet and Duan, 1995).

Chen and Jiang (1998) proposed another event-based spatio-temporal data model for vector cadastral data (Figure 2.7). Several particular events relating to cadastral application are identified and modeled in this approach. There are temporal succession relationships between these predefined events.

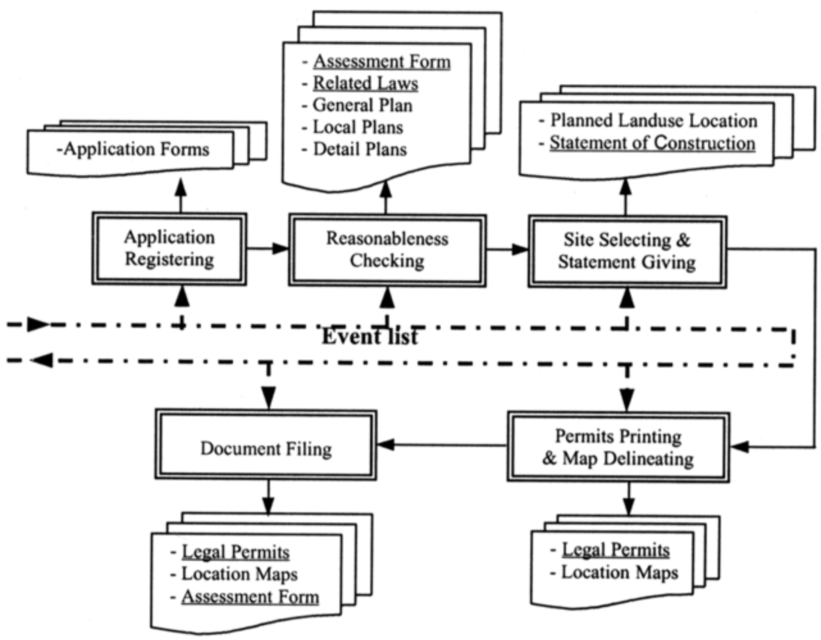


Figure 2.7 Event flow (Chen and Jiang, 1998).

2.3.1.6 Object-, feature-, entity-, identity-, process-, or activity-based approaches

A feature is an entity in the real world and an object in the information system (Tang *et al*, 1996). Object-oriented (Wachowicz, 1999; SAIF, 2003), feature-based (Tang *et al*, 1996; Usery, 1996), entity-based (Peuquet, 1999), identity-based (Hornsby and Egenhofer, 2000), process-based (Yuan, 1997), and activity-based (Wang and Cheng, 2001) approaches are all conceptually similar. All of them treat an identifiable object, feature, entity, process, or activity as a base for spatio-temporal modeling. The object-oriented approach has been explored by many researchers. This type of approach, which originated in computer software, allows for a cohesive representation of time. The Spatial Architecture and Interchange Format (SAIF), an object-oriented spatio-temporal model, has been adopted as a Canadian national standard (SAIF, 2003).

Wachowicz (1999) proposed an object-oriented approach for modeling the evolvement of public boundaries. Wachowicz studied Hägerstrand's (1970) space-time paths in the space-time hyperspace. By identifying discrete spatio-temporal change in the spatio-temporal path for a public boundary, she developed a spatio-temporal data model based on space-time paths and object-orientation. Version mechanism is used to facilitate tracking of the history. A space-time path of a public boundary (Figure 2.8) defined by Wachowicz (1999) is similar to the event list in Chen and Jiang's (1998) event flow.

Usery (1996, 2000 and 2003) proposed a feature-based GIS model with three basic dimensions: space, theme, and time (Table 2.1). Each dimension has attributes and relationships. Temporal relationships, such as ‘was_a’ and ‘will_be’, are employed to represent the temporal succession relationships between features. Attributes related with changes, such as change rate and erosion speed, are also considered as temporal relationships. This approach needs to be further explored in the temporal aspect. For example, explicit version management is not mentioned, and temporal relationships between features based on location are hard to track. Also, attribute-level timestamps put forward in this model are excellent in concept, but will slow down the operation of accessing to the entire record when implemented in a traditional database system. If the data are stored in simple files, it may be worse. How can we create an index to facilitate the access speed, which is essential to a database? This approach requires a fully developed object-oriented database management system to facilitate data storage, accessing, indexing, and management. The feature-based GIS model has advantages over others because it captures all three dimensions of a feature. For example, Hägerstrand's (1970) space-time path only emphasizes the space and time dimension, and does include themes explicitly.

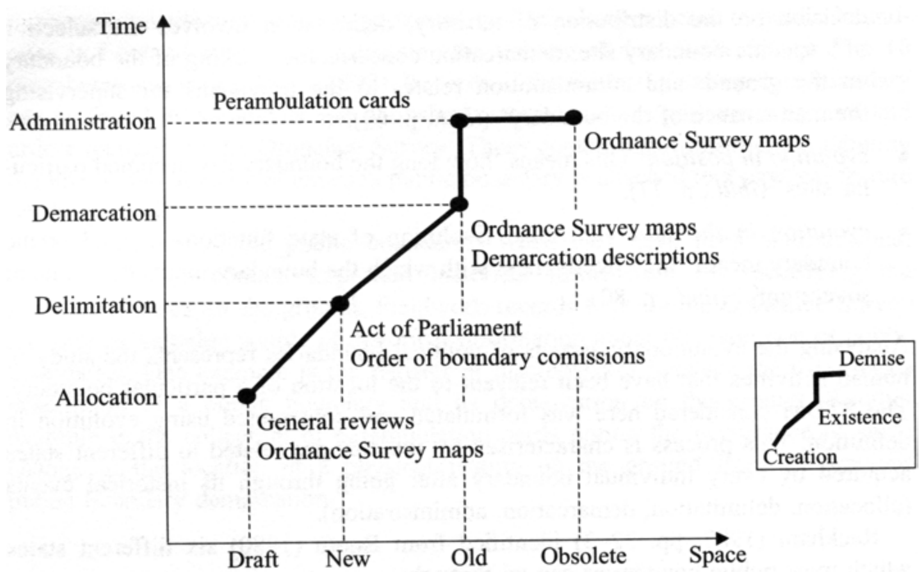


Figure 2.8 An example of space-time path of a public boundary (Wachowicz 1999).

Wang and Cheng (2001) developed a spatio-temporal approach based on transport activities of a single person (Figure 2.9). They identified three types of spatio-temporal behavior: continuous, discrete, and stepwise, and two types of activities that a person interacts with locations: ‘stay at’ and ‘travel between’. These activities are treated like an object in the spatio-temporal approach. An extended-entity-relationship diagram is employed to represent the conceptual framework of the hierarchical relationships in the activity-based transport data model. Wang and Cheng stated this specific approach could answer time-, person-, activity-, and location-based questions.

Table 2.1 Feature-based GIS conceptual model (Usery, 1996).

	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 ...

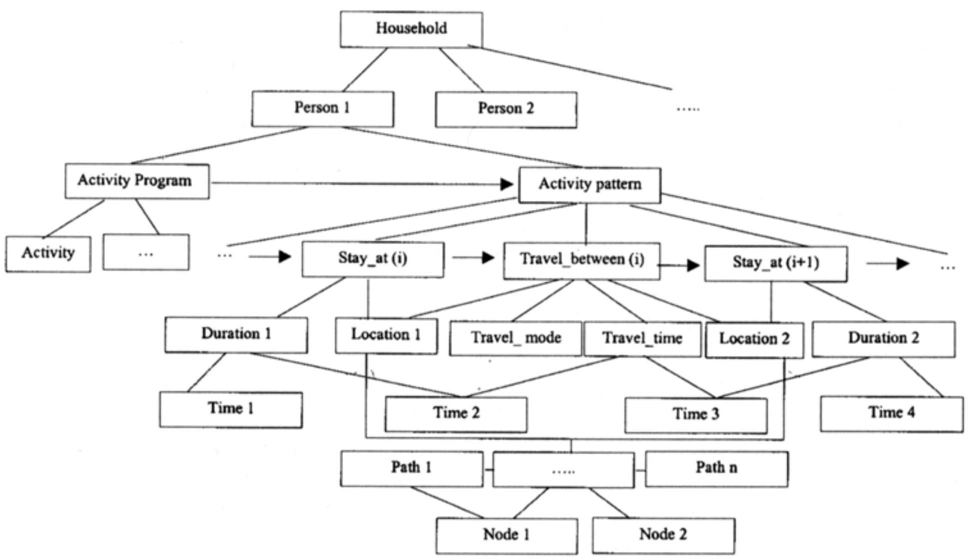


Figure 2.9 Activity-based transport modeling (Wang and Cheng, 2001).

Hornsby and Egenhofer (2000) developed a spatio-temporal approach based on the object identity, which is distinct from an object's properties. Change rather than world status is modeled using a change description language. In fact, the idea of object identity is implicitly applied in other spatio-temporal approaches. For example, each feature in Usery's (1996) feature model has a unique feature identifier.

2.3.1.7 Combined / integrated approaches

Most of the approaches discussed above are location- or feature-based, and are efficient in answering only location-based or feature-based spatio-temporal questions. A location-based framework is good at tracking histories at one location or sets of locations, while feature-based schemata allow for histories related with each feature. In reality, a spatio-temporal data model is required to provide temporal information from multiple perspectives (Peuquet, 1994, 1999; Yuan, 1999). For example, the activity-based approach proposed by Wang and Cheng (2001) can provide time-, person-, activity-, location-based views.

Peuquet (1988) proposed a Dual framework with both location-based and object-based representations. Based on the Dual framework, Peuquet (1994) developed the Triad (Figure 2.10), a framework with three representations: object-, location-, and time-based view. These three representations are important to efficiently solve ‘what’, ‘where’, and ‘when’ questions, which correspond to 'themes', 'space', and 'time', respectively. Galton (2001, p.184) argued "the Triad framework of Peuquet is more purely schematic and cannot avoid unacceptable duplication of information in implementation".

Koncz and Adams (2002) presented a data model for a transportation application, called the multi-dimensional location referencing system (MDLRS) (Figure 2.11). The MDLRS data model provides four representations for ‘what’, ‘where’, ‘when’, and ‘how’ questions.

2.3.1.8 Event-oriented approaches

Worboys (2005) identified four stages: static, snapshots, object change, and event and action, in the development of spatio-temporal modeling. Following the ontological distinction between continuant and occurrent entities (Galton, 2004; Grenon and Smith, 2004), Worboys drew the 'things'-'happenings' distinction in space-time and argued that 'happenings' are as important as 'things'. In his event-oriented approaches, 'happenings' are represented as events.

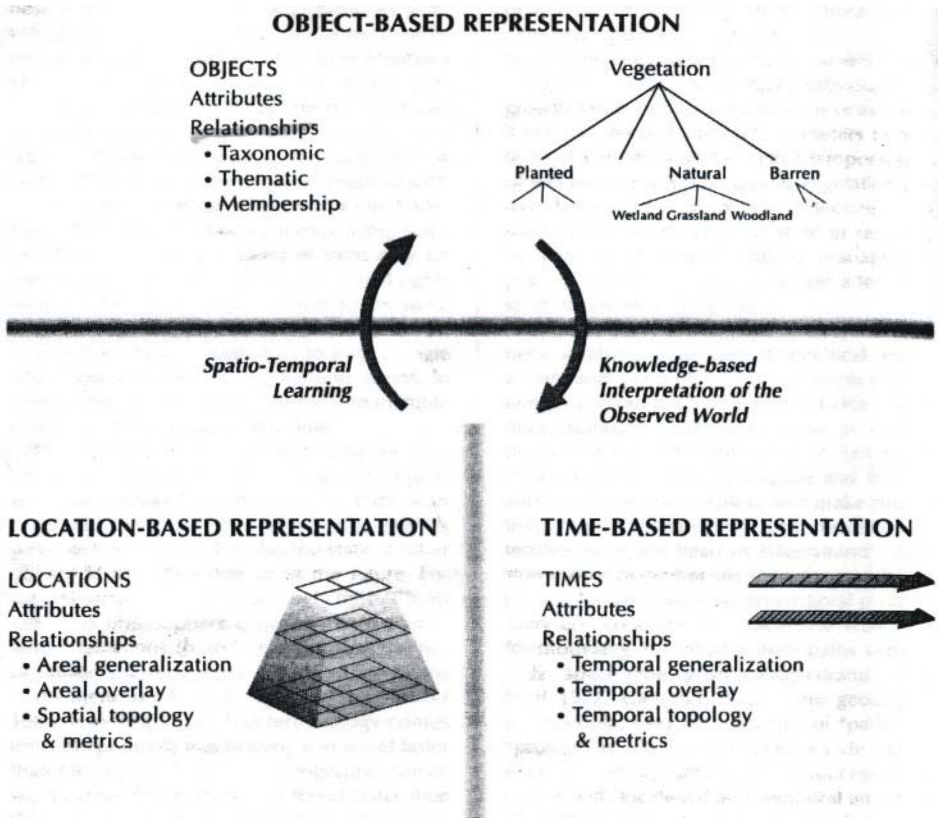


Figure 2.10 The Triad representational framework (Peuquet, 1994).

Although the event-oriented approach sounds like event-based models, it is closer to process-based approaches in nature. Worboys' (2005, p. 19) approach is good at spatio-temporal reasoning and appropriate for clear-defined processes or activities, such as a vehicle's motion—"brake the vehicle, then it slows down and stops". However, it is difficult to figure out specific events in the geographic reality. For example, a land parcel changes from agriculture to urban. Why does it happen and how does one define the events? There are so many possible reasons that it is difficult to give a simple reason like the vehicle's motion. In another example, from two maps of the same location in 1980 and 2000, one reads: 1) there is a county, 2) its boundary is bigger in 2000, and 3) its name is changed. What users learn from the maps is about a county, an entity in reality, which has different space and different attributes at different times.

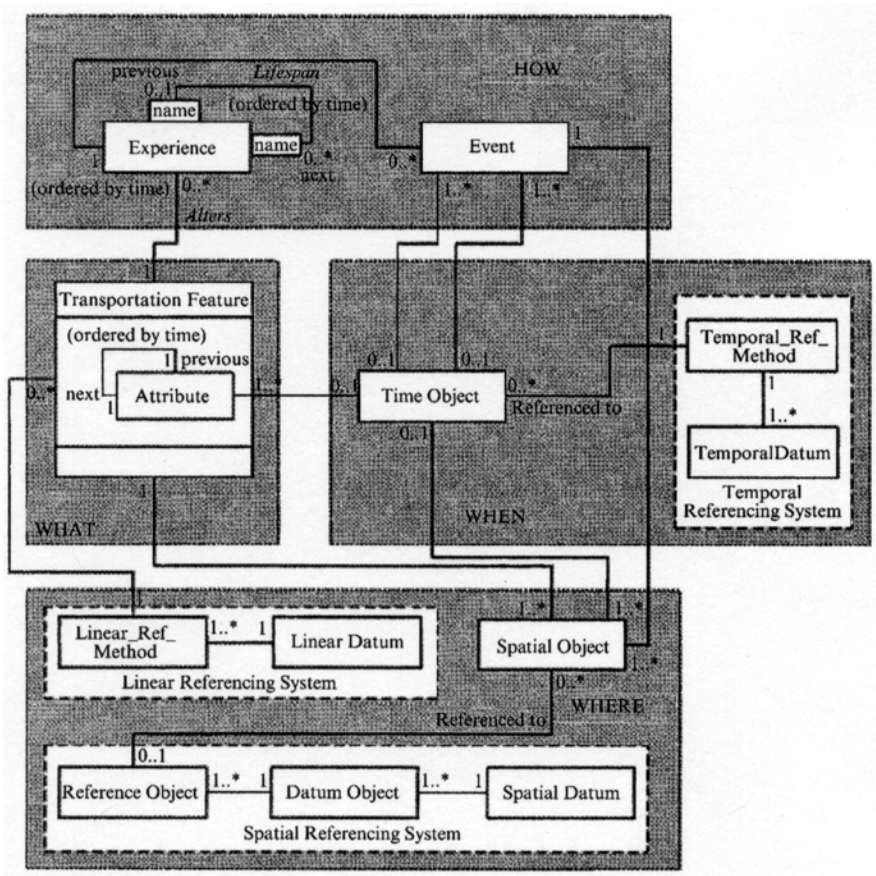


Figure 2.11 Conceptual framework for MDRLS data model (Koncz and Adams, 2001).

2.3.1.9 Other approaches

Dragicevic and Marceau (2000) proposed to model time using a fuzzy set approach. Temporal interpolation is performed using fuzzy membership, which is derived between two consecutive snapshots. This approach is good for areas undergoing continuous and dynamic changes, including atmosphere, vegetation, and rural urban environment.

Table 2.2 lists spatio-temporal models described above. The names of models are given by the developer, and there is no rule for naming. Most approaches are based on a single data model and for spatial data in either field- or object-form. Although some approaches can be used for both fields and objects, they are not suitable for both, and are usually implemented differently for fields and objects. For example, base state with amendments (Figure 2.4) has distinct implementations for fields and objects and is better for fields than objects.

In reality, some applications cannot be represented using a single approach, and many applications use both fields and objects. Therefore, multiple approaches may be employed for a single application or system based on the spatial data, characteristics of the time, types of spatio-temporal changes, and the problem being posed on the system. For example, four data models are developed to represent the wildfire lifecycle (Yuan, 1997) (Figure 2.12). Among these four conceptual data models, three are supported by current GIS. They are location-based snapshots for raster data, entity-based snapshots for vector data, and fire mosaics for vector data. The fourth conceptual model, the layer-based model for wildfire is inadequately supported. Therefore, a fire is treated as a feature, and a data model based on fire is proposed. With these four conceptual models, the lifecycle of wildfire is modeled by the information cycle. Since four conceptual data models are different in spatial and temporal resolutions, data of one model must be spatially and temporally aggregated and disaggregated before they are used in another model. Although Yuan employed four models for both raster and vector data, those models do not work together but one by one in the wildfire lifecycle. Another difference between Yuan's study and others' is that a wildfire is a continuously moving entity in a space-time hyperspace, and is much more difficult to represent. Because of the complexity in modeling a dynamic process, it is recognized as one of the four medium-term research objectives by UCGIS (Yuan *et al,* 2004).

Table 2.2 Spatio-temporal models

Model		Applicable to			
Name	Developed by	Fields	Objects	Particular applications	Continuous change
space-time cube	Thrift (1977)	√	√		√
sequential snapshots		√	√		
space-time paths	Hägerstand (1970)	√	√		√
space-time paths	Kwon *et al* (2003)		√	transportation	
base state with amendments	Langran (1992)	√	√		
space-time composite	Chrisman and Langran (1988)	√	√		
event-based	Chen and Jiang (1998)		√	cadastre	
event-based	Peuquet and Duan (1995)	√			
event-oriented	Claramunt and Thériault (1995)		√	cadastre	
process-based	Yuan (1997)	√	√	wildfire	√
object-oriented	Wachowicz (1999), SAIF (2003)		√	boundary	
feature-based	Usery (1996), Tang *et al* (1996)	√	√		
identity-based	Hornsby and Egenhofer (2000)		√		
activity-based	Wang and Cheng (2001)		√	transportation	
the Dual framework	Peuquet (1988)	√	√		
the Triad framework	Peuquet (1994)	√	√		
multi-dimensional transportation	Koncz and Adams (2002)		√	transportation	
a fuzzy set approach	Dragicevic and Marceau (2000)	√			√
event-oriented	Worboys (2005)		√		√

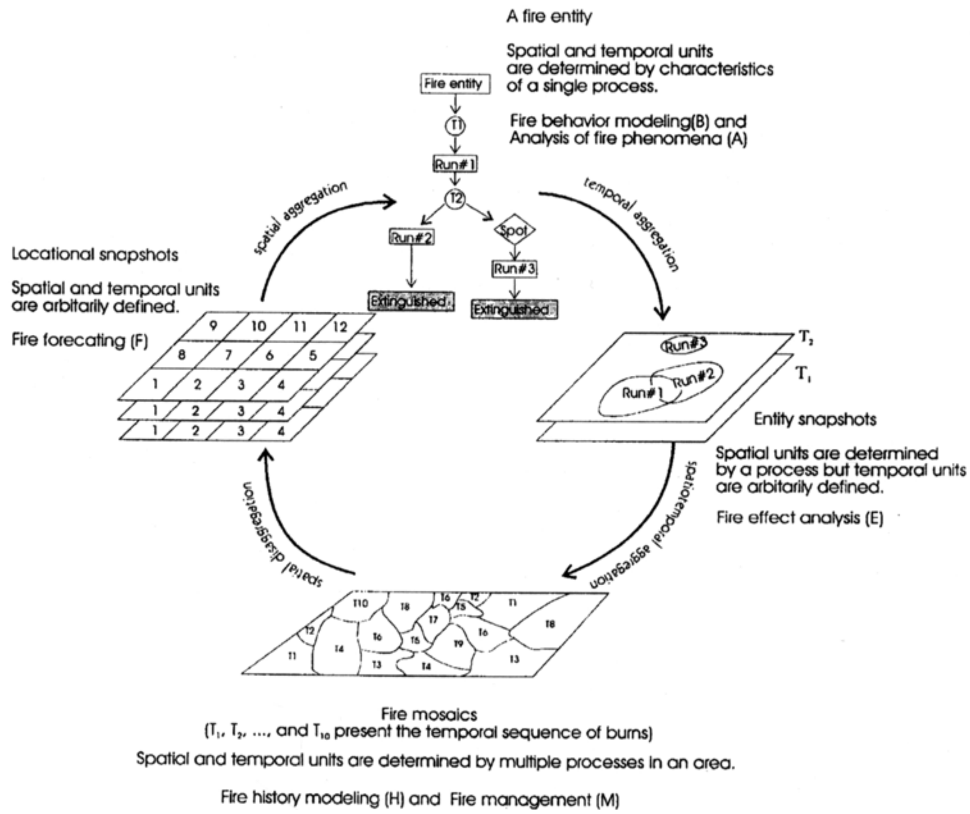


Figure 2.12 Four representations in a wildfire's lifecycle (Yuan, 1997).

2.3.2 Spatio-temporal query

Spatio-temporal data models determine the way and efficiency that the data are accessed and manipulated. For approaches, which model world status such as snapshots, it is straightforward to retrieve the world status, but difficult to query changes. For approaches modeling changes such as base state with amendments, it is easier to retrieve changes than world status. For feature-based approaches, the history of single feature is much easier to access than the history on one location. For location-based frameworks, it is straightforward to track the history on the same location. For combined or integrated approaches, such as the Triad framework, it is efficient to retrieve histories based on location, feature, and time. Therefore, the combined or integrated approaches are more flexible than others in data access. Of course, integrated approaches are more complex and require more storage space compared to others.

In GIScience, various studies on spatio-temporal query have been completed (Langran, 1992; Worboys, 1994; Claramunt and Thériault, 1995). Actually, temporal relationships and spatio-temporal topology (Peuquet, 1994, 1999; Muller, 2002) have been examined more than the spatio-temporal query language. To increase the speed of spatio-temporal query, indexing, partitioning, and other mechanisms are required (Langran, 1992; Claramunt and Thériault, 1995, Peuquet 1995). Based on a unified spatio-bi-temporal model, Worboys (1994) classified possible spatio-temporal operations including equality, subset, spatio-temporal projection, spatial selection, and temporal selections. Oosterom *et al* (2002) developed a generic query tool for spatio-temporal data, and employed four database views: thematic, temporal, spatial, and aggregate for easy querying.

2.3.3 Visualization of spatio-temporal information

Spatio-temporal query, visualization, and analysis are closely related. Visualization and analysis use the results from query as input data. Geographic visualization (GVis) may provide a three-dimensional and temporal view unlike static graphics or maps. GVis can be used for both communication and exploration (MacEachren, 1995). Peuquet (1994) argued there are three methods for spatio-temporal analyses: qualitative, quantitative, and visual. She also argued that spatio-temporal data retrieval is a fundamental form of spatio-temporal qualitative analysis. To Yuan (1997), temporal query and analysis included: change rate or frequency, life expectancy, and temporal relations. In GVis, spatio-temporal resolution and scale are important, and visualization with different spatio-temporal resolution or granularity can be quite different.

Analysis of spatio-temporal processes is very useful for urban dynamics research. Advanced visualization techniques, such as time animation or time as a third dimension, can facilitate spatio-temporal analysis (Oosterom *et al*, 2002). By animating change of specific modeling parameters, significant spatio-temporal change patterns can be explored, and the human-environment interrelationships such as urban growth can be discovered.

In the Apoala project (GeoVISTA, 2003), linear and cyclical interaction tools are combined in the graphic interface to facilitate locating and understanding the time dimension (Figure 2.13). The study by Edsall *et al* (1997) showed there was no significant difference in performance and efficiency between three legend types: ‘text’, linear, and cyclical.

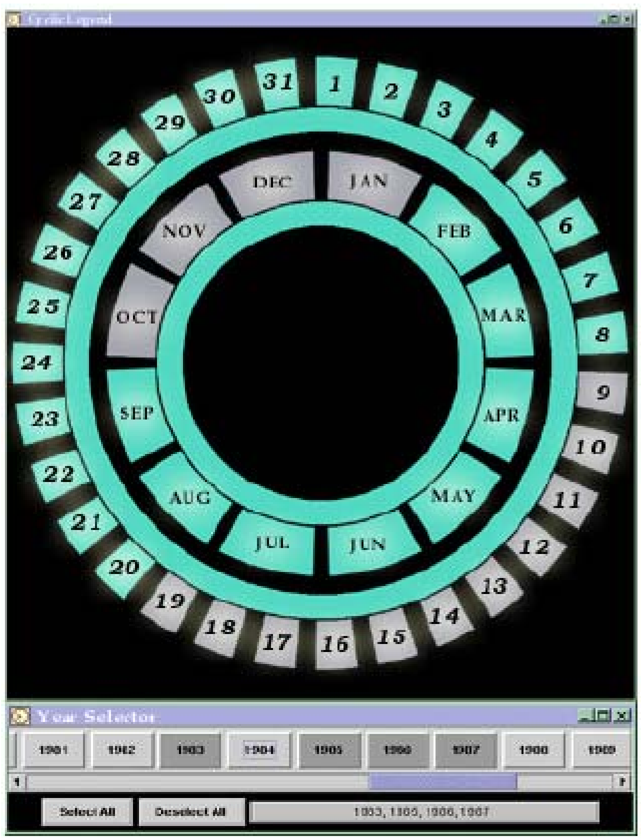


Figure 2.13 Cyclical and linear temporal query tool (Brewer *et al*, 2000).

Kwan *et al* (2003) uses a space-time prism to visualize the space-time accessibility of a person in a space-time cube. Any position in the prism is a possible spatio-temporal location that the person can reach. The space-time paths of a person and its prism can be used for modeling transport demands based on individual activity.

2.3.4 Temporal GIS

So far, the most used temporal systems are still the traditional GIS, which are static in nature. Existing GIS can only work with spatio-temporal data represented in layer-based approaches, including sequential snapshots and changed-based models. For example, the national historical geographic information system (NHGIS, 2005) represents spatio-temporal census boundaries with sequential snapshots and can be accessed using existing systems.

In order to visualize spatio-temporal data, the person who proposes a spatio-temporal approach usually has to develop a temporal system to work with that specific model (Wachowicz 1999; Koncz and Adams 2002). For example, TEMPEST is developed for the event-based model of Peuquet and Duan (1995). As a result, although certain GIS with temporal capabilities have been introduced for specific data models, they can only work with data represented in that model. In reality, it is frequently required to work with spatio-temporal data represented in different data models together. For example, temporal data of transportation, population, and land use are required for post-analysis of the planning of a highway, and these data may be represented in different data models.

2.3.5 Scale problem and inexactness

There is a scale problem with time as well as space. For example, Wang and Cheng (2001) assumed that an individual had an activity pattern on a daily base. At the temporal scale of hours, the person is at different locations at certain times. But at the temporal scale of days, we may say the person is always at home every night. If the temporal scale is 100 years, maybe the person will never exist or just appear once or twice in the database. The person does not change in real world. What changes is the temporal scale that we use to represent and view the real world in the information system. Peuquet (1994) argued that the ideal temporal scale and resolution depended upon the specific phenomenon under observation and the problem posed about it.

Another problem with time is inexactness or uncertainty. This may result from the scale problem with the spatial dimension if the old database has much lower or higher spatial resolution than the current imagery. Inexactness may also result from errors existing in the database. The question is how to distinguish these two types of inexactness from changes.

2.4 Spatio-temporal database in computer science

Along with research in GIScience, time is also studied in computer science, especially database, and cognitive science. The database community is interested in spatio-temporal models, as well as access methods and implementations (Koubarakis and Sellis, 2003). Medak (1999) described a features' life using its lifestyles. With spatio-temporal constraints, Tryfona *et al* (2003) extended the entity-relationship (E/R) model and the unified modeling language (UML). An E/R model is an abstract representation of the structure of a database using entity sets, attributes and relationships. The UML defines a standard notation for describing object-oriented models (Gomma, 2005). Güting *et al* (2003) and Grumbach *et al* (2003) proposed to model spatio-temporal data based on data types and constraints, respectively. These data models are at an abstract level (Güting *et al*, 2003) and therefore do not capture the appropriate ontological commitment for time in base geographic date. Erwig *et al* (1999) proposed to model temporal objects with abstract data type (ADT), and argued that the ADT approach is more versatile and more controllable than the traditional flat view. An ADT contains two parts: 1) one or more domains and 2) mathematical operations defined on elements from the domains (Lewis and Denenberg, 1991). An ADT is neither a data structure nor a data type. When it is implemented in a particular language such as Oracle, the domains can be data types.

Temporal query for non-spatial database has been studied in the domain of computer science. The temporal structured query language 2 (TSQL2) is extended from SQL-92 by Jensen *et al* (1995). Much research has been focused on temporal databases, including temporal topology, query language, and indexing (Sellis, 1999; Tensen and Snodgrass, 1996, 1999; Date *et al*, 2003). Allen (1984) identified seven types of temporal topological relationships between two interval times: before, equal, meet, overlap, during, start, and end.

In non-spatial temporal databases, there are two ways to incorporate time into traditional static database. One is using an object-oriented database, another is extending the relational database. Temporal information is added as timestamps. In an extended relational database, timestamps can be added at table-, record-, or attribute-level. Conceptually, timestamp at table-level is straightforward, but has much redundancy. Timestamp at attribute-level has minimal redundancy, but it takes time to retrieve all attributes for one feature.

Currently, there are three ways to manage slowly changing attributes in a commercial database (Kimball Group, 2000; Chuo-Han Lee, 2005). In type 1 dimension, a record is simply updated and the original data are lost. In type 2 dimension, a new record is added to the table and both the original and the new data are present. In type 3 dimension, two more columns are added, one for the new data and another for the change time. However, Type 3 dimension cannot hold all historical information. If the attributes change more than once, only the last two versions of the attribute values, the current and the one before the current are kept in the table. For example,

Table 2.3 presents a person--Jason, who lived in Georgia before 1995, then moved to California, and finally settled down in Washington in 2003.

Table 2.3 An example of type 1, 2 and 3 slowly changing dimensions.

a) Original table, 1990

ID	Name	State
100	Jason	Georgia

b) In type 1 dimension, 2003

ID	Name	State
100	Jason	Washington

c) In type 2 dimension, 2003

ID	Name	State
100	Jason	Georgia
101	Jason	California
102	Jason	Washington

d) In type 3 dimension, 2003

ID	Name	Original state	Current state	Change time
100	Jason	California	Washington	2003

2.5 Space and time in cognitive science

In cognitive science, there is a growing body of literature working on spatio-temporal information (Galton, 2001; Frank, 2003; Grenon and Smith, 2004). Galton (2003, 2004) identified key desiderata for a spatio-temporal ontology, and discussed the distinction between field- and object-based approaches to space, time and space-time. Grenon and Smith (2004) argued dynamic spatial ontology should combine a purely spatial ontology and a purely spatio-temporal ontology. These studies are helpful to the research of time in GIScience. For example, Worboys (2005) proposed event-oriented approaches based on the ontological distinction between continuant and occurrent entities.

2.6 Summary

This chapter reviews the development of temporal GIS modeling during the last decade. With the development in relating technologies, progress has been made in temporal GIS modeling. This chapter describes various spatio-temporal approaches. Former research shows explicitly ordered events are better than implicitly dated versions (Claramunt and Thériault, 1995; Peuquet and Duan, 1995; Cheng and Le, 1996). Because of the complexity of spatio-temporal data, these approaches represent certain types of time, model world status or change, are based on location or feature, and are designed for raster or vector data. Most approaches are proposed for specific application such as a cadastral application. One trend in temporal GIS modeling is multi-view within a single framework. Using location-, time-, and object-based temporal information accommodates complex spatio-temporal analysis and provides answers to 'what', 'when', and 'where' questions. However, there exist redundancies in these multi-view approaches. Another trend is representing continuous spatio-temporal changes, such as a dynamic process, but it is relatively difficult.

Spatio-temporal query and visualization are largely determined by the temporal GIS model. Several technologies, including indexing and separating the current state from history, should be employed to increase the speed of data access. Spatio-temporal visualization is useful to communicating and exploring spatio-temporal information. Scale issues and inexactness in time are discussed.

Although temporal GIS has been researched from different perspectives, including cartography, data model and spatial database, and various conceptual models have been designed during the last decade, no temporal framework except the layer-based approach has been adopted in exisiting GIS (Hornsby and Egenhofer, 2000) and no commercial temporal GIS is available now to handle spatio-temporal information easily. Time is particularly hard to model in GIS when there are multiple time concepts (Frank, 1998; Hornsby and Egenhofer, 2000), complex spatio-temporal topology (Claramunt and Thériault, 1995), multiple temporal scales or resolutions, and different types of spatial data. To incorporate time in GIS, we must take into account the type of spatial data, properties of time, and spatio-temporal change type and rate. That is to say, the best approach for different spatio-temporal data may be distinct. This will bring about difficulties and diversities to temporal GIS. Actually, this situation is also true for spatial data. Some phenomena are best represented in raster format, while others are best modeled as vector data. Currently, most GIS can handle both vector and raster data. If we determine the best approaches for different types of spatio-temporal data, then we would expect a comprehensive temporal GIS to store, query, analyze, and visualize different types of spatio-temporal data.

In addition to research on time in GIScience, spatio-temporal modeling and query are studied in cognitive and computer Science. Research on cognitive science can provide ontological support to GIScience researchers, because "a representational theory that closely reflects human cognition is highly efficient and minimally complex from a computing standpoint" (Yuan *et al,* 2004, p.148). The study in computer science, especially database, provides new spatio-temporal data models, temporal query language and indexing methods, and gives support in formalization and implementation. The ADT is recognized as useful in spatio-temporal data modeling (Erwig *et al,* 1999).

CHAPTER 3

REPRESENTING TIME IN BASE GEOGRAPHIC DATA WITH DIFFERENT APPROACHES[1]

[1] Le, Y. and E.L. Usery. To be submitted to *International Journal of Geographic Information Science*.

Abstract: This paper proposes to represent time in base geographic data such as boundary, land cover, elevation and transportation, with different approaches. First, we study the characteristics of time and spatio-temporal changes in base geographic data. Next, we explain why we do not represent time with a single framework, but different ones. This is followed by an introduction of three spatio-temporal models for base geographic data. Then we discuss temporal query capabilities to support the integration of multiple models based on snapshots at instants. Finally, we address implementation issues related with different spatio-temporal representations.

Keywords: Representation, Time, Base geographic data

3.1 Introduction

Temporal information is useful for better understanding of geographic phenomena or human-environment interaction, such as transportation analysis, urban sprawl and disease spread. This paper presents a study of representation of time in base geographic data. Here, "base geographic data" refers to geographic data that are used commonly in geographic information system (GIS) applications. Base geographic data are major components of the National Spatial Data Infrastructure, GIS data clearinghouses, and topographic maps. Since base geographic data are frequently used in many applications, they are usually maintained by government agencies or organizations and made available to the public in the U.S. Realizing the importance of time in base geographic data, the U.S. Geological Survey (USGS) proposed to provide a temporal dimension in *The National Map—Topographic Mapping for the 21st Century* (USGS, 2001). This paper focuses on time in base geographic data, not physical phenomena such as storms or personal activities on daily schedule.

Currently, there exist two major spatial representations, object and field, and a single temporal representation, layer-based, in base geographic data. However, the traditional layer-based temporal framework is insufficient for representing temporal information, because only snapshots or changes are represented in a layer-based schema (Langran, 1992; Worboys, 1994; Hornsby and Egenhofer, 2000).

Because of the complexity of spatio-temporal data and the specific purpose of a single application, most temporal representations proposed so far are designed for either objects or fields, and usually for one particular application, such as cadastre (Al-Taha, 1992; Chen and Le, 1996), wildfire (Yuan, 1997), atmosphere (Peuquet, 1994, 2002), public boundaries (Wachowicz, 1999), transportation management (Koncz and Adams, 2002), or transportation planning (Frihida *et al*, 2002). Since base geographic data are spatially represented in different forms and should be used in different GIS applications, it is still a research challenge to determine appropriate representation of time for base geographic data (McMaster and Usery, 2004; UCGIS, 2004).

Along with research in GIScience, time is also studied in computer science, especially database, and cognitive science. The database community is interested in spatio-temporal models, as well as access methods and implementations (Koubarakis and Sellis, 2003). Medak (1999) described a features' life using its lifestyles. With spatio-temporal constraints, Tryfona *et al* (2003) extended the entity-relationship (E/R) model and the unified modeling language (UML). An E/R model is an abstract representation of the structure of a database using entity sets, attributes and relationships. The UML defines a standard notation for describing object-oriented models (Gomma, 2005). Güting *et al* (2003) and Grumbach *et al* (2003) proposed to model spatio-temporal data based on data types and constraints, respectively. These data models are at an abstract level (Güting *et al*, 2003) and therefore do not capture the appropriate ontological commitment for time in base geographic data.

In cognitive science, there is a growing body of literature working on spatio-temporal information (Galton, 2001; Frank, 2003; Grenon and Smith, 2004). Galton (2003, 2004) identified key desiderata for a spatio-temporal ontology, and discussed the distinction between field- and object-based approaches to space, time and space-time. Grenon and Smith (2004) argued dynamic spatial ontology should combine a purely spatial ontology and a purely spatio-temporal ontology. These studies are helpful to the research of time in GIScience. For example, Worboys (2005) proposed event-oriented approaches based on the ontological distinction between continuant and occurrent entities.

This paper suggests representation of time in base geographic data with different approaches, rather than a single framework. The feature-based temporal model is proposed for objects, and the layer-based model for fields. The layer-based approach can be further divided into sequential snapshots and current-state-with-changes (CSC); the former models status and the latter models change. Spatio-temporal query capabilities demonstrate the power of different spatio-temporal approaches, which enable spatio-temporal analysis using both object and field data. The paper discusses implementation issues, and ends with future research needed on a temporal GIS. By providing temporal information for base geographic data, it will be easy for many GIS applications to implement spatio-temporal query, visualization, and analysis. This paper makes a contribution to move traditional static GIS toward temporal GIS.

The concept of representation can be explained at three levels: data models, formalization, and visualization (Yuan *et al*, 2004). A data model conceptualizes the real world in a computer information system (Goodchild, 1987), and constrains that which can be formalized and visualized (Yuan *et al*, 2004). This paper studies representations at the data model level. Balley *et al* (2004) and Hangouët (2004) discussed multiple-representation, which models a single feature in various ways depending on differences in viewpoint and resolution (Balley *et al*, 2004). In this paper, we are not concerned with representation of a single feature in different models, but how to optimally represent time for base geographic data.

The remainder of this paper is as follows. The next section presents the characteristics of time and spatio-temporal changes in base geographic data. Section 3.3 explains why we choose to use different representations rather than a single model. Section 3.4 briefly introduces three models of time for base geographic data. Section 3.5 discusses spatio-temporal query capability supported by these representations. Section 3.6 talks about implementation issues related with the multiple representations. Finally, section 3.7 concludes the discussion.

3.2 Characteristics of time and spatio-temporal changes in base geographic data

3.2.1 Time and spatio-temporal changes

The way people think about time in the real world is important to the way that time is represented in the computer system. There exist different concepts of time as listed below.

- Absolute vs. relative time

In Newton's absolute view, time is composed of instants and exists independently of the frame of time; while in Leibniz's relative view, objects are located relative to each other instead of a single dimensional time axis (Kern, 1983).

- Linear vs. cyclical time

In linear time, time is "a straight line stretched into past and future"; while in cyclical time, time "has no direction and events are parts of repeating cycles" (Gould 1987, p.10-12).

- Discrete vs. continuous time

Time may be measured continuously or discretely. Discrete time is measured at certain instants or intervals, while continuous time is measured always. Peuquet (1994) argued that time is continuous in essence and is divided into discrete units for the purpose of measurements.

- World vs. database time

World and database time are considered as two dimensions (Langran, 1992; Jensen *et al*, 1995; Worboys, 1998). World time means a fact is true in the real world, while database time indicates a specific phenomenon is recorded in the database. World and database time are also called valid and transaction time, respectively (Jensen *et al*, 1995; Date *et al*, 2003). Jensen and

Snodgrass (1996) argued that world time was needed if changes to the past were important, while database time was required if rollback to a previous database state was necessary. A data model that supports both world and database time is called bi-temporal (Jensen *et al*, 1995; Jensen and Snodgrass, 1996; Worboys, 1998).

- Point vs. interval time (Snodgrass, 2000)

Point time is an instant or a single moment in the time dimension, while interval time is a period of time with a starting and an ending point on the time dimension. Point time is also termed as an instant (Snodgrass, 2000). The concepts of point and interval time are similar to those of a point and an interval in space.

- Temporal granularity (Dyreson *et al*, 1995, Jensen *et al*, 1995)

Temporal granularity is the unit of measurement in the time dimension (Dyreson *et al*, 1995). For example, the temporal granularity of birthday is a day, while that of flight schedule is minutes. Dyreson *et al* (1995) stated that the mixture of different temporal granularities in a single database is common but causes problem.

- Spatio-temporal changes

Changes in both space and time dimensions have been studied by Claramunt and Thériault (1995), Peuquet (1999), Wang and Cheng (2001), and others. Wang and Cheng (2001) distinguished three types of spatio-temporal change: continuous, discrete, and stepwise. Peuquet (1999) argued that temporal duration, frequency, and pattern were important temporal characteristics. She identified four types of spatio-temporal changes: continuous, majorative, sporadic, and unique, and defined four temporal distribution patterns: steady, oscillating, random, and chaotic.

3.2.2 Characteristics of time and spatio-temporal changes in base geographic data

The main characteristic of time in base geographic data are absolute and linear, although there also exists cyclical time. For example, the shorelines change from season to season. Both discrete and continuous time exist in base geographic data. Elevation and land use/cover may evolve continuously or discretely, while census boundaries usually change discretely. In base geographic data, point time is applied for events or changes, while time interval is used for status. For example, we say land use of a parcel changes from agriculture to residential at one instant, or the land use is agriculture during the particular time interval.

For base geographic data, world time is more important than database time, but world time is not always available. For example, it is easy to get exact temporal information about the changes of a census boundary, but relatively difficult to monitor the changes occurring to other base geographic data such as land use/land cover. Usually, the temporal information obtained lags behind world time, and the time when changes are detected or collected is often used as a substitute for world time.

The temporal granularity of base geographic data is different from that of a weather forecast or flight schedule. It may be one month, one year, or even ten years. For census boundaries, granularity is ten years based on the decennial collection process. For land use/land cover, the temporal granularity may be one year or one month, or even a day when rapid changes take place. Although, *The National Map* wishes to update data in 7 days when changes take place in reality (USGS, 2001), currently the temporal granularity of most base geographic data is one to several years.

The spatio-temporal changes in base geographic data may be continuous, discrete, or stepwise. For example, changes in census boundaries are discrete, while those in roads may be stepwise since the construction of roads lasts for a period of time. Changes in elevation may be continuous, or discrete if an earthquake takes place. For simplicity of representation, all changes to base geographic data are treated as discrete in this paper. In this way, an event or change happens at one point in time and a world status is kept during a time interval.

In Figure 3.1, the geographic data have four simplified statuses: A, B, C and D, with five discrete world times: T_0, T_1… T_4. Each status is valid during a time interval. For example, status B is valid during $[T_1, T_2)$. However, with current collecting method for most base geographic data, the changes are not detected until they are collected at three times: t_0, t_1 and t_2, and only three statuses: A, C and B, are captured. We are sure status B is valid at t_1 but not at t_0 and t_2. However, it is impossible to infer the world time interval $[T_1, T_2)$ of status B just from the data collecting times. In this paper, we give each status a simplified time interval $[t_i, t_j)$ for lifetime/duration, where t_i and t_j refer to when a status is detected to appear and disappear, respectively. If changes are detected as soon as they happen, then the change detecting times will be very close to the world time and the simplified lifetime will be close to the true lifetime. *The National Map* wishes to detect change in 7 days (USGS, 2001). When it is realized, the simplification will be more reasonable.

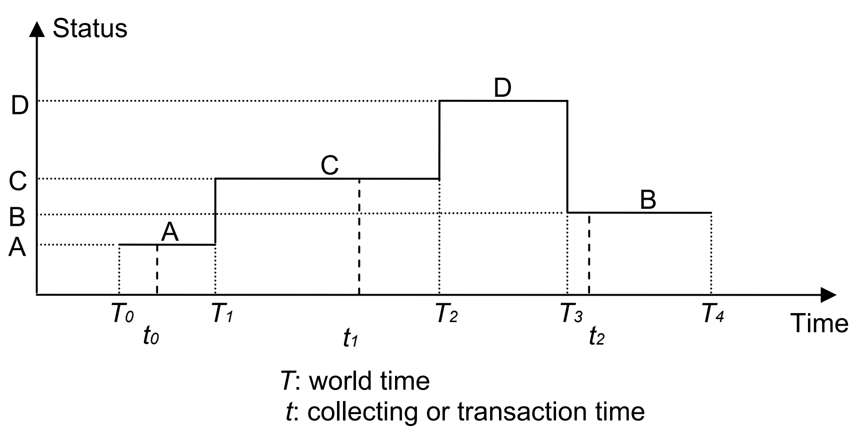


Figure 3.1 Discrete world and collecting times.

3.3 Why different approaches?

Is there a single best representation for time in base geographic data? If not, can we propose such an approach? As stated above, there are two major spatial representations in base geographic data: object and field. For example, boundary and transportation data are usually in object-form, while elevation and land cover are often in fields. In the field-object dichotomy discussed by Couclelis (1999), fields are good for variations of properties over a space, such as elevation and soil moisture and objects are good for identifiable entities, such as boundaries and roads. Although object data can covert to field-form and vise versa, some data are better represented as fields while others are better represented as objects. Because of the importance and coexistence of fields and objects, both of them are supported by existing GIS software, including ArcGIS, Imagine, Idrisi, and Intergraph. Therefore, if time is represented for base geographic data, both spatial representations should be taken into consideration. Then, the question becomes whether we can find/introduce an appropriate single approach to represent time in base geographic data in both field- and object-form.

Since initial work on temporal representation in GIS began in the early 1990's, many approaches have been developed. Among them, most are applicable to only objects or fields, and only a few use one single approach for both. For example, space-time cubes, snapshots, and base state with amendments can be employed for both fields and objects (Langran, 1992). Others including event-based (Claramunt and Thériault, 1995; Peuquet and Duan, 1995), process-based (Yuan, 1997), activity-based (Wang and Cheng, 2001), object-oriented (Wachowicz, 1999), identity-based (Hornsby and Egenhofer, 2000), integrated (Koncz and Adams, 2002) approaches, and the geospatial event model (Worboys and Hornsby, 2004), are developed for either fields or objects data, but not both.

The space-time cube is a 3-D cube representing 2-D space and 1-D time, and is difficult to implement (Langran, 1992). The layer-based approach, such as sequential snapshots is the only temporal data model currently supported by commercial GIS (Peuquet, 1999). The sequential snapshots approach has a large amount of redundancy. Base state with amendments is better than snapshots because it models changes instead of world states and therefore has less redundancy (Langran, 1992). This approach is better for location-based queries (Peuquet and Duan, 1995). To provide answers to 'what', 'where', and 'when' questions, Peuquet (1994) proposed a Triad framework capable of three views: object-, location-, and time-based. However, Galton (2001, p.184) argued "the Triad framework of Peuquet is more purely schematic and cannot avoid unacceptable duplication of information in implementation".

Based on the discussion above, there is not a single optimal model for both objects and fields. First, most temporal representations introduced so far are not applicable for both fields and objects. Second, although there are a few temporal models for both spatial representations, none are adequate for both.

Next, we do not think a single approach suitable for time in base geographic data in both field and object form is feasible. There are three basic characteristics of geographic phenomena: space, theme, and time (Berry, 1964). Spatial data in field- and object-form differ not only in space, but also in theme. In object data, space is controlled and themes vary; while in field data, theme is controlled and space varies. When time is incorporated, the situation is even more complex, and we do not think there will be such a single approach in the near future, especially when data management, query and visualization are taken into consideration.

If it is a widely accepted fact that space is represented differently in traditional static GIS, why use a single framework for spatio-temporal systems? In this paper, we suggest to employ different spatio-temporal approaches, feature- and layer-based, for base geographic data in object and field form, respectively. This idea presented by Le (2004) is similar to Galton's (2003, 2004) discussion on space and time.

3.4 Different approaches for time in base geographic data

The distinction between objects and fields does not only exist in space, but also in time and space-time. The dichotomy in time is also called continuants and events, respectively (Galton, 2004). If we combine the distinctions in space and in time, there are four options: continuous space with continuous time, continuous space with discrete time, discrete space with continuous time, and discrete space with discrete time (Table 3.1). In this paper, time and changes are regarded as discrete, so there are only two possible options, continuous space with discrete time and discrete space with discrete time. For these two combinations, we suggest employing two spatio-temporal frameworks, one for spatial data in object form and another for field form.

Table 3.1 Four options in space-time.

		Time	
		discrete	continuous
Space	objects	discrete space with discrete time	discrete space with continuous time
	fields	continuous space with discrete time	continuous space with continuous time

For each type of base geographic data, we first choose to spatially represent it as either objects or fields, and then only one temporal framework is applied to it. For example, land cover and elevations are spatially represented as fields and we use the temporal approach for fields; while transportation and boundaries are spatially represented as objects and another temporal approach is applied for them. Although each type of data may be represented in both fields and objects, we study different temporal representations for different data. Next, we briefly describe the temporal approaches introduced/chosen for time in base geographic data.

3.4.1 Feature-based temporal model for objects

The feature-based temporal model is proposed for base geographic data in object-based form. This approach is based on the feature-based model introduced by Usery (1996). In the featured-based model, a feature has three dimensions: space, theme, and time. The spatial and thematic characteristics of a feature evolve over time. Therefore, the feature is temporal, and has temporal spaces and temporal themes. In the feature-based temporal model discussed in this paper, the time dimension is incorporated into the feature and its other two dimensions, space and theme. This means a feature is a temporal feature, which may have multiple temporal spaces and multiple temporal themes during its lifespan.

In the UML conceptual framework of the feature-based temporal model (Figure 3.2), there exist temporal relationships, "Was/Became", between temporal features, between temporal spaces, and between temporal themes. Besides the temporal relationships, there also exist two other kinds of non-temporal relationships. First, there are spatial topological relationships between the temporal spaces, which coexist at certain time-periods. Second, there are other non-temporal relationships such as 'Connects To' and 'Flows To'. For example, one highway 'Connects To' another highway, or a river "Flows To" a lake or another river. These non-temporal relationships are not further discussed in this paper.

This approach is reasonable for objects, because a feature is the basic element in an object-based data model. It represents the status rather than the change of the temporal feature. In order to get the spatio-temporal changes, temporal spaces have to be compared for differences.

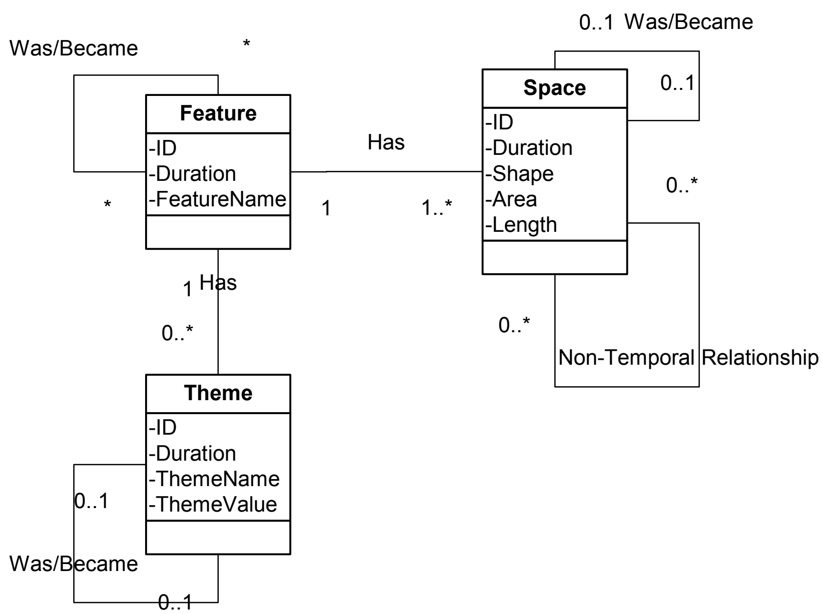


Figure 3.2 UML conceptual framework of feature-based temporal model (Le and Usery, 2005).

3.4.2 Layer-based approach for fields

Base geographic data in field form are typically extracted from aerial photographs or remotely sensed images and organized layer-by-layer, so we choose a layer-based approach for fields. A layer in this temporal representation may represent a snapshot or the change between two consecutive snapshots. Therefore, this framework can be further divided into two categories: change-based and sequential snapshots. The former is based on change, while the latter is based on snapshots. There is no strict specification for field data that should be represented in one model or the other. Our suggestion is that the change-based is better for fields without much change over space through time such as elevation, and the sequential snapshots for others, especially for thematic fields with fragmented changes such as land cover. However, there is no major difference between them and again no strict distinction.

The change-based approach is introduced in order to save database space (Langran, 1992) and is efficient in spatio-temporal query (Yuan *et al*, 2004). It is composed of one base state and a series of changes. There are some variations based on the definitions of the base state and the changes. Theoretically, the base state can be of any snapshot, but the original and the current are the most studied (Langran, 1992; Peuquet and Duan, 1995). The change may represent the old, the new, or the difference. In the following section, we briefly introduce the CSC, which uses the current state as the base and the differences as changes.

In the layer-based approach, each layer has a timestamp. Usually it refers to when the data are collected. As discussed in Section 3.2, it is difficult to get the world time for base geographic data, and the data collecting time t_i is often substituted for the world time. The lifetime/duration of each layer is simplified as $[t_i, t_{i+1})$. Although it may be over-simplified, it is the best we can model based on the current data collection method for most base geographic data.

3.4.2.1 The CSC

The CSC uses the current state and a temporal series of changes to represent the changing fields (Figure 3.3). This approach is modified from the base-state-with-amendments (Langran, 1992). We suggest CSC for field data with little change, such as elevation in order to reduce redundancy and save storage space.

In Figure 3.3, change $_i$ represents the i^{th} change between world status at time t_{i-1} and t_i. When changes occur or are detected at time t_i, historical data about the changed areas are modeled as change $_i$, and the current state is updated with the new data. Backward and forward pointers are applied to explicitly represent the temporal relationship. The pointers facilitate retrieving of temporal information.

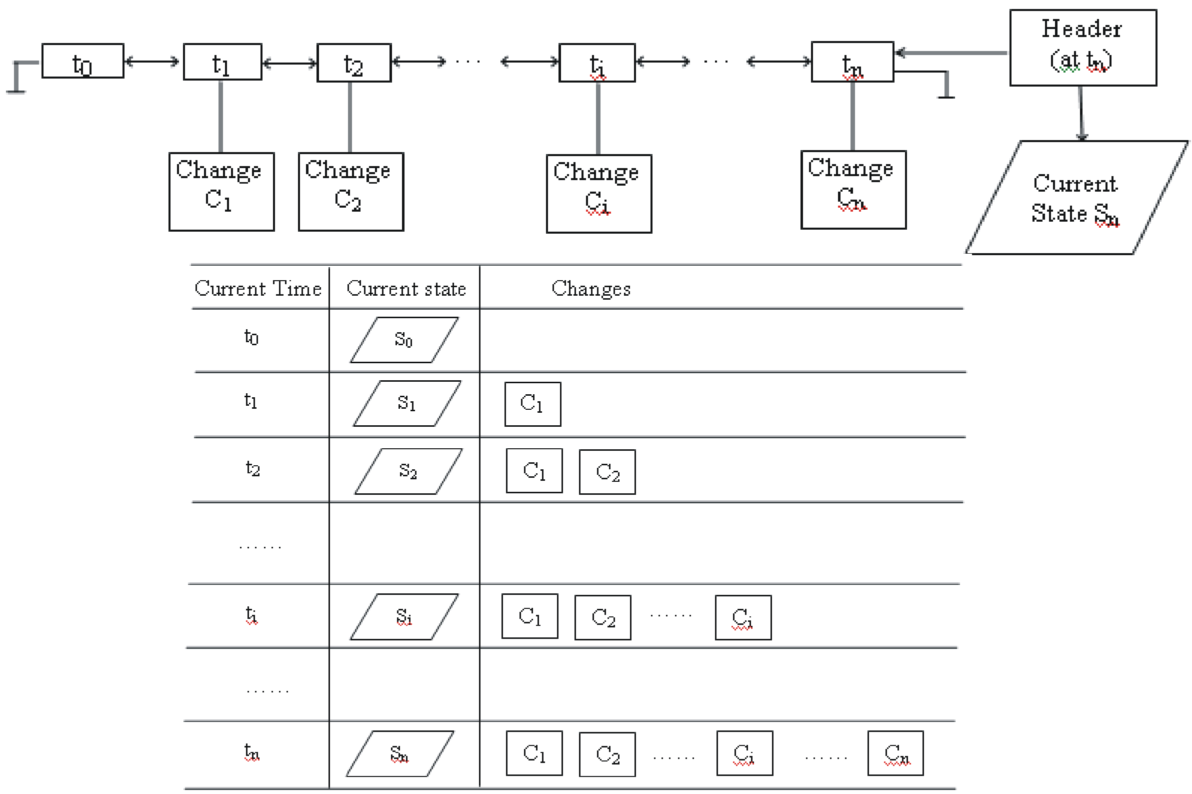


Figure 3.3 Current-state-with-changes (Le, 2005).

The CSC uses the current as the base state because people are more interested in the current than in the original and the current is frequently used in GIS applications (Ohsawa and Kim, 1999). If the original is taken for the base state, then it will be inefficient to get the current status. Of course, the base-state-with-amendments framework has advantage over CSC in animation because it is more straightforward in animating from the original snapshot and overlaying with changes layer-by-layer. If both aspects are important, we may keep both the original and the current. There is a tradeoff between storage space and efficiency in spatio-temporal query with these two approaches.

3.4.2.2 Sequential snapshots

The sequential snapshots approach (Figure 3.4) simply records world statuses at specific times, and represents spatio-temporal changes with a temporal series of snapshots $\{S_i\}$ (Langran, 1992). In addition to its original definition, we assign a simplified lifetime/duration $[t_i, t_{i+1})$ to each snapshot S_i, which means the status of base geographic data in snapshot S_i becomes true at t_i and expires at t_{i+1}. We suggest use this approach for field data experiencing great amount of fragmented changes.

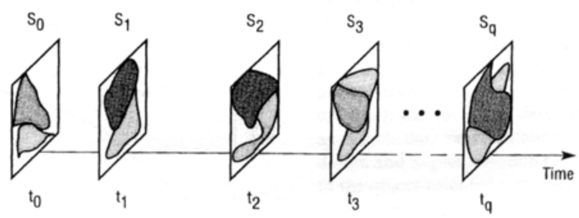


Figure 3.4 Sequential snapshots (Peuquet and Duan, 1995).

This approach was initially criticized for redundancy in modeling time (Langran, 1992). However, for certain types of data such as land cover, spatio-temporal changes do fragment space through time. In those circumstances, the change map does not absolutely save much storage space compared with the original snapshot. For thematic fields such as land cover, the class number of the change map is the square of that of the original data, and hence is much greater than the original one. For example, for land cover data with 6 classes, there are 36 (6×6=36) classes in the change map. When 30 more thematic classes are used in the change map, the fragmentation problem deteriorates. Therefore, we suggest use sequential snapshots approach for fields, especially with great amount of fragmented spatio-temporal changes.

3.5 Spatio-temporal queries supported by multiple representations

The most significant capabilities of a spatio-temporal representation arise from its ability to perform spatio-temporal queries, which are necessary for spatio-temporal analysis. Spatio-temporal data models determine the way and efficiency that spatio-temporal data are accessed. For the feature-based temporal model, it is straightforward to get the history of one feature and the world status. For the CSC, it is easy to retrieve the current state and changes. For sequential snapshots, it is straightforward to get the world status. All temporal representations discussed above provide specific temporal query capabilities for base geographic data. These temporal queries are elemental building blocks for implementing complex spatio-temporal analysis. This section will discuss four elemental temporal queries and one complex spatio-temporal analysis:

1) Retrieve a snapshot at a given point time.
2) Retrieve the history during a given time interval.
3) Retrieve the history of a feature
4) Retrieve changes during a given time interval.
5) Calculate the total area changed to urban land use within 5 miles of a highway and changed in 2 years after it was initially constructed

3.5.1 Retrieve a snapshot at a given point time

Retrieving a snapshot at a given point time is provided by all temporal representations proposed in this paper. For feature-based temporal model, this type of query is easy to conceive. We would get the snapshot at point time T by retrieving any feature valid at that time together with its space and themes also valid at time T. This query may be described using the structured query language (SQL) fragment shown below.

```
SELECT  *
FROM    CensusTract
WHERE   T DURING FeatureDuration
        AND T DURING SpaceDuration
        AND T DURING PopDuration;
```

In the SQL above, 'CensusTract' is the name of the feature table, and 'Space' and 'Pop' are its spatial and thematic dimensions, respectively. If there exits other themes, for example 'Theme$_i$' which changes not exactly simultaneous with 'Pop', then additional criteria such as 'AND T DURING Theme$_i$ Duration' will be appended in the WHERE clause. If all other themes change together with 'Pop', they will be treated as a theme group and no more criteria are required. 'DURING' is a Boolean temporal operation or function between point time data type and time interval data type. Suppose T, t_1 and t_2 are three point times and $[t_1, t_2)$ is a time interval, the operation 'T DURING $[t_1, t_2)$' returns TRUE if $t_i \leq T < t_{i+1}$. Besides 'DURING', there are other temporal operations between the point time data type and the time interval data type, or between two time interval data types, include 'BEFORE', 'AFTER', 'EQUALS', 'MEETS', 'OVERLAPS', 'STARTS', 'ENDS' (Peuquet, 1994; Claramunt and Thériault, 1995).

For CSC, the snapshot at point time T, where $t_i \leq T < t_{i+1}$, can be recovered by modifying the current state with changes at time t_n, t_{n-1} … and t_{i+1}. The order of modification in the recovery is important and must be obeyed. Since the change at time t_n, C_n, models difference or spatio-temporal change taken place at time t_n, we would get the snapshot at time t_{n-1}, S_{n-1}, which was also valid for any point time during the time interval $[t_{n-1}, t_n)$. Further modifying the snapshot S_{n-1} using change at time t_{n-1}, C_{n-1}, yields the snapshot, S_{n-1}, valid for any point time during the time interval $[t_{n-2}, t_{n-1})$. Finally, we would retrieve the snapshot, S_i, by modifying S_{i+1}, with change C_{i+1}. Since the snapshot, S_i is valid during the time interval $[t_i, t_{i+1})$ and $T \in [t_i, t_{i+1})$, S_i models the real world state at point time T.

An example of SQL below searches the right i, with $t_i \leq T < t_{i+1}$, from an Elevation table.

```
SELECT  i
FROM    Elevation
WHERE   T DURING [ti, ti+1);
```

And the following pseudo code recovers the status with the current status S_n and a temporal series of changes $\{C_j\}$.

$S \leftarrow$ Current State S_n

for j $\leftarrow$ n **to** i+1

do $S \leftarrow C_j$ overlay S

For sequential snapshots, the status at time T can be retrieved by searching for a duration $[t_i, t_{i+1})$, where $t_i \leq T < t_{i+1}$, then you can get the snapshot S_i directly. It is straightforward and easy. Here is the SQL for an example of Land Cover:

```
SELECT  Si
FROM    Land Cover
WHERE   T DURING [ti, ti+1);
```

3.5.2 Retrieve the history during a given time interval

Retrieving the history during a given time interval is relatively easy for field data represented in the layer-based approach, especially sequential snapshots. For a given time interval $[T_1, T_2]$, we first search a sub-list, $\{t_i, t_{i+1} \ldots t_j\}$, from the whole time list, $\{t_0, t_1, t_2 \ldots t_k \ldots t_n\}$, supposing $t_i \leq T_1 < t_{i+1}$, and $t_{j-1} \leq T_2 < t_j$. In case of $T_1 \leq t_0$ and $T_2 \geq t_n$, the whole list might be retrieved. If $T_2 < t_0$ or $T_1 > t_n$, then the list is blank and the history is unavailable. Next, for the sequential snapshots, we can retrieve a temporal series of snapshots, $\{S_i, S_{i+1} \ldots S_j\}$, for each point time in the sub-list using the temporal query described in section 5.1. This temporal series of snapshots tells the story of the history during that time interval. For visualization purposes, the temporal series may be examined one by one or organized into an animation.

The following SQL is an example of Land Cover represented using the sequential snapshots approach. The first two SELECT commands search the indexes i and j for the sub-list, $\{t_i, t_{i+1} \ldots t_j\}$. The last one retrieves the series of snapshots with corresponding duration/lifetimes. Since each snapshot S_k has a duration/lifetime $[t_k, t_{k+1})$, the history can be recovered by putting them together.

```
SELECT  i
FROM    Land Cover
WHERE   T1 DURING [ti, ti+1);

SELECT  j
FROM    Land Cover
WHERE   T2 DURING [tj, tj+1);
```

```
SELECT  Sk, duration/lifetime of Sk
FROM    Land Cover
WHERE   k DURING [i, j];
```

It is not straightforward to retrieve the history for the feature-based temporal model, particularly when temporal granularity is small and spatio-temporal changes are frequent during that time interval. If it is necessary to show each change during that time interval, we can follow a method similar to that for CSC described above. That means we first extract a point time list from the database corresponding to the given time interval, and then retrieve a temporal series of snapshots for each point time in the list. However, this method is time consuming when there are great amounts of change. Usually, a temporal scale and a starting time will be specified at first. For example, we will show the history using snapshots based on an interval of one year or one month, starting from 1/1/1990. With such information, the number of snapshots will be greatly reduced. For example, to show the history of roads from 1990 to 1999, we only need five point times, 1/1/1990, 1/1/1992, 1/1/1994, 1/1/1996 and 1/1/1998, with a two-year temporal scale and a starting data of 1/1/1990.

From above discussion, it is clear that this type of query is available for all temporal representations. However, it is relatively easy with the temporal model for fields. For the feature-based temporal model, specification of a temporal scale and starting time will make the query more meaningful and operable.

3.5.3 Retrieve the history of a feature

Retrieving the history of a feature is only available to the feature-based temporal model because there is no feature in temporal approaches for fields. For this question, first, we retrieve temporal spaces and themes of a feature. Next, chronologically order the temporal spaces and themes based on the starting time of their duration. Finally, show each status of the feature based on the chronological order. This query tells a story about a feature in its lifetime.

If a feature has temporal 'Was/Became' relationships with other features, we can step through different features. For example, if interstate highway A is developed from low level road B, it is easy to find road B from highway A, or vise versa, with the feature-based temporal model. Themes of road B, such as maintenance history, might be useful to future management of highway A. The capabilities to retrieve information from temporally related features would enrich the story about the feature.

3.5.4 Retrieve changes during a given time interval

Retrieving changes during a given time interval is a two-step process. Since CSC models spatio-temporal changes, it is easy to retrieve changes for a given time interval $[T_1, T_2]$. The first step is to search a sub-list, $\{t_i, t_{i+1} \ldots t_j\}$, from the whole time list, $\{t_0, t_1, t_2 \ldots t_k \ldots t_n\}$, supposing $t_i \leq T_1 < t_{i+1}$, and $t_{j-1} \leq T_2 < t_j$. This is the same as the first step in section 3.5.2. Next, retrieve the corresponding change list, $\{C_i, C_{i+1} \ldots C_j\}$. An example of SQL is shown below. The changes might be accumulated to show the overall change.

SELECT C_i

FROM Elevation

WHERE $[t_i, t_{i+1})$ OVERLAP $[T_1, T_2]$;

For the sequential snapshots approach, we first search two statuses, S_i and S_j, valid at time T_1 and T_2, respectively. This is the same as section 3.5.1. Next, overlay these two snapshots for change. An example of SQL and pseudo code is given below:

```
SELECT  Si
FROM    Land Cover
WHERE   T1 DURING [ti, ti+1);

SELECT  Sj
FROM    Land Cover
WHERE   T2 DURING [tj, tj+1);
```

$S \leftarrow S_j - S_i$

For the feature-based temporal model, which models status instead of change, it is difficult to tell the spatio-temporal changes explicitly. Change is implicitly modeled by comparing two consecutive states of a feature. For example, if a highway was constructed in two phases, it will have two temporal spaces. For that highway, the change might be expressed by comparing the lengths of two spaces, numbers of lanes, surface materials, and so on. We can answer the question, ‘How many miles of highway have been constructed during a given time interval’, by summing over differences in lengths for each highway during that period.

Retrieving changes during a given time interval is easy with layer-based temporal approach for fields, and difficult with the feature-based temporal model for objects. However, the latter might have more options because it might tell changes in space or theme dimension.

3.5.5 Calculate the total area changed to urban land use within 5 miles of a highway and changed in 2 years after it was initially constructed

Suppose the highway and land use are represented in the featured-based temporal model and sequential snapshots approach, respectively. This spatio-temporal analysis can be done with the following sequential queries.

1) Search the highway feature, and retrieve its initial space and the starting time, T, of the duration of the feature (temporal query in Section 3.5.3).
2) Create a 5-mile buffer around the initial space (spatial analysis).
3) From land use data, retrieve changes during time interval [T, T + 2 years] (temporal query in Section 3.5.4).
4) From each change map retrieved, extract those changed to urban and accumulate (thematic query and spatial analysis)
5) Overlay with the 5-mile buffer (spatial analysis)
6) Calculate the urban area

3.6 Implementation issues

3.6.1 Database issues

Database issues are an indispensable consideration to a spatio-temporal model. Since it is relatively simple to manage fields represented in the temporal layer-based approach, including sequential snapshots and CSC, this section focuses on feature-based temporal model. In Figure 3.2, a temporal feature might have multiple temporal spaces and multiple themes, and there may exist m:n temporal relationships among temporal features and 1:1 temporal relationships among temporal spaces and among temporal themes. This representation may be implemented using a traditional relational database management system (RDBMS) or an object-relational database (ORDBMS). Since a feature has multiple spaces and multiple themes, the ORDBMS database is more appropriate for this approach than the relational. This is also supported by database research (Wang *et al*, 1999; Grumbach *et al*, 2003). The ORDBMS fits the temporal representation proposed in this research very well. It provides object-oriented features including abstract data type (ADT) and inheritance. An ADT contains two parts: 1) one or more domains and 2) mathematical operations defined on elements from the domains (Lewis and Denenberg, 1991). It is neither a data structure nor a data type. When an ADT is implemented in a particular language such as Oracle, the domains can be data types. Temporal representations can take advantage of these features, especially nested tables, collection, and reference data types. For example, a user-defined data type, “Interval_objtyp” with built-in functions including ‘DURING’, ‘BEFORE’, ‘AFTER’, ‘EQUALS’, ‘MEETS’, ‘OVERLAPS’, ‘STARTS’, ‘ENDS’, can greatly facilitate temporal queries. A simple query may retrieve all information about a feature.

Although ORDBMS fits well with feature-based temporal model, there still exist some difficulties. For example, ADT is not fully supported in commercial GIS software such as ArcGIS. Currently, ArcGIS only supports one predefined ADT, SDO_GEOMETRY, in the Oracle™ database. To get around this problem, alternative solutions must be considered.

3.6.2 System issues

To efficiently work with temporal geographic data represented in multiple temporal approaches described in this paper, a temporal GIS is needed. Theoretically, the temporal GIS might be programmed from scratch or extended from a traditional GIS. On one hand, the latter is more operable because there is no need to recreate the existing functions. On the other hand, the former provides more flexibility in handling complex spatio-temporal data, especially ADT, although developing a temporal GIS from scratch means extensive work.

Since three temporal approaches are employed, the temporal GIS should have three modules, one for objects represented in a feature-based temporal model, and the other two for fields represented in the approach of CSC and sequential snapshots. Each module should have capabilities to edit, query, and visualize temporal data.

3.6.3 Scale problems and inexactness

There is a scale problem with time as well as space. For example, Wang and Cheng (2001) assumed that an individual had an activity pattern on a daily base. At the temporal scale of hours, the person is at different locations at certain times. However, at the temporal scale of days, we may say the person is always at home every night. Peuquet (1994) argued that the ideal temporal scale and resolution depended upon the specific phenomenon under observation and the problem posed about it.

Another problem with time is inexactness or uncertainty. It may result from the scale problem with the spatial dimension if the old database has a much lower or higher spatial resolution than the current imagery. This is called modifiable area unit problem (MAUP). MAUP is a potential source of error for geographic studies which use aggregated data. Geographic data are often aggregated into different scale units, which are often arbitrary in nature, and suffer from MAUP. For example, aggregate a 30 m land use/land cover data to 90 m, the percentage of each type of land use/land cover can be different. Inexactness may also result from errors existing in the database. The question is how to distinguish these two types of inexactness from changes.

3.7 Conclusions

Based on the characteristics of time and spatio-temporal changes in base geographic data, this paper simplifies time and spatio-changes as discrete for base geographic data. Since there are different spatial representations in traditional static GIS, we argue time does not have to be represented using a single framework, but maybe different approaches. According to the object-field-dichotomy, we recognize two combinations for time in base geographic data: continuous space with discrete time and discrete space with discrete time. We suggest a feature-based temporal model for the latter, and two other approaches for the former.

In the feature-based temporal model for objects, we represent time using different states of a feature. In this model, a feature is a temporal feature, which may have multiple temporal spaces and multiple temporal themes during its lifespan. There exist “Was/Became” temporal relationships between temporal features, between temporal spaces, and between temporal themes. In the CSC approach, we model time in fields using the current state and a series of spatio-temporal changes. This approach uses the current state and not the original state, as the base state. The sequential snapshots approach is recommended for fields where space is frequently fragmented through time. However, there is no strict distinction between CSC and sequential snapshots, and each field data could be represented in either way.

With these temporal models, we discuss temporal query capabilities, including four elemental temporal queries and one complex spatial-temporal analysis. Next, we address the implementation, database and system issues related to these temporal models, and the scale problem and inexactness.

In conclusion, this paper proposes to represent time in base geographic data using different approaches, and these models can provide useful temporal queries for spatio-temporal analysis. In the future, we will continue our research on this topic in several directions. First, a temporal GIS will be required to integrate different spatio-temporal approaches, because different data represented in different approaches are often used together in many GIS applications. Second, we will attempt to represent stepwise and continuous time in base geographic data. Third, visualization of spatio-temporal data is another important aspect that will be addressed.

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CHAPTER 4

A FEATURE-BASED TEMPORAL MODEL FOR BASE GEOGRAPHIC DATA IN OBJECT-FORM[2]

[2] Le, Y. and E.L. Usery. To be submitted to *Transactions in GIS*.

Abstract: This paper introduces a feature-based temporal model for base geographic data in object-form, and studies its implementation. In this temporal model, a feature is a temporal feature, which can occupy multiple temporal spaces and have multiple temporal themes during its lifespan; time is simplified as discrete and represented using different states of temporal features. There exist m:n temporal relationships between temporal features, and 1:1 temporal relationships between spaces and between themes. Next, we compare the implementation of the temporal model in relational (R), object- relational (OR), and object-oriented (OO) database, and argue the OR fits the model best. Two approaches are discussed to visualize spatio-temporal data stored in the OR schema, which is not currently supported by most geographic information systems (GIS). One is to create a flat view based on an OR table, and work with the view instead of the original OR table in GIS. Another is to develop a new temporal GIS, which can work with the OR schema directly. In the case study, status and history of temporal census tracts of Gwinnett County, GA are visualized in snapshots and animation, respectively. This paper aims to provide temporal information for base geographic data in object-form.

Keywords: Feature, Temporal, Model, Object, GIS

4.1 Introduction

The geographic environment is changing either gradually or abruptly. Geographic representation, which models the real world in the computer information systems, should also represent the changing reality. After forty years of development, geographic information science (GIScience) and technology are now successful at representing spatial information. However, temporal information is not well represented (Yuan *et al*, 2004; Worboys, 2005). When the environment changes, the most current information is collected, and the geographic database is updated with the new data. Usually, old data are simply deleted and can no longer be retrieved. This approach was cost efficient to most database owners when computers were expensive, slow, and had only small storage space. However, temporal information is useful for better understanding dynamic geographic reality and human-environment interaction. For example, spatio-temporal information is required for geographic analysis such as urban growth and disease spread over time and space. Because of the importance of time, spatio-temporal representation is recognized as a long-term research challenge by University Consortium for Geographic Information Science (McMaster and Usery, 2004; UCGIS, 2004), and the U.S. Geological Survey (USGS) (2001) proposed to provide a temporal dimension in *The National Map—Topographic Mapping for the 21st Century*. The research objective of this paper is to propose a spatio- temporal framework for base geographic data in object-form and study its implementation.

In this paper, 'base geographic data' refers to geographic data, such as elevation, land cover, and transportation, which are used commonly in many GIS applications. Since base geographic data are used so frequently in GIS applications, they are often collected by government agencies or organizations such as the USGS and Bureau of Census in the United States and shared as a part of the National Spatial Data Infrastructure (NSDI, 2004). Currently, there are two major spatial representations in base geographic data, objects and fields. Here, we focus on base geographic data in object-form, such as boundaries and transportation. In total, there are three research problems in this study: 1) how to represent time for base geographic data in object-form; 2) how to implement the temporal model in a database, or how to manage spatio-temporal data represented in this model; and 3) how to visualize the spatio-temporal data.

The remainder of this paper is as follows. We first examine characteristics of time and spatio-temporal changes in base geographic data, and review literature in spatio-temporal modeling in the remainder of this section. Next, we introduce a feature-based temporal model for base geographic data in object-form, and study its implementation in database and visualization in a temporal system. Lastly, we present a case study with census tracts of Gwinnett County, Georgia and provide conclusions.

4.1.1 Characteristics of time and spatio-temporal changes in base geographic data

For base geographic data, the main characteristics of time are absolute and linear, although there also exists cyclical time. For example, shorelines change from season to season. Both discrete and continuous time exist in base geographic data. Elevation and land use/land cover may evolve continuously or discretely, while census boundaries change discretely. An event or change takes place at a point in time, and a world status is valid during a time interval. For example, we say land use of a parcel was changed from agriculture to residential at one point in time, or the land use was agriculture during the particular time interval.

World time, the time that a fact is true in reality, is more important than database time, the time that the data are recorded in computer system, but world time is not always available. For example, it is easy to get exact temporal information about the changes of a census boundary, but relatively difficult to monitor the changes occurring to other base geographic data such as land use/land cover. Usually, the acquisition of temporal information lags behind that of world time, and the time when a change is detected is often used as a substitute for world time.

Temporal granularity of base geographic data is coarser than that of a weather forecast or flight schedule. It can be one month, one year, or even ten years. For census boundaries, granularity is ten years based on the decennial collection process. For land use/land cover, the temporal granularity can be one year or one month, or even several days when rapid changes take place.

The spatio-temporal changes in base geographic data can be continuous, discrete, or stepwise. For example, changes in census boundaries are discrete, while those in roads are stepwise since the construction of roads lasts for a period of time. Changes in elevation can be continuous, or discrete if an earthquake takes place. For simplicity of representation, all changes to base geographic data are treated as discrete in this paper. In this way, an event or change happens at one point in time and a world status is kept during a time interval. Here, we study linear world time and discrete spatio-temporal change; temporal granularity for base geographic data is not fixed, but relatively coarse such as one- or several-years.

4.1.2 Background

Hägerstrand (1970) recognized the importance of time in geography and introduced the concept of time geography. Thrift (1977) proposed time as an additional dimension to the space. Thereafter, little was done until the early 1990s (Hazelton, 1991; Kelmelis, 1991; Al-Taha, 1992). Langran's (1992) *Time in Geographic Information System* is regarded as a landmark in spatio-temporal modeling (Hornsby and Egenhofer, 2000; Peuquet, 2002). Among the various spatio-temporal approaches proposed heretofore, most of them work with either object- (Worboys, 1994; Chen and Le, 1996; Hornsby and Egenhofer, 2000) or field-data (Peuquet and Duan, 1995). Although there exist spatio-temporal frameworks for object- and field-data, such as the Triad by Peuquet (1994) and the sequential snapshots (Langran, 1992), different models are often required to optimally represent time in object- or field-data because of the complexity of spatio-temporal data (Sengupta and Yan, 2004). This is analogous to the object-field dichotomy in spatial representation (Couclelis, 1999), which means some phenomena are better represented as objects while others as fields.

Similar to the object-field dichotomy in space, there is a distinction in temporal domain: continuants and events, corresponding to continuous and discrete changes respectively (Galton, 2003 and 2004; Grennon and Smith, 2004). Although modeling dynamic processes or continuous change is identified as a research challenge by Yuan *et al* (2004), the large body of literature in GIS community studies discrete spatio-temporal changes, which is relative simple (Hornsby and Egenhofer, 2000). In the community of computer science, especially regarding database, continuous spatio-temporal change is theoretically modeled as functions of time (Erwig *et al*, 1999; Frank, 2003), but little has described how to implement such temporal function in GIS.

As we observe, there are several reasons that continuous processes are not widely studied compared to either discrete change or continuous space-fields. First, they are more complex and difficult to model than discrete change. Second, there is little data about continuants in time, but an abundance of fields in space such as remotely sensed images and their derivative products. Therefore, fields are not under-studied in space, while continuous change is in time or space-time. Weather (Peuquet, 2002) and wildfire (Yuan, 1997) are two types of continuants studied in the temporal domain, not only because they are important but also those data are available.

Third, spatial interpolation technology is mature in GIScience and enables generation of continuous surfaces based on observations at sample locations in space, while temporal interpolation is not. Moreover, current temporal granularities of base geographic data are coarse, such as several years, and bring difficulties in temporal interpolation. Therefore, this paper aims to represent simplified discrete time and spatio-temporal change for base geographic data in object-form.

Worboys (2005) proposes a pure event-oriented approach to dynamic geographic phenomena, and argues events are at higher stage or level than objects. His viewpoint may be true for certain type of geographic phenomena, such as an individual’s activities in a day, and suitable for temporal reasoning of a vehicle’s motion—"brake the vehicle, then it slows down and stops" (Worboys, 2005, p.19). However, for base geographic data, it is difficult or may be impossible to determine specific events. For example, a land parcel is changed from agriculture to urban. Why does it happen and how does one define the events? There are so many reasons and it is difficult to give a simple reason like the vehicle’s motion. Base geographic phenomena are different from that studied by Worboys. For example, reading a map produced in 1980, you understand there is a county. With another in 2000, you may find the county boundary is bigger and its name is changed. What users learn from the maps is about a county, an entity in reality, which has different spaces and different attributes at different times. Therefore, this paper represents time in base geographic data based on features/objects, not events.

A feature is an entity in the real world, and an object in the computer system (Usery, 1996). It has three basic characteristics: space, theme, and time (Berry, 1964). Usery (1996) proposed a conceptual framework of feature-based GIS (FBGIS) from region theory for both object- and field-based data. In FBGIS, space, theme, and time are three separate dimensions and each dimension has attributes and relationships. The FBGIS is at an abstract level and does not provide details for implementing the three dimensional conceptual model, especially for both spatial representations. This paper follows the direction of FBGIS by conceptualizing the spatio-temporal information based on features, but time is modeled differently from that in FBGIS and an implementation is provided.

4.2 Methodology

4.2.1 A feature-based temporal model

In the feature-based temporal model, a feature has three components, space, time, and theme, but these three components are not considered as three separate dimensions. Instead, the time dimension is incorporated into the feature and its other two components like an independent variable (Figure 4.1). Therefore, a feature is a temporal feature, and it may have multiple temporal spaces and multiple temporal themes during its lifespan. In other words, a feature and its space and theme are all functions of time (Equations 1, 2 and 3). This definition is close to the study in database (Erwig *et al*, 1999; Frank, 2003).

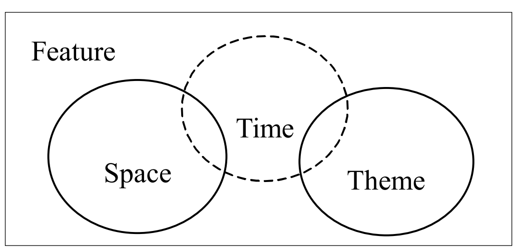


Figure 4.1 Feature and its space, time, and theme.

$$\text{Temporal feature} = f\,(\text{t}) \tag{1}$$

$$\text{Temporal space} = s\,(\text{t}) \tag{2}$$

$$\text{Temporal theme}_{\text{i}} = t_i\,(\text{t}) \tag{3}$$

In equation 3, $theme_i$ is one of the themes belonging to the feature. In this paper, time and spatio-temporal changes are simplified as discrete. Therefore, function f (t) can be simplified as below (Equation 4).

$$f(t) = \begin{cases} f_0 \ldots\ldots t \in [t_0, t_1) \\ f_1 \ldots\ldots t \in [t_1, t_2) \\ \ldots \\ f_n \ldots\ldots t \in [t_n, NOW] \end{cases} \tag{4}$$

In equation 4, f_0, f_1, and f_n are all constants, representing the status of the feature during corresponding time intervals $[t_0, t_1)$, $[t_1, t_2)$, and $[t_n$, NOW], respectively. The word 'NOW' means the feature is still valid as status f_n at the current time. Similar to f (t), functions s (t) and t (t) can be simplified as equation 5 and 6.

$$s(t) = \begin{cases} s_0 \ldots\ldots t \in [t'_0, t'_1) \\ s_1 \ldots\ldots t \in [t'_1, t'_2) \\ \ldots \\ s_m \ldots\ldots t \in [t'_m, NOW] \end{cases} \tag{5}$$

$$t_i(t) = \begin{cases} t_{i0} \ldots\ldots t \in [t''_0, t''_1) \\ t_{i1} \ldots\ldots t \in [t''_1, t''_2) \\ \ldots \\ t_{ik} \ldots\ldots t \in [t''_k, NOW] \end{cases} \tag{6}$$

The time intervals such as $[t_0, t_1)$ in equation 4 can be different from those, $[t'_0, t'_1)$ and $[t''_0, t''_1)$, in equations 5 and 6.

In the universal modeling language (UML, a standard notation for describing object-oriented models) diagram of the feature-based temporal model (Figure 4.2), a temporal feature can have one or many temporal spaces and one or many temporal themes; there exist temporal relationships, 'Was/Became', between temporal features, between temporal spaces, and between temporal themes. The difference is temporal relationships between temporal features are m:n, while those between temporal spaces and between temporal themes are 1:1. A temporal featured can be evolved from several different features or may combine with others and change into one or many new features, so the temporal relationships between temporal features are m:n. On the other hand, a temporal feature can only have one valid space at one point in time, then the temporal relationships between temporal spaces of one feature is 1:1. Otherwise, a feature may occupy two different spaces at the same time. This is also true with temporal themes. Temporal themes related with temporal space, such as area and length, are treated as attributes of temporal space, while others are modeled as temporal themes belonging to temporal features.

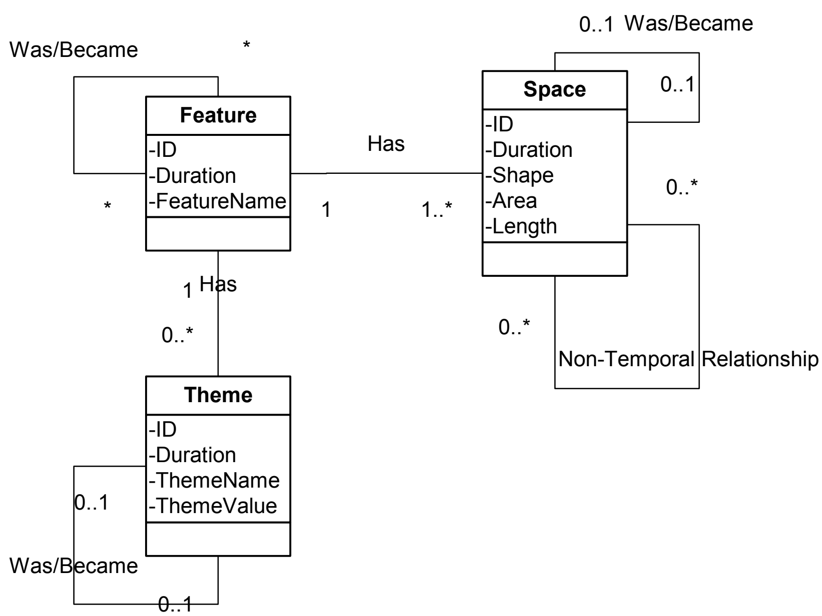


Figure 4.2 UML conceptual framework of feature-based temporal model.

In Figure 4.2, there are durations for the feature, space, and themes. The ‘Duration’ is a time interval, modeling the lifetime of a feature, space, or theme. Therefore, all of them have an interval timestamp. If several themes always change together, they can be grouped and have only one duration/lifetime. For example, almost all attributes of census data are changing together, so they can be grouped and have a single timestamp for the duration/lifetime. Compared to a traditional layer-based temporal framework, which models time at a layer or table level, the feature-based temporal model represents time at record-level for feature, attribute-level for space, and attribute- or attributes-group-level for themes.

Besides the temporal relationships, there also exist two other kinds of non-temporal relationships. First, there are spatial topological relationships between the temporal spaces, which coexist at certain time-periods. Second, there are other non-temporal relationships such as 'Connects To' and 'Flows To'. For example, one highway 'Connects To' another highway, or a river 'Flows To' a lake or another river. These non-temporal relationships are not the focus of this paper and are not further discussed.

This approach is reasonable for object-based data, because a feature is the basic element in an object-view of spatial representation. It represents time in temporal feature using its status rather than the change. In order to get the spatio-temporal changes, temporal spaces have to be compared for differences.

Table 4.1 gives an example of a temporal feature. There is only one feature in the table. It has three temporal spaces and two temporal themes. Temporally, the feature has 'Was' relationships with features 12 and 16 in 1996 and feature 13 in 1999, and 'Became' relationships with features 28 and 30 in 1999.

Table 4.1 An example of a temporal feature (Le, 2005).

<table>
<tr><th colspan="5">Feature</th><th rowspan="2">Space</th><th rowspan="2">Theme</th></tr>
<tr><th>Feature ID</th><th>Feature Type</th><th>Feature Time</th><th>Predecessor</th><th>Successor</th></tr>
<tr>
<td>25</td>
<td>Trans-portation</td>
<td>[1993, Now]</td>
<td><table><tr><th>Pres</th><th>Pre Time</th></tr><tr><td>12, 16</td><td>1995</td></tr><tr><td>13</td><td>2000</td></tr></table></td>
<td><table><tr><th>Sucs</th><th>Suc Time</th></tr><tr><td>28, 30</td><td>2000</td></tr></table></td>
<td><table><tr><th>Space ID</th><th>Space Time</th><th>Space info</th><th>Area</th><th>Length</th><th>Pre.</th><th>Suc.</th></tr><tr><td>1</td><td>[1993, 1995)</td><td>Line1</td><td>…</td><td>…</td><td>Null</td><td>7</td></tr><tr><td>7</td><td>[1995, 2000)</td><td>Line7</td><td>…</td><td>…</td><td>1</td><td>18</td></tr><tr><td>18</td><td>[2000, Now]</td><td>Line18</td><td>…</td><td>…</td><td>7</td><td>Null</td></tr></table></td>
<td><table><tr><th colspan="5">Theme i (i = 0, 1, .., n)</th></tr><tr><th>Theme ID</th><th>Theme Time</th><th>Theme Value</th><th>Pre.</th><th>Suc.</th></tr><tr><td>1</td><td>[1993, 1995)</td><td>…</td><td>Null</td><td>5</td></tr><tr><td>5</td><td>[1995, Now]</td><td>…</td><td>1</td><td>Null</td></tr></table>……</td>
</tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

Note: Columns in bold font are temporal data.

4.2.2 Implementing the temporal model in database

To efficiently manage the huge volume of spatio-temporal base geographic data, we must think about database management systems (DBMS). If the data size is small, it is usually convenient to store data in a file for simplicity. However, when the size is large, the file structure is no longer a good choice, especially for frequent data manipulation. File structure and file management are inefficient for data manipulation, including editing and query. The feature-based temporal model can be implemented in relational (R), object-relational (OR) or object-oriented (OO) DBMS.

Among these three types of databases, ORDBMS fits the feature-based temporal model best. The RDBMS is insufficient at modeling complex spatio-temporal features represented in the feature-based temporal framework. A UML model like Figure 4.2 has to be divided into several relational tables for feature, space and themes; so JOIN or RELATE, which are the least efficient operations, are unavoidable in data manipulation. The OODBMS takes the advantages of object-oriented programming into database management. However, an OODBMS is not successful in the commercial database marketplace for certain reasons and almost died (Garcia-Molina *et al*, 2002). One of the shortcomings of OODBMS is its weakness at backwards compatibility to RDBMS, which is used by many of the databases available. The ORDBMS implements object-oriented features in a relational database, so ORDBMS has good backwards compatibility to RDBMS. It provides object-oriented features including abstract data type (ADT) and inheritance, and is more mature than OODBMS in commercial database. An ADT contains two parts: 1) one or more domains and 2) mathematical operations defined on elements from the domains (Lewis and Denenberg, 1991). Thought an ADT is neither a data structure nor a data type, the domains can be data types when implemented in a particular language such as Oracle.

The feature-based temporal model can take advantage of the object-oriented features supported by ORDBMS, especially nested tables, collection, and references. For example, the 1-m ‘has’ relationships between a temporal feature and its temporal spaces or temporal themes can be well represented using a nested table, and the m:n temporal relationships between temporal features can be modeled using a collection data type together with a nested table. Therefore, the ORDBMS is the best in managing spatio-temporal data represented in the feature-based temporal model.

4.2.3 Visualizing the spatio-temporal data

Although ORDBMS fits the feature-based temporal model very well, it encounters difficulties in visualizing the spatio-temporal data within an existing GIS environment. Almost all commercial GIS today support data managed by RDBMS, but not ORDBMS. The spatial column, such as SDO_GEOMETRY of Oracle, is the only ADT currently supported by existing GIS. Generally, there are two possible ways to get around this problem. One approach is to create a flat view based on an OR table, and then work with the view instead of the original OR table in GIS. Another is to develop a new GIS, which can work with the OR schema directly. The second approach has advantages over the first one.

In the first approach, a view should be created based on an OR table because the flat view is similar to a relational table and is readable in GIS. Further query can be conducted with the view rather than with the original object-relational table. However, current GIS must be extended in order to edit the spatio-temporal data or visualize the history of a temporal feature or a geographical area in animation mode, which may be very difficult, and the advantages of OR schema is lost in data manipulation in this approach.

In the second approach, a new temporal GIS supporting ORDBMS should be designed. It provides more flexibility in working with ADT, but substantial programming would be required in developing a new temporal GIS from scratch. A prototype temporal GIS is designed and developed by Le (2005) using the object-oriented programming language--Java. The prototype system allows the users to query and visualize a snapshot at a specified point in time or an animation of a history during a time period at a specified time interval.

In addition to flexibility, there is another advantage in developing a new temporal GIS. Most existing GIS are layer based, and each layer has fixed spatial type--point, line, or polygon. While in ORDBMS such as Oracle, spatial type of a feature is not specified at table-, but at record-level. Therefore, one type of feature can be represented as multiple spatial types, and this can benefit the spatial representation of base geographic data. For example, in base geographic data, a building should be represented as point or polygon according to its size and map scale. Within existing GIS, we cannot define such a building feature class, which can be a point or a polygon. However, this is possible using ORDBMS and the prototype temporal GIS. An original small house changed to a big building can be represented from a point to a polygon in an OR table and visualized as such in the prototype temporal GIS.

4.3 Case study

The study area is Gwinnett County, Georgia, located within the Atlanta metropolitan area (Figure 4.3). Three datasets, census tracts in 1980, 1990 and 2000, are entered in the temporal census tract table, which is managed by an ORDBMS--Oracle 10*i*. The definitions of the OR table and related ADTs are listed in Appendix A.

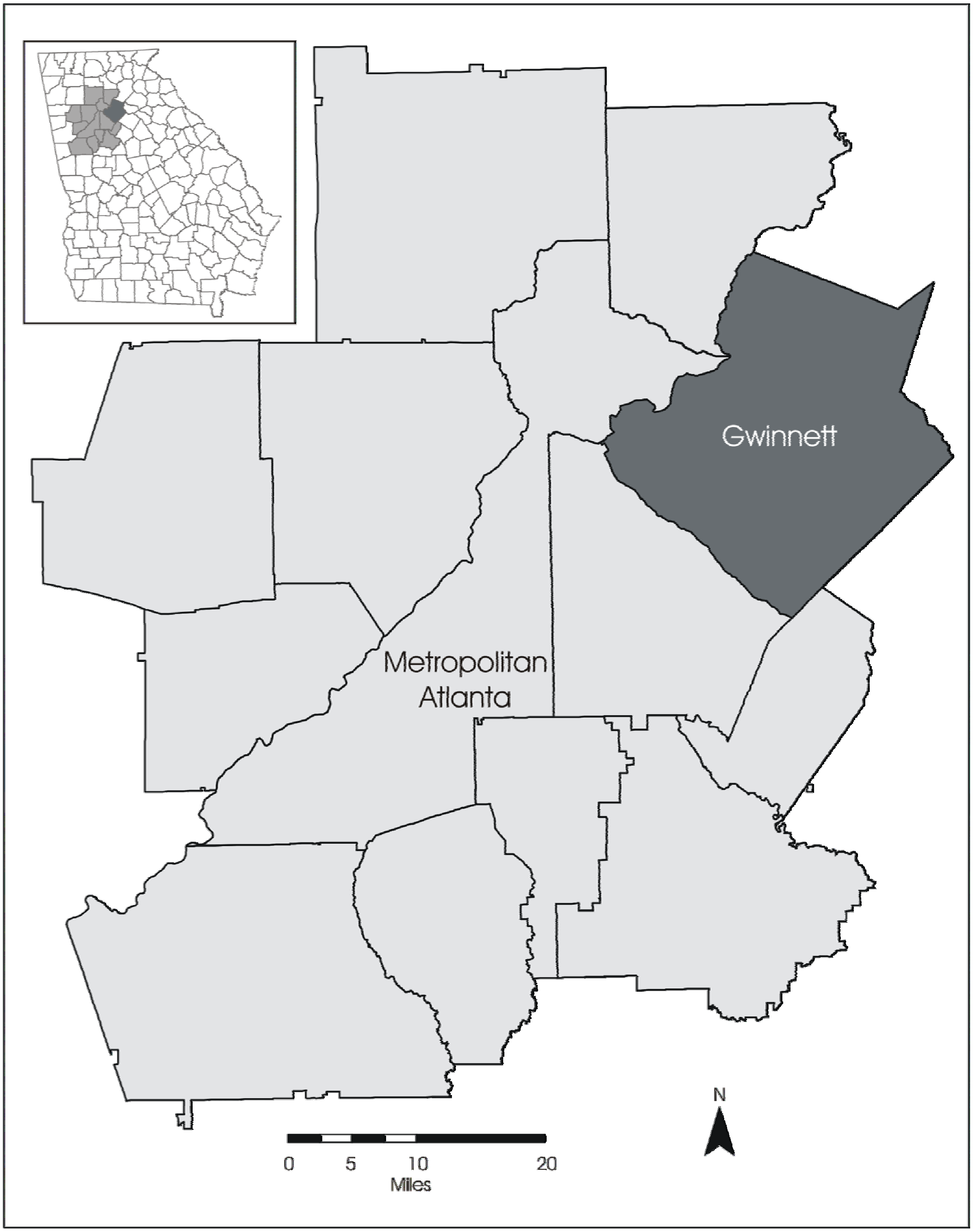


Figure 4.3 Study Area of Gwinnett County, Georgia.

Figures 4.4-4.9 are some examples of query and visualization from the census tract OR table. Figure 4.4 shows a status of tracts in 2005. Figure 4.5 is a snapshot in an animation, which displays the history of census tracts in Gwinnett County from 1980 to 2005. Figure 4.6 is a status in 1992, with one tract selected. Its attribute table is presented in Figure 4.7. At the top table window in Figure 4.7, the highlighted record shows the attributes of the selected tract in Figure 4.6, which is valid at the query time of 1992. The bottom table window of Figure 4.7 tells the history of the selected feature, which is a record in the OR table. For example, there is one record in the 'Was' nested table and two in the 'Became' nested table, respectively. It tells the selected tract was evolved from another in 1990 and was split into two new ones in 2000. Figures 4.8 and 4.9 give another example in 2000. Figure 4.9 is composed of two graphs, displaying different location of the same table window. The table window shows the selected tracts has two temporal spaces valid at [1980-2000) and [2000, Now), and three temporal 'Pop' themes during its lifetime. It has a total population of 1555, 3047 and 18593 in 1980, 1990 and 2000, respectively.

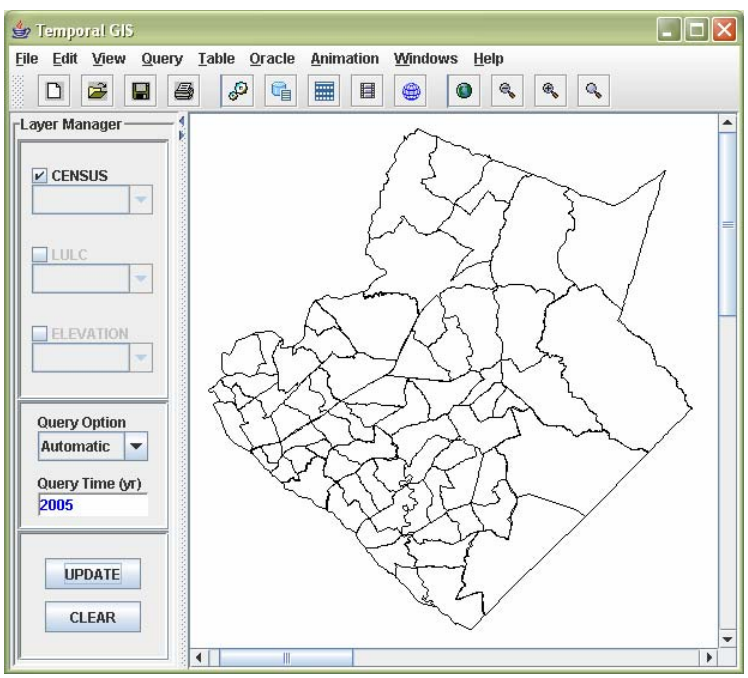


Figure 4.4 Census tracts, 2005.

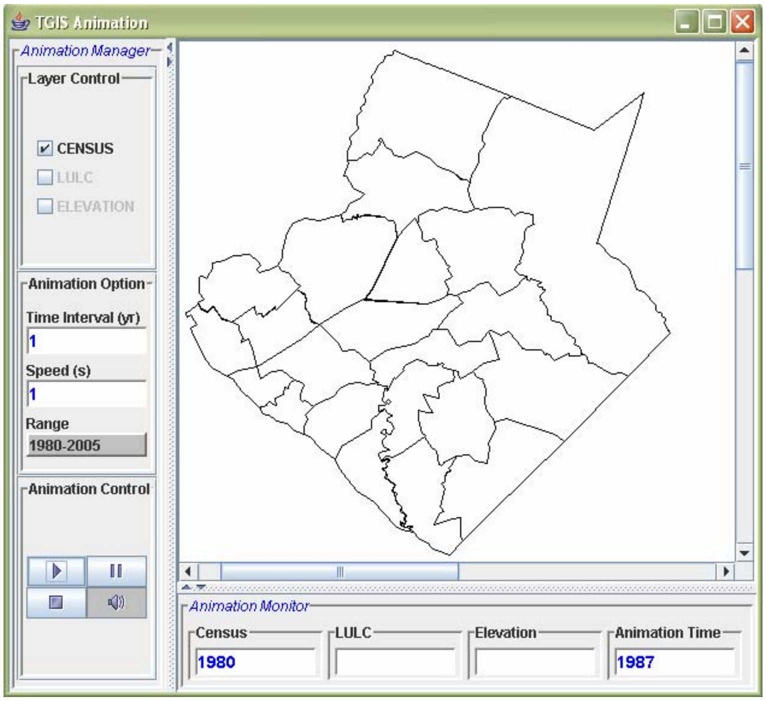


Figure 4.5 A snapshot in an animation.

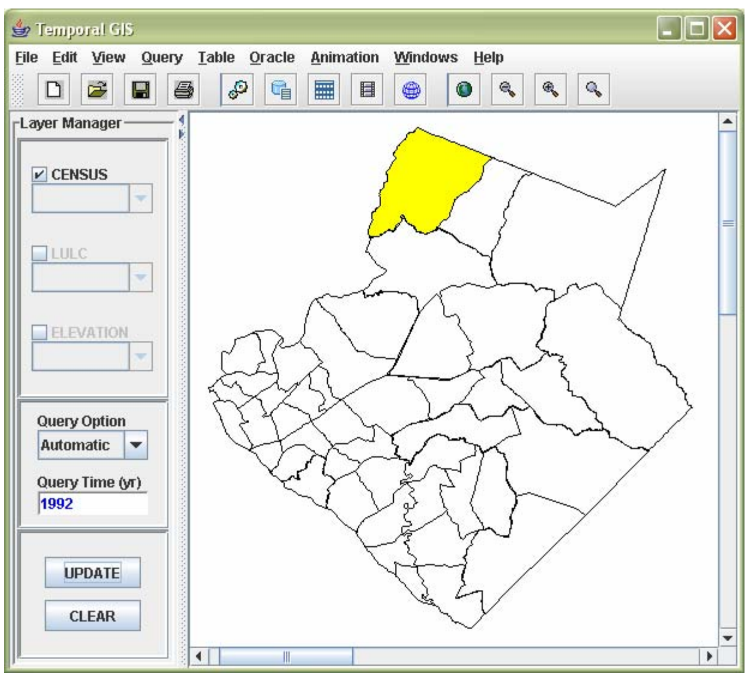


Figure 4.6 Census tracts, 1992.

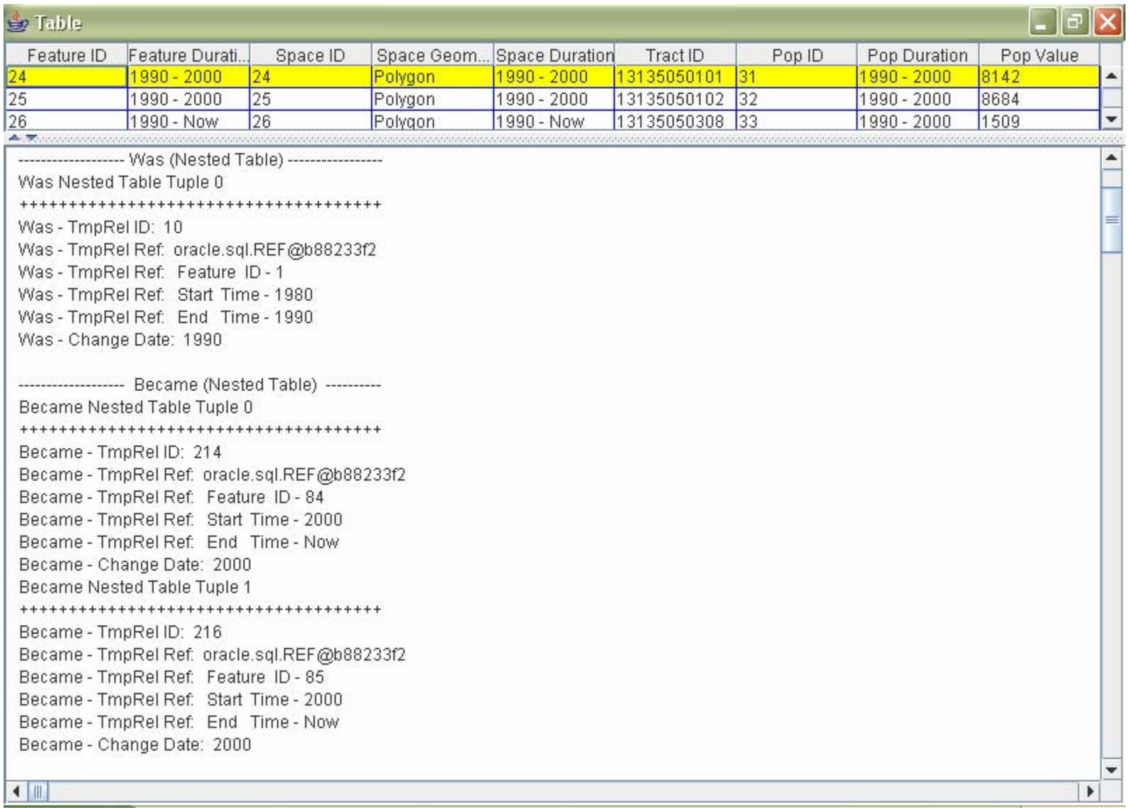


Figure 4.7 Census tracts, 1992.

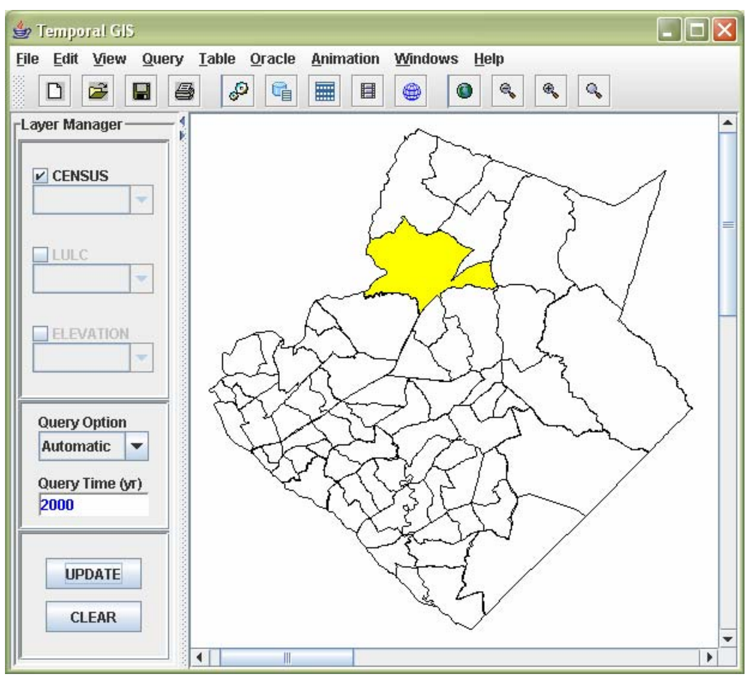
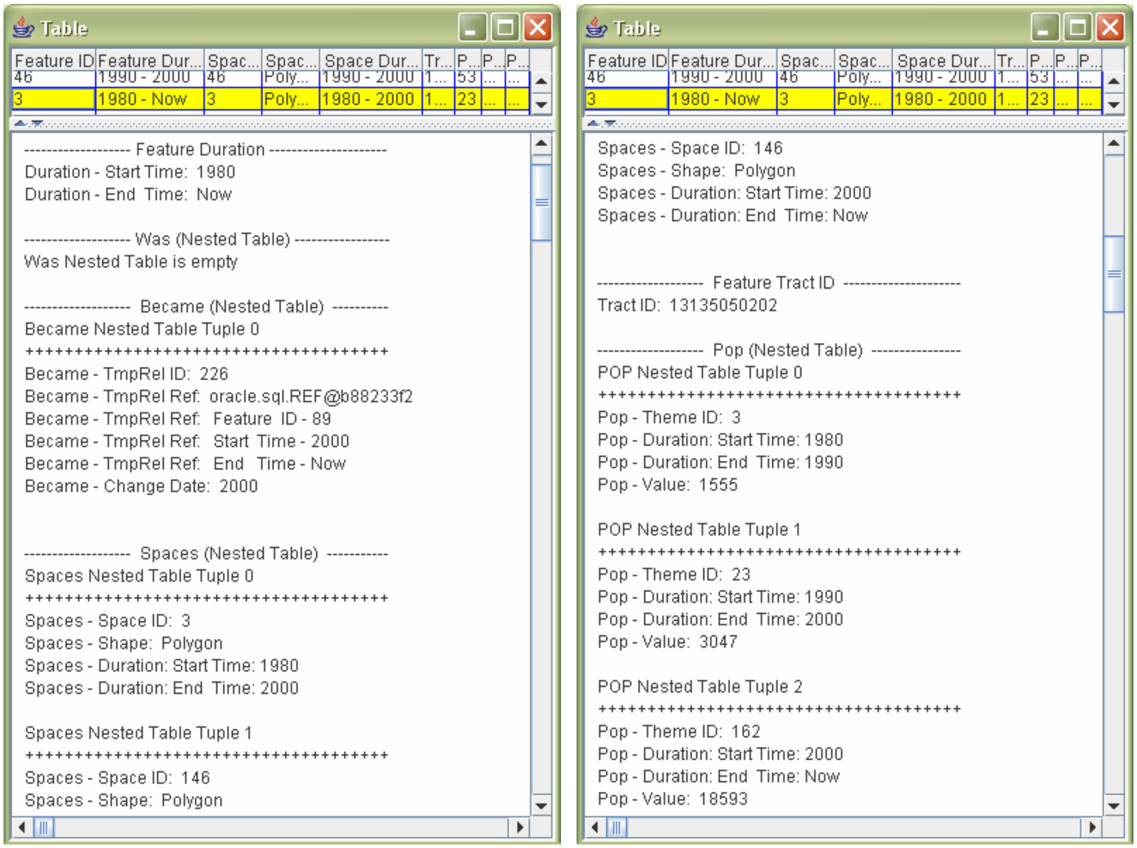


Figure 4.8 Census tracts, 2000.



a) b)

Figure 4.9 Attribute table of census tracts, 2000.

4.4 Discussion and conclusions

In conclusion, this paper proposes a spatio-temporal model for base geographic data in object-form. It simplifies time and spatio-temporal changes in base geographic data as discrete, and represents time based on temporal features. A temporal feature can have multiple temporal spaces and multiple temporal themes during different time periods. All of them are functions of time. When time and change are treated as discrete, these temporal functions can be simplified as constants during corresponding time intervals. This makes it possible to model a feature history with several time intervals and corresponding states.

The temporal model proposed in this paper can be best implemented in ORDBMS, which supports ADT and fits the feature-based temporal data model very well. In order to visualize spatio-temporal data organized in OR tables, we suggest the development of a new temporal GIS rather than extending an existing one, because the existing GIS environment overall limits the advantages of OR schema. However, there is much work to developing a new system.

Another finding in this paper is one feature class can be spatially represented as different spatial types such as point and polygon, and this can benefit the spatial representation of base geographic data in visualization and spatio-temporal change between different spatial types. In other words, spatial geometry can be defined not only at the feature class or layer level, but also at the feature level.

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Appendix A

The following code in SQL language shows the definition of the OR table and related ADTs in the Oracle database. The detailed member function for object type, "Interval_objtyp", is not given.

```
CREATE TYPE Interval_objtyp AS OBJECT (
    StartTime           DATE,
    EndTime             DATE,
    MEMBER FUNCTION     Before RETURN BOOLEAN,
    MEMBER FUNCTION     After  RETURN BOOLEAN,
    MEMBER FUNCTION     Equals RETURN BOOLEAN,
    MEMBER FUNCTION     Meets  RETURN BOOLEAN,
    MEMBER FUNCTION     Overlaps       RETURN BOOLEAN,
    MEMBER FUNCTION     During         RETURN BOOLEAN,
    MEMBER FUNCTION     Starts RETURN BOOLEAN,
    MEMBER FUNCTION     Ends   RETURN BOOLEAN);
CREATE TYPE Space_objtyp AS OBJECT(
    SpaceID             NUMBER,
    Shape               MDSYS.SDO_GEOMETRY,
    SpaceTime           Interval_objtyp,
    Area                NUMBER,
    Length              NUMBER);
CREATE TYPE Theme_objtyp AS OBJECT (
    ThemeID             NUMBER,
```

```
        ThemeTime       Interval_objtyp,
        Value           NUMBER);
CREATE TYPE Space_ntabtyp AS TABLE OF Space_objtyp;
CREATE TYPE Theme_ntabtyp AS TABLE OF Theme_objtyp;
CREATE TYPE Feature_objtyp;
CREATE TYPE TmpRel_vartyp AS VARRAY(1000) OF REF Feature_objtyp;
CREATE TYPE TmpRel_objtyp AS OBJECT (
        TmpRelID        NUMBER,
        TmpRel          REF     Feature_objtyp,
        ChangeDate      DATE);
CREATE TYPE TmpRel_ntabtyp AS TABLE OF TmpRel_objtyp;
CREATE OR REPLACE TYPE Feature_objtyp AS OBJECT (
        FeatureID       NUMBER,
        FeatureTime     Interval_objtyp,
        Was             TmpRel_ntabtyp,
        Became          TmpRel_ntabtyp,
        Spaces          Space_ntabtyp
) NOT FINAL;
CREATE TYPE Census_objtyp UNDER Feature_objtyp (Pop  Theme_ntabtyp);
CREATE TABLE Census_objtab OF Census_objtyp (
      PRIMARY KEY (FeatureID) )
      OBJECT IDENTIFIER IS PRIMARY KEY
      NESTED TABLE Was STRORE AS Was_ntab (
```

```
    (PRIMARY KEY (Nested_table_id, TmpRelID))
    ORGANIZATION INDEX COMPRESS)
    RETURN AS LOCATOR
NESTED TABLE Became STRORE AS Became_ntab (
    (PRIMARY KEY (NESTED_TABLE_ID, TmpRelID))
    ORGANIZATION INDEX COMPRESS)
    RETURN AS LOCATOR
NESTED TABLE Spaces STRORE AS Shape_ntab (
    (PRIMARY KEY (NESTED_TABLE_ID, SpaceID))
    ORGANIZATION INDEX COMPRESS)
    RETURN AS LOCATOR
NESTED TABLE Pop STRORE AS Pop_ntab (
    (PRIMARY KEY (NESTED_TABLE_ID, ThemeID))
    ORGANIZATION INDEX COMPRESS)
    RETURN AS LOCATOR;
```

CHAPTER 5

A PROTOTYPE TEMPORAL GIS FOR MULTIPLE SPATIO-TEMPORAL REPRESENTATIONS[3]

[3] Le, Y. Submitted to *Cartography and Geographic Information Science*.

Abstract: Development of a temporal geographic information system (GIS), together with spatio-temporal data modeling, are key issues in incorporating time into geographic information science. This paper studies how to design and develop a temporal GIS, which aims to work with spatio-temporal data represented in various data models, and introduces such a prototype temporal GIS with a case study. In temporal GIS, the integration of multiple spatio-temporal representations is based on common spatial and temporal reference systems. In other words, a map window of temporal GIS visualizes spatio-temporal data valid at the same time within one spatial area. To achieve this goal, separate modules on data editing and query are required for each spatio-temporal data model (STDM). In the temporal query interface, after a user specifies a time, the system will automatically hire correspondent modules to retrieve spatio-temporal data valid at that time. Besides temporal queries common to all STDMs, each module may provide additional temporal query capabilities specific to that model. In the case study, we design and develop a prototype temporal GIS for three STDMs. The examples of query and visualization using three datasets, census data, land use/land cover and elevation, demonstrate the prototype temporal GIS can integrate multiple temporal representations.

Keywords: Temporal, GIS, Multiple, Representation

5.1 Introduction

Is geographic reality changing gradually or rapidly, continuously or discretely? How do human activities interact with the environment? Temporal information is useful in answering these questions and better understanding the dynamic world. After almost forty years of development, current GIS are still static in nature and ineffective at working with spatio-temporal data (Hornsby and Egenhofer, 2000; McMaster and Usery, 2004; Worboys and Hornsby, 2004). Because of the complexity of spatio-temporal data, many spatio-temporal representations have been proposed for different types of data (Yuan, 1997; Sengupta and Yan, 2004; Worboys, 2005). However, only a few, such as the sequential snapshots approach, are supported by existing GIS (Langran, 1992; Peuquet and Duan, 1995). In order to visualize spatio-temporal data, the person who proposes a STDM usually has to develop a temporal system to work with that specific model (Wachowicz, 1999; Koncz and Adams, 2002). As a result, although certain GIS with temporal capabilities have been introduced for a specific STDM, they can only work with data represented in that specific data model. In reality, we usually need to work with spatio-temporal data represented in different data models together. For example, temporal data of transportation, population, and land use are required for post-analysis of the planning of a highway, and these data may be represented in different data models. Therefore, there is a need for temporal GIS to work with spatio-temporal data represented in different models.

We studies temporal GIS capable of manipulating spatio-temporal data represented in different data models, and introduces a prototype temporal GIS. In this paper, the integration of various STDMs is based on common spatial and temporal reference systems. By providing temporal information, it will enable many GIS applications to perform spatio-temporal query, visualization, and analysis. This study contributes to moving traditional static GIS toward temporal GIS.

The remainder of the paper is organized as follows. The next section discusses why temporal GIS should be based on common spatial and temporal reference systems and how to design and develop a temporal GIS capable of working with spatio-temporal data represented in different data models. In section 5.3 in a case study, we briefly describe three STDMs, and introduce a prototype temporal GIS to work with these. Section 5.4 draws conclusions and provides some discussion.

5.2 Temporal GIS based on common spatial and temporal reference systems

5.2.1 How can temporal GIS work with multiple spatio-temporal representations?

How can temporal GIS work with multiple spatio-temporal representations? Before this question is answered, another should be considered -- how do traditional GIS work with multiple spatial data models? In Figure 5.1, there are two graphs showing spatial data represented in different spatial data models, vector and raster. The top layers are transportation data in vector form and the bottom layers are land use/land cover in raster form. All datasets in the figure are correctly registered in one coordinate system. The transportation and land use/land cover data in the left (Figure 5.1a) cover different areas and have no overlap, while those in the right (Figure 5.1b) cover the same area or at least have some overlap in space dimension. In traditional GIS, the two datasets in the left cannot overlay and work together, while those in the right can. For example, one may overlay transportation and land use data of Atlanta, Georgia for visualization or spatial analysis, but will not combine transportation data of Atlanta, Georgia and land use data of Las Vegas, Nevada. In other words, a map window of GIS only shows objects and/or fields within one spatial region. Therefore, traditional GIS integrate multiple spatial data models, including fields and objects, based on common spatial reference system.

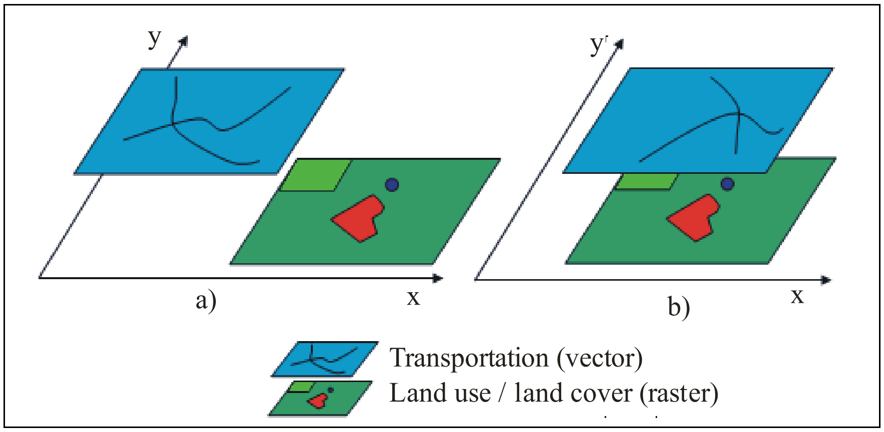


Figure 5.1 Spatial data in different spatial data models covering a) different and b) same areas.

Since there are analogies between time and space (Galton, 2001, 2004), we propose to integrate multiple spatio-temporal representations based on common spatial and temporal reference systems. In other words, a map window of temporal GIS visualizes spatio-temporal data valid not only at the same location in space, but also at the same location in time. For example, temporal GIS will put 1990 land use and 1990 population data together; but it does not often put land use data at 1960 together with population data at 2000 for analysis, unless both datasets are valid at a certain time. In temporal GIS presented in this paper, the map window visually represents geographic objects and/or fields valid at the same location in both space and time.

Figure 5.2 presents spatio-temporal data covering the same spatial area, and are valid at a) different and b) common time periods. Similar to in Figure 5.1, the top layers are transportation data in vector form and the bottom ones are land use data in raster form. These two types of data are represented in different STDMs. All datasets cover the same spatial region. In addition to the XY spatial coordinate system, there is a time axis in Figure 5.2. On the time axis, the red/dark wide lines show the lifetimes of the land use/land cover datasets, and the yellow/light narrow lines are those of the transportation datasets. In Figure 5.2a, the transportation dataset is valid during 1980-1990, while the land use dataset is valid during 1996-1998. Because these two datasets do not “overlap” in the time dimension, usually they are not used together. In Figure 5.2b, the transportation and land use datasets are valid during 1992-1999 and 1996-1998, respectively. Since there is an overlap between 1992-1999 and 1996-1998, they can overlay during 1996-1998, the common time period or intersection of both datasets in the time dimension.

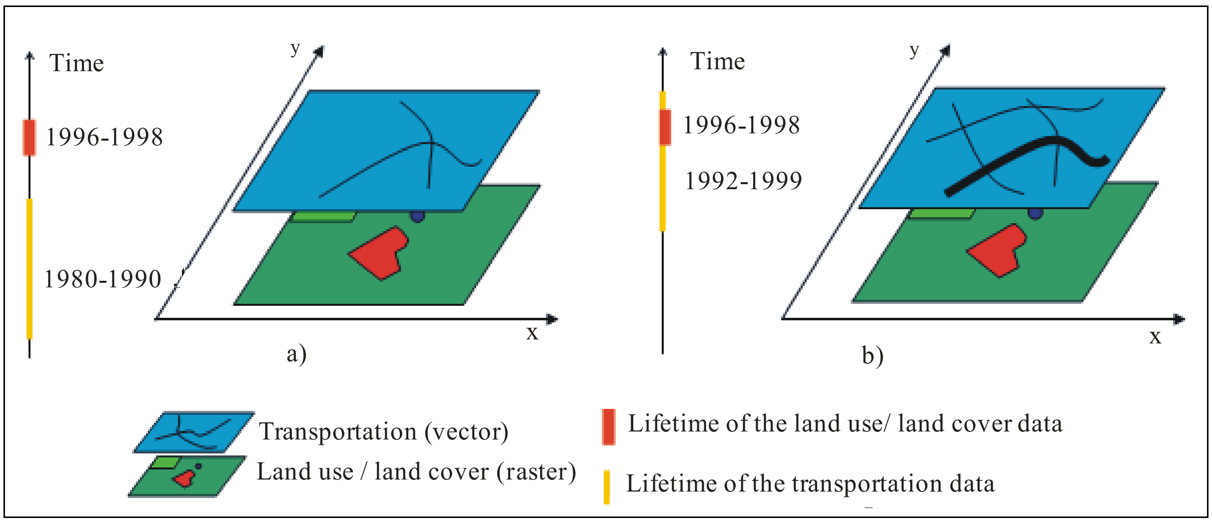


Figure 5.2 Spatial-temporal data valid at different a) and b) common time periods.

In some cases, data at different locations in time are required for geographic analysis, such as temporal series analysis. The rule of common spatial and temporal reference systems is violated under those circumstances. However, those situations are not the focus of this research and will not be further discussed in the paper.

5.2.2 System architecture

In order to integrate multiple spatio-temporal representations in temporal GIS based on common spatial and temporal reference systems, separate program modules are required for STDMs. The system architecture of the temporal GIS is illustrated below.

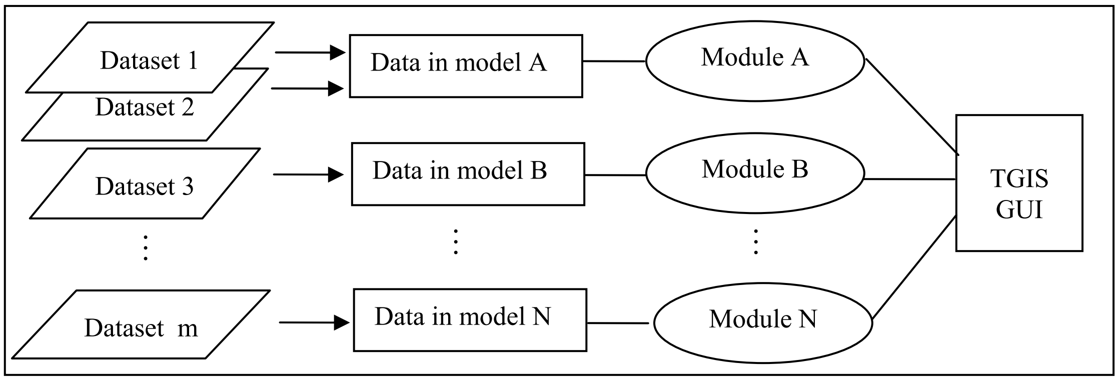


Figure 5.3 System architecture of temporal GIS.

In Figure 5.3, datasets 1 and 2 are represented in STDM A and are processed by module A, dataset 3 is represented in model B and is manipulated by module B, and dataset m is represented in model N and is handled by module N. There is a 1:1 relationship between STDM and module. Each program module has temporal data editing and query functions for one STDM. If a new STDM is required, a new module will be added correspondingly. The relationships between spatio-temporal datasets and STDMs are managed in a system table called "TmpDataDefinition", which is defined as:

TmpDataDefinition: {Dataset, STDM, Temporal Resolution, Initial Time}.

Temporal resolution and initial time are designed for temporal queries.

After users specify a time in the temporal query interface, the temporal GIS automatically uses correspondent modules to retrieve spatio-temporal data valid at that time. Besides temporal queries common to all data models, each module may provide additional temporal query capabilities specific to that data model. For example, users may query the history of a feature if it is represented in feature-based STDM. An example will be given in the case study.

5.2.3 Implementation

5.2.3.1 Object-oriented system design

Figure 5.4 presents an object-oriented system design for the temporal GIS. There are three major parts in the temporal GIS: STDMs, interfaces, and graphic user interface (GUI). The GUI communicates with STDMs through interfaces. Each dataset is an instance of one STDM.

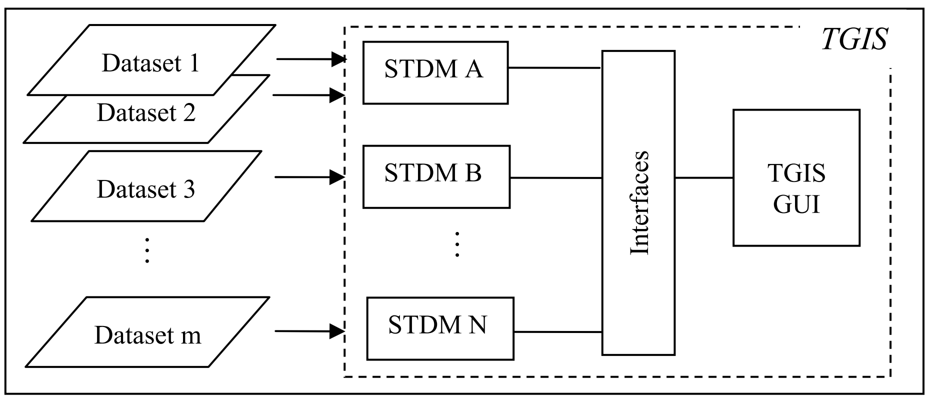


Figure 5.4 Object-oriented system design.

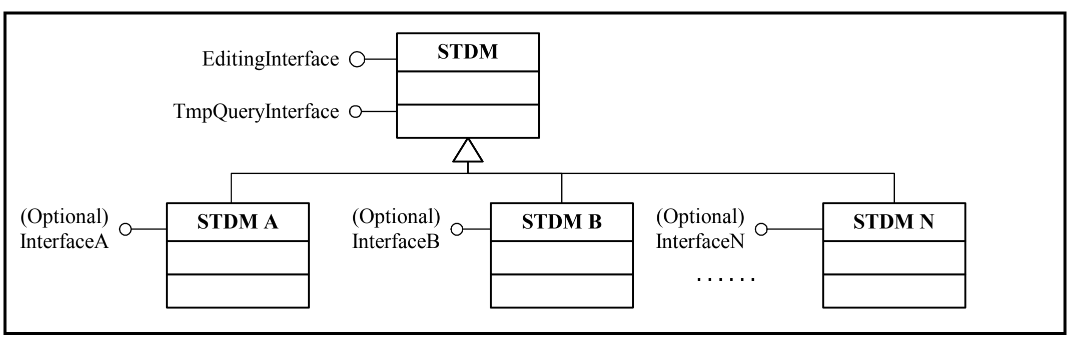


Figure 5.5 Object models of STDM.

In the object models diagram of STDM (Figure 5.5), the interfaces in Figure 5.4 can be divided into two types: mandatory and optional. Each STDM must implement the mandatory common interfaces, and may provide optional interfaces specific to that object model. The mandatory interfaces can be further divided into interfaces for temporal data editing and queries. Temporal data editing includes creating new data, "updating" and "deleting" existing data. Here, "updating" and "deleting" are double quoted because they are different from those in traditional static GIS. For example, a temporal feature still exists in the temporal database and is retrievable after its lifetime ends and is "deleted" in temporal GIS, and an "updated" temporal feature contains both old and new information. A set of fundamental spatio-temporal queries is identified below. Among these four spatio-temporal queries, the first three are required for all STDMs, and the last one is only implemented in the STDM based on feature.

1) Retrieve a snapshot at a given time.
2) Retrieve the history during a given interval time.
3) Retrieve changes during a given interval time.
4) Retrieve the history of a feature

5.2.3.2 Developing strategies

Generally, there are two ways to develop a temporal GIS. One is extending from an existing GIS, and another is developing from scratch. Both approaches have advantages and disadvantages. The first approach is relatively simple because existing GIS provides many functions, such as spatial data editing and analysis. Obviously, this will save much time in programming. However, the extended temporal GIS will be constrained by the specific underlying GIS system. For example, ArcGIS 9 is good for spatial data editing, management, visualization and analysis. However, it does not support abstract data type (ADT) or spatial data managed in object-relational or object-oriented databases (ESRI, 2004), which are gaining more and more interest in spatio-temporal data modeling (Wachowicz, 1999; Worboys and Hornsby, 2004; Yuan *et al*, 2004). An ADT consists of one or more domains and operations defined on elements of the domains (Lewis and Denenberg, 1991). An ADT is not a data type, but when it is implemented in a particular language such as Oracle, the domains can be data types. The second approach gives much more flexibility and may be used for more STDMs, but requires heavy programming because the entire system has to be coded. Fortunately, object-oriented programming languages such as Java have already provided many packages that developers of which can take advantage.

Whether extending an existing system or developing from scratch depends on the STDMs that are intended in the temporal GIS. If all STDMs are supported within an existing GIS, then it may be easier to follow the first approach. Otherwise, the second approach is better.

5.2.3.3 Database issues

Database issues are an indispensable consideration in developing a temporal GIS. Similar to developing strategies, these issues are highly dependent upon the STDMs with which the temporal GIS works. Therefore, these issues will be discussed in the next section of the case study, which clarifies the STDMs with which it works.

5.3 Case study

5.3.1 Study area and data

The study site in this paper is Gwinnett County, Georgia, which is located within the Atlanta metropolitan area. In the past decades, metropolitan Atlanta has experienced rapid urbanization and has been studied for urban sprawl (Yang and Lo, 2003). In this paper, we choose Gwinnett County instead of metropolitan Atlanta because of the time constraints of editing temporal feature data.

There are three types of data as listed below in the case study.

- Census tracts: 1980, 1990 and 2000
- Land use/land cover (LULC): 1988, 1996 and 1998
- Elevation: 1979 and 1999

Spatial data of census tracts are in object form, while those of others are in field form. The 1990 and 2000 census tracts data are created by U.S. Bureau of Census, and the 1980 tracts data are by Geolytics, Inc. The land use/land cover and elevation datasets have 30 m resolution. The 1988, 1996 and 1998 land cover datasets are created by the Georgia Department of Natural Resource, the U.S. Geological Survey (USGS) and University of Georgia Natural Resources Spatial Analysis Laboratory, respectively. Both elevation datasets are originated by USGS, the 1979 elevation in DEM format (units: feet), and the 1999 data in NED format (units: meter). The 1979 DEM dataset is merged from several small images and has edge problems, while the 1999 NED dataset is interpolated using better methods and has this problem removed. Therefore, the simple difference between the DEM and NED surfaces does not represent the change.

5.3.2 STDMs incorporated in this prototype temporal GIS

Since STDMs are important to system implementation, we first briefly describe STDMs incorporated in this prototype temporal GIS, then introduce the prototype temporal GIS. There are three STDMs in this prototype temporal GIS.

- Feature-based temporal model (census tracts)
- The current-state-with-changes (CSC) (LULC, elevation)
- Sequential snapshots (LULC, elevation)

Census tracts are represented in the feature-based temporal model. We represent LULC and elevation data in both snapshots and CSC in order to evaluate their appropriateness on spatial data in field form.

5.3.2.1 Feature-based temporal model

This STDM is proposed for spatio-temporal data in object form, where temporal changes can be treated as discrete. In the feature-based temporal model, a feature is a temporal feature, and it may have multiple temporal spaces and multiple temporal themes during its lifespan. A temporal feature, space or theme is valid during corresponding time interval—duration or lifetime. There exist temporal relationships, "Was/Became", between temporal features, between temporal spaces, and between temporal themes. The difference is temporal relationships between features are m:n, while those between spaces and between themes are 1:1. If a theme should never change during the lifetime of a feature, then it is classified as themes-at-feature-level and is separated from other themes. For example, a census tract keeps the same ID during its lifetime, so tract ID is a theme-at-feature-level. A census tract is treated as a new feature if its tract ID changes. In this STDM, timestamps are used at both record- and attribute-levels. A temporal feature schema is listed below.

Temporal feature: {FeatureID, FeatureDuration, Themes_at_Feature_Level,
{Was}, {Became}, {Space, SpaceDuration}, {Theme, ThemeDuration}}

Table 5.1 presents an example of a temporal feature, which has three temporal spaces and two temporal themes.

Table 5.1 An example of a temporal feature.

<table>
<tr><th colspan="5">Feature</th><th rowspan="2">Space</th><th rowspan="2">Theme</th></tr>
<tr><th>Feature ID</th><th>Feature Type</th><th>Feature Time</th><th>Predecessor</th><th>Successor</th></tr>
<tr><td>25</td><td>Trans-portation</td><td>[1993, Now]</td>
<td><table><tr><th>Pres</th><th>Pre Time</th></tr><tr><td>12, 16</td><td>1995</td></tr><tr><td>13</td><td>2000</td></tr></table></td>
<td><table><tr><th>Sucs</th><th>Suc Time</th></tr><tr><td>28, 30</td><td>2000</td></tr></table></td>
<td><table><tr><th>Space ID</th><th>Space Time</th><th>Space info</th><th>Area</th><th>Length</th><th>Pre.</th><th>Suc.</th></tr>
<tr><td>1</td><td>[1993, 1995)</td><td>Line1</td><td>…</td><td>…</td><td>Null</td><td>7</td></tr>
<tr><td>7</td><td>[1995, 2000)</td><td>Line7</td><td>…</td><td>…</td><td>1</td><td>18</td></tr>
<tr><td>18</td><td>[2000, Now]</td><td>Line18</td><td>…</td><td>…</td><td>7</td><td>Null</td></tr></table></td>
<td><table><tr><th colspan="5">Theme i (i = 0, 1, .., n)</th></tr>
<tr><th>Theme ID</th><th>Theme Time</th><th>Theme Value</th><th>Pre.</th><th>Suc.</th></tr>
<tr><td>1</td><td>[1993, 1995)</td><td>…</td><td>Null</td><td>5</td></tr>
<tr><td>5</td><td>[1995, Now]</td><td>…</td><td>1</td><td>Null</td></tr></table>
……</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

Note: Columns in bold font are temporal data.

5.3.2.2 The CSC

The CSC is modified from Langran's (1992) base-state-with-changes. It manages temporal information by recording the current state and the changes between consecutive snapshots (Figure 5.6). The current state is kept in this STDM because it is more frequently used than the base state in GIS applications. In this case study, there are two snapshots for elevation and three snapshots for LULC, so there is one current state with one change map for the elevation, and one current state with two change maps for the LULC.

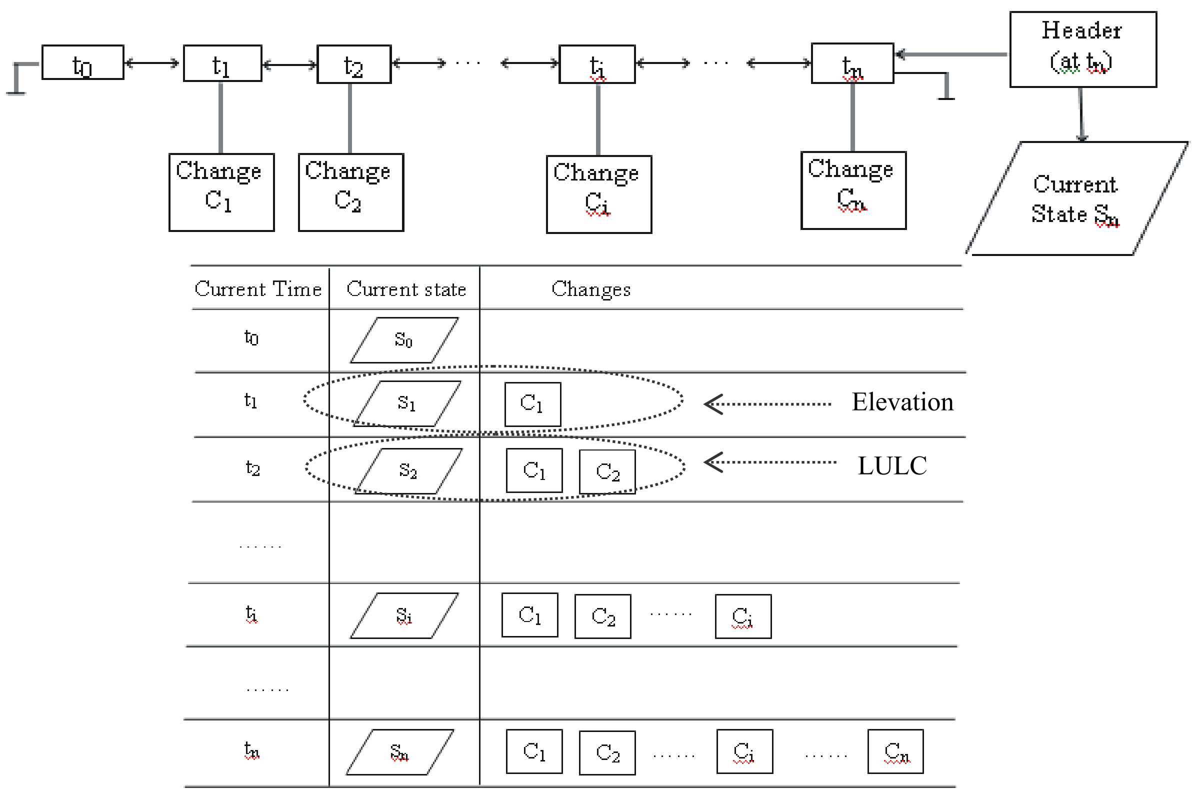


Figure 5.6 Current-state-with-changes spatio-temporal data model.

5.3.2.3 Sequential snapshots

The sequential snapshots approach was introduced by Langran (1992). It is the only STDM supported by existing traditional GIS. Its schema is very simple, each snapshot having a TimeStamp indicating when it is captured.

Temporal Layer: {Layer ID, Raster, TimeStamp}

5.3.3 The prototype temporal GIS

5.3.3.1 Database design

The first STDM, feature-based temporal model, is not easy to implement in a relational database. In a relational database, a temporal feature has to be split into several tables, including a 'FEATURE' table, a 'SPACE' table, several 'THEME' tables, a 'WAS' table, and a 'BECAME' table. To retrieve data for a feature, these tables must be joined/related together, which is inefficient. Compared to a relational database, an object-relational (OR) database provides object-oriented features including ADT and fits the feature-based temporal model better (Wang *et al*, 1999; Grumbach *et al*, 2003).

The CSC and snapshots approaches are relatively simple and easy to manage by either relational or OR databases. In this case study, each raster dataset is stored as a separate image file, with file location recorded in the temporal layer table. The Temporal Layer schema is as follows.

Temporal Layer: {Layer ID, RasterFileLocation, TimeStamp}

In this case study, Oracle 10*g* is used to manage spatio-temporal data for several reasons. First, it is an OR database and fits all three STDMs well. Second, this version of Oracle Spatial not only provides MDSYS.SDO_GEOMETRY data type for objects, but also supports

MDSYS.SDO_ GEORASTER data type, which can be used for fields. In Oracle 10*g*, the MDSYS.SDO_GEOMETRY and MDSYS.SDO_ GEORASTER can organize the shape of a feature and a raster image in a single row and in a single column, respectively (Oracle, 2003a, 2003b). Although we do not manage field data in Oracle Spatial with MDSYS.SDO_ GEORASTER in this case study, there is a chance that all STDMs can be managed in one database in a future study.

5.3.3.2 System development

Although an OR database fits well with the feature-based temporal model, there are difficulties in working within existing GIS. For example, ADT is not fully supported in commercial GIS software such as ArcGIS. Currently, ArcGIS only supports few predefined ADTs for shape, such as MDSYS.SDO_GEOMETRY in Oracle (ESRI, 2004). Therefore, this prototype temporal GIS is not extended from any existing GIS or GIS engine, such as MapObjects, but programmed using Java.

Figure 5.7 presents the main and Figure 5.8 the animation windows of the prototype temporal GIS. In Figure 5.7, the right panel is the map area, and the left is for layer management and temporal query. The prototype temporal GIS supports two ways to query temporal data: manual and automatic. When the automatic option is selected, users are required to specify the "Query Time", then the prototype temporal GIS will retrieve spatio-temporal data of selected layers valid at that time and draw in the map area. With the manual option, users are allowed to specify time for each selected layer. The manual option may be applied for special geographic analysis, such as environmental pollution analysis. For example, printing and dying factories can pollute lakes and rivers downstream if they fail to treat the water flowing out, and the lakes and rivers polluted can be harmful to the human body for at least 10 years. Although such a factory is closed in 1990 and the land is changed to another use, we can overlay the 1990 pollution data with the 2000 census data to evaluate how many persons were exposed to that pollution in 2000. This example shows entities are not only spatially, but also temporally related.

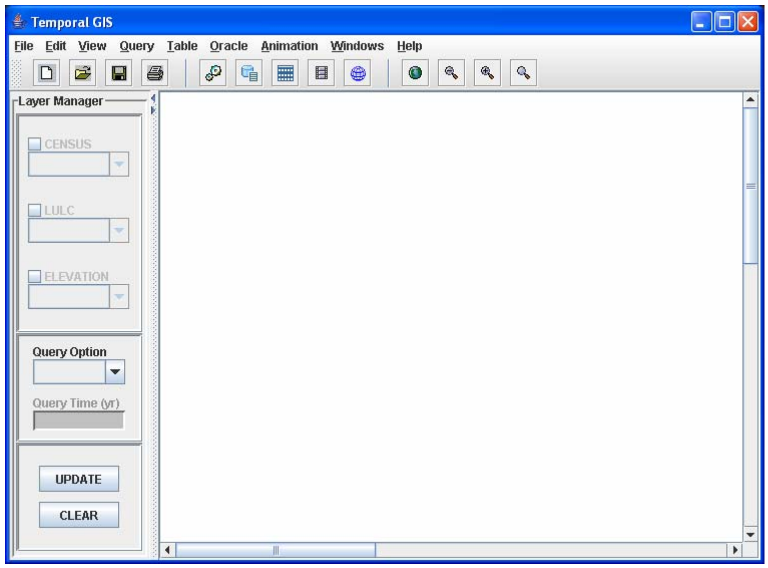


Figure 5.7 The main window of the prototype temporal GIS.

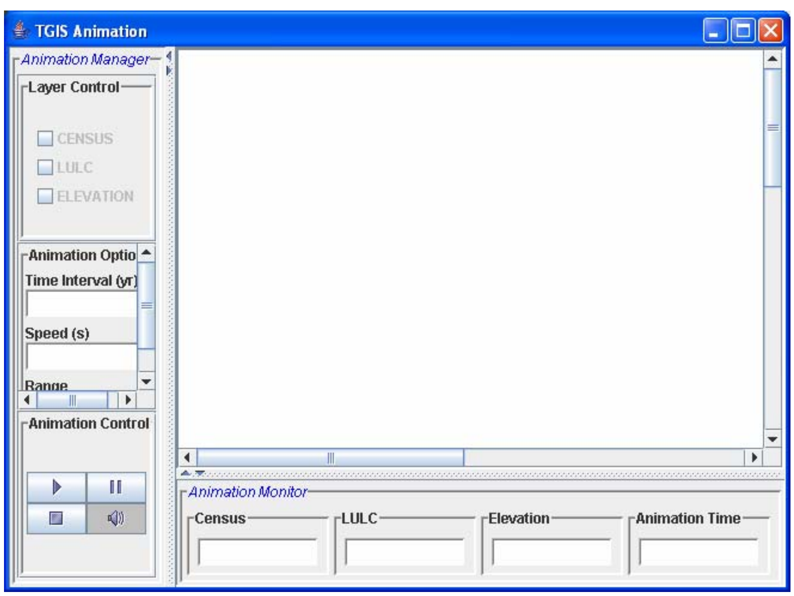


Figure 5.8 The animation window of the temporal GIS.

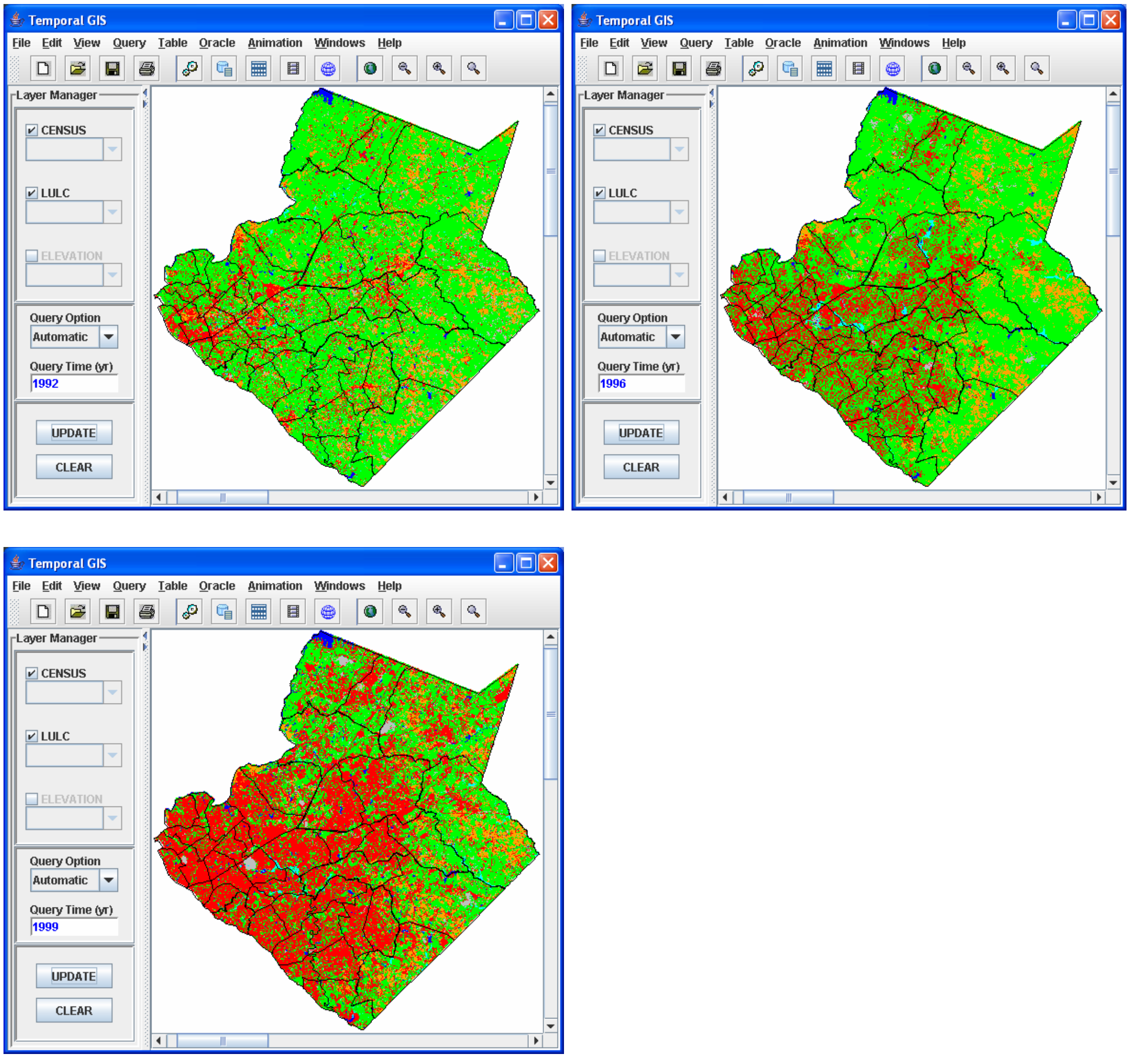
5.3.4 Query and visualization examples

This case study implements the four temporal queries discussed in section 5.2.3. The prototype temporal GIS is capable of querying snapshots from all datasets represented in three STDMs, and querying the history of a temporal feature represented in the feature-based temporal model. The following graphs (Figures 5.9-5.16) are examples of temporal query and visualization.

Figure 5.9 presents the states of LULC and census tracts at a) 1992, b) 1996 and c) 1999. On these maps, the census tracts are the same, but LULC differs. That census tracts data are valid since 1990 and expires before 2000.

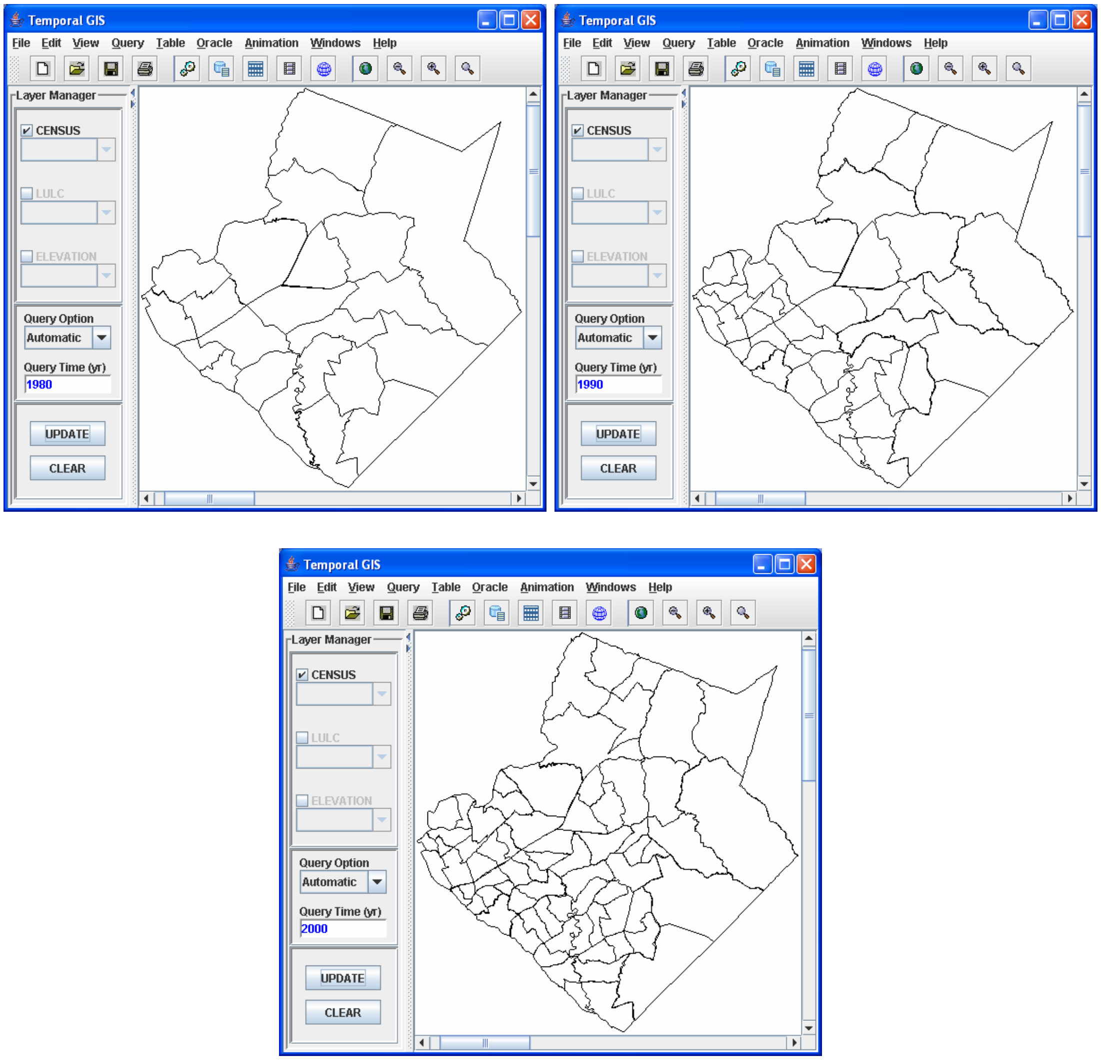
Figure 5.10 shows census tract data valid during temporal periods: a) 1980-1990, b) 1990-2000 and c) after 2000. Figure 5.11 presents the table window of census tracts at 1990. The upper panel shows the valid feature information at the time of 1990, and the bottom displays all information of the selected feature. Therefore, the history of a temporal feature is displayed in the bottom window of the feature table in Figure 5.11. From the one and two records in the "Was" and "Became" nested table of the feature history, respectively, we can tell this feature was changed from another temporal feature with Feature ID 1 in 1990 and evolved into two others with Feature IDs 84 and 85 in 2000. These temporal relationship data match well with what Figure 5.10 conveys.

Figure 5.12 displays the elevation data valid in a) 1979 and b) 1999, which are represented at the CSC STDM. Figure 5.13 shows the elevation data in 1979, which is represented in the sequential snapshots approach and has edge problems because the original DEM dataset is merged from several small maps. However, this problem does not exist in Figure 5.12a, because that 1979 elevation image is recovered using the current state and the change map.



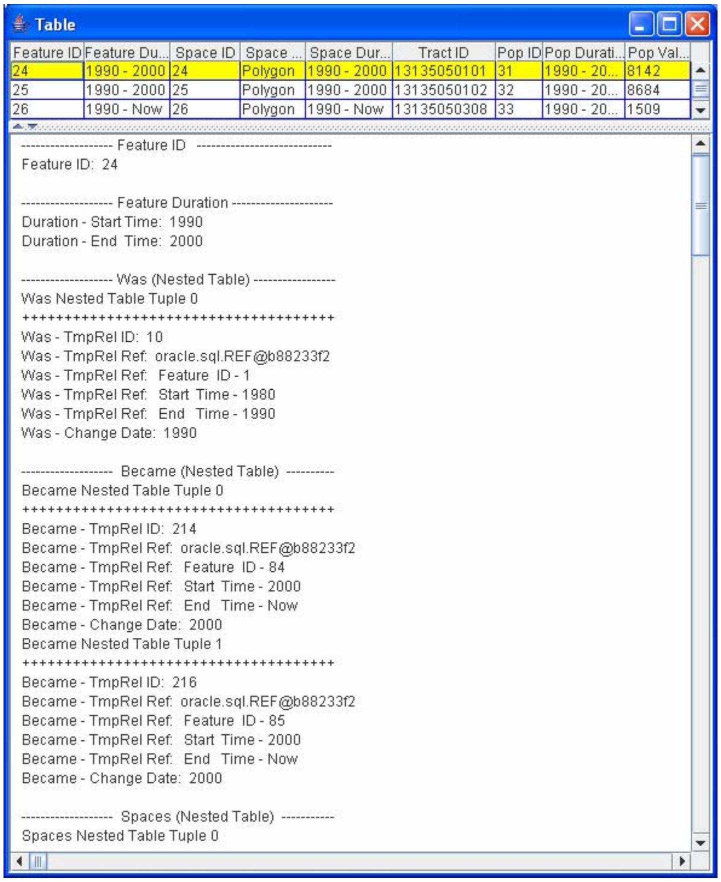
a) 1992 b) 1996 c) 1999

Figure 5.9 Land use/land cover and census tracts at a) 1992, b) 1996 and c) 1999.

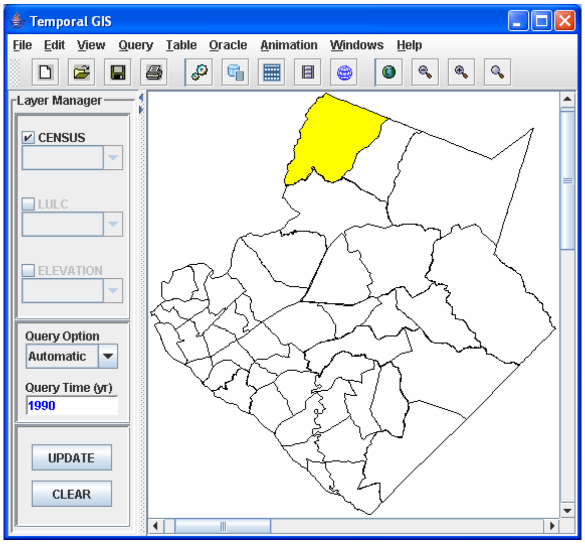


a) 1980-1990 b) 1990-2000 c) After 2000

Figure 5.10 Census tracts valid during a) 1980-1990, b) 1990-2000 and c) after 2000.

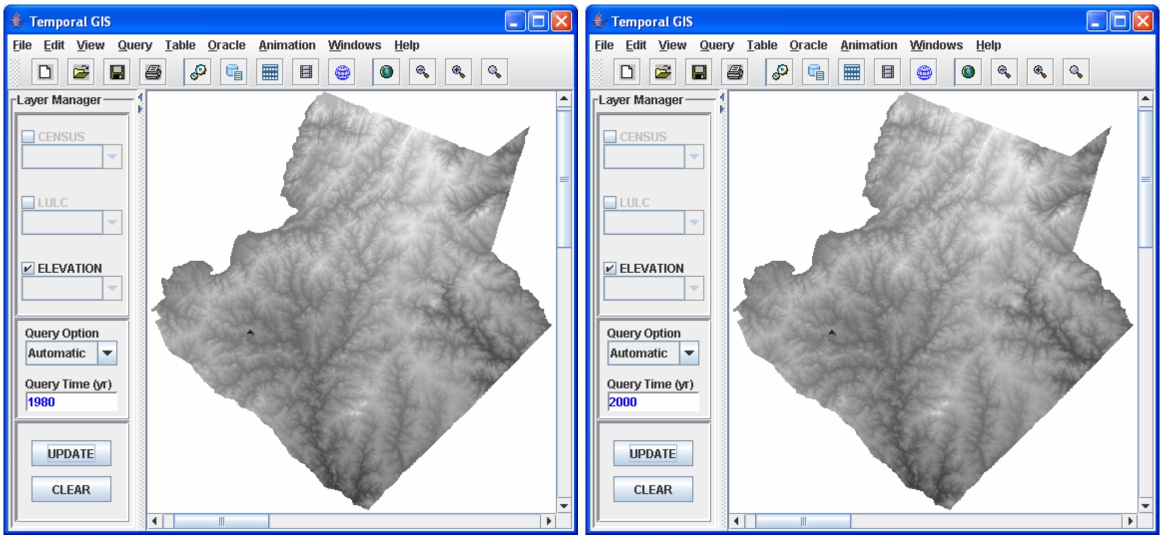


a)



b)

Figure 5.11 The a) table and b) map windows of a selected census tract in 1990.



a) 1979 b) 1999

Figure 5.12 The elevation data represented at the CSC approach.

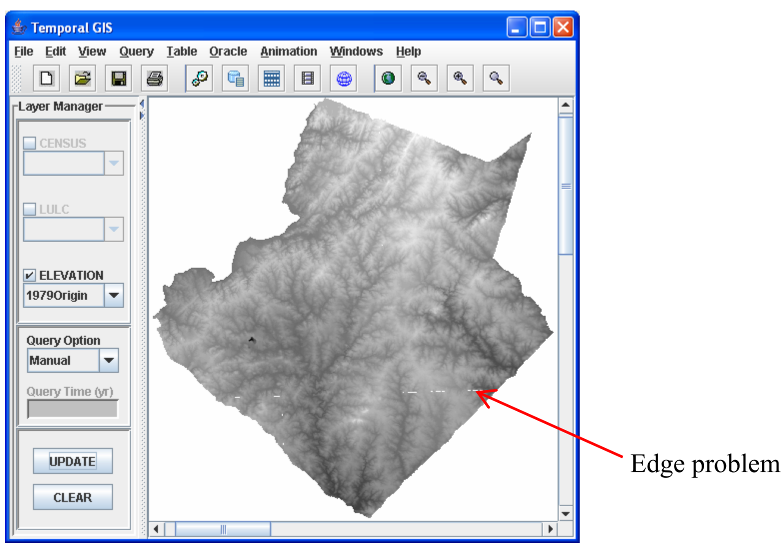


Figure 5.13 The 1979 elevation data represented at the sequential snapshots approach.

Figure 5.14 presents change in elevation 1979-1999 and Figure 5.15 shows change in LULC 1988-1996. Since there is only a little change in elevation and the difference image is smaller in size than a snapshot, the current-state-with-change approach is better for the elevation data than the sequential snapshot. On the other hand, the sequential snapshots approach is better for LULC, because the changes in the current-state-with-change do not save much space but are not as meaningful as the original snapshot.

Figure 5.16 (a-g) provide seven snapshots in an animation of the prototype temporal GIS with census tracts and LULC layers selected. In this animation, we use a 4-year temporal interval, so there is a snapshot every four years. In the prototype temporal GIS, we use the original images as key frames, and simply keep the key frames for those between them. No morphing is applied in this prototype temporal GIS, so the change in animation is abrupt.

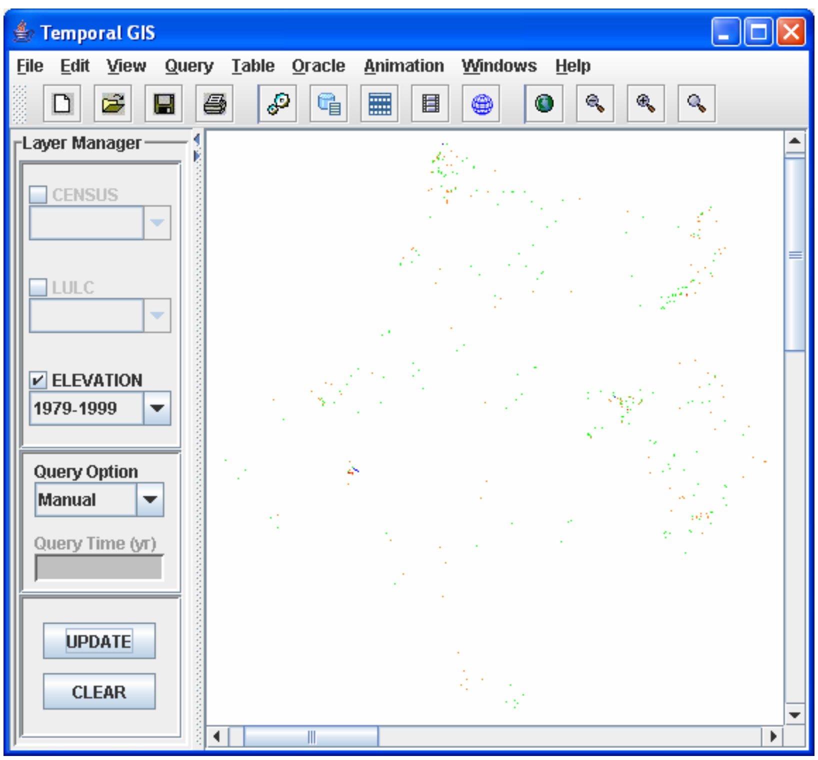


Figure 5.14 The change in elevation, 1979-1999.

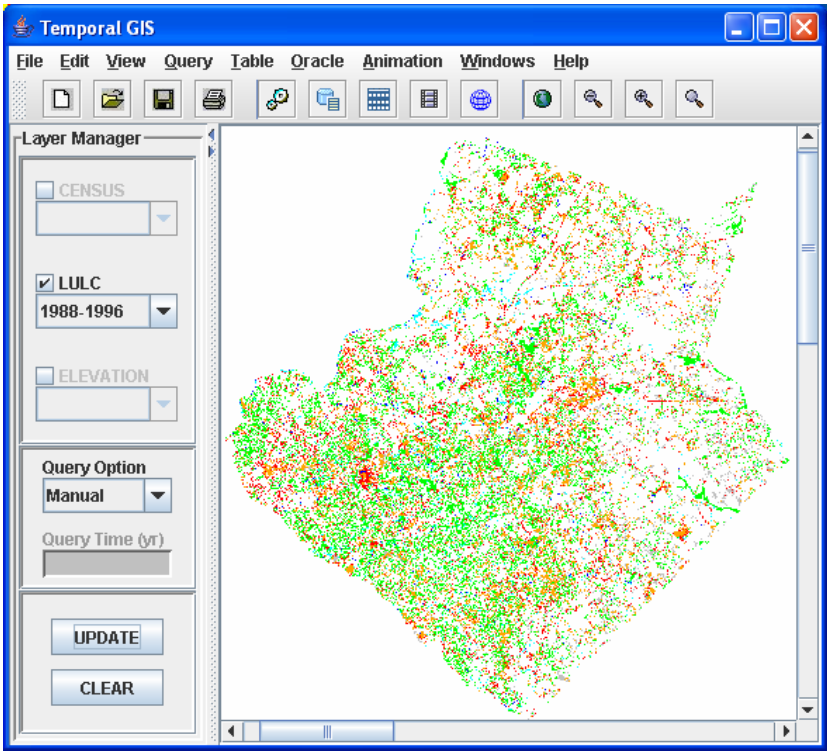
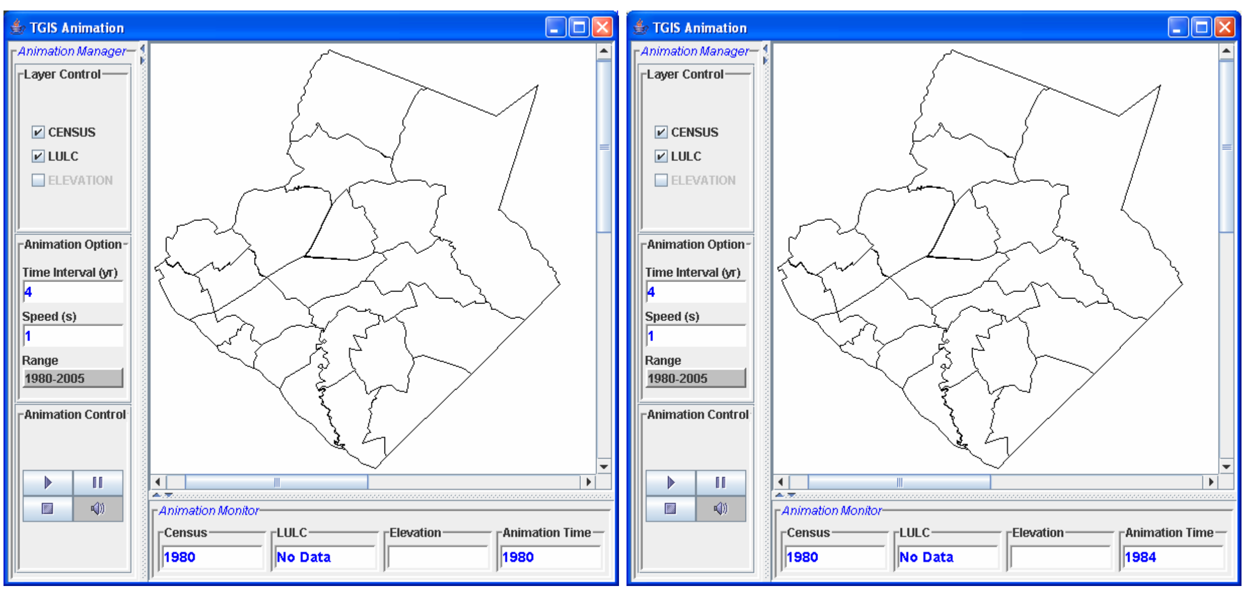
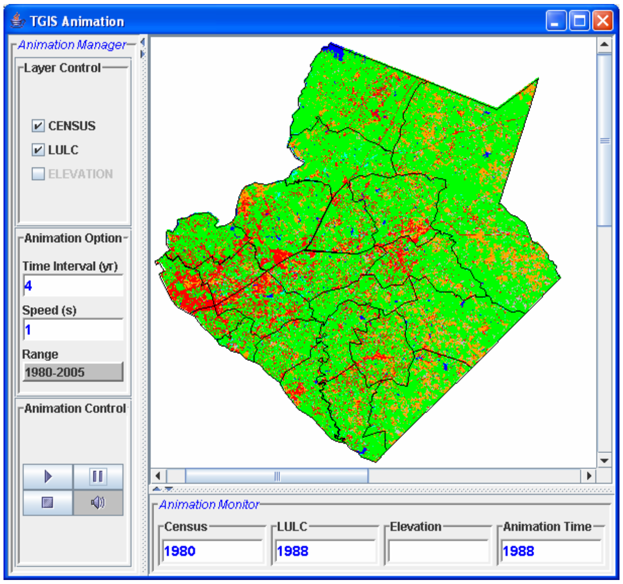
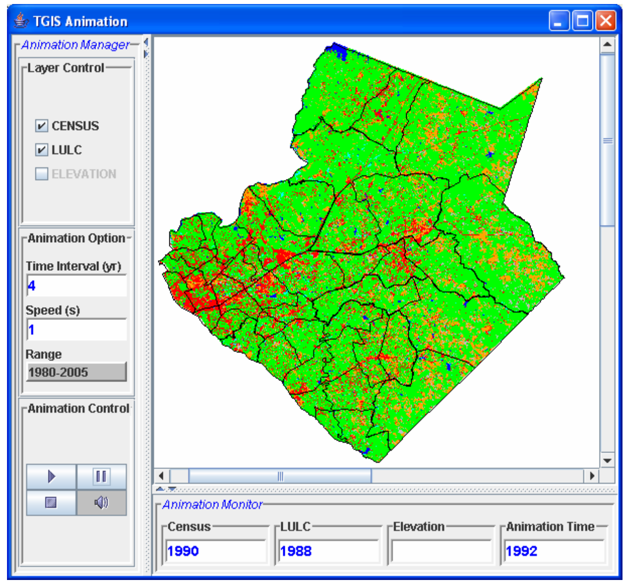


Figure 5.15 The change in LULC, 1988-1996.

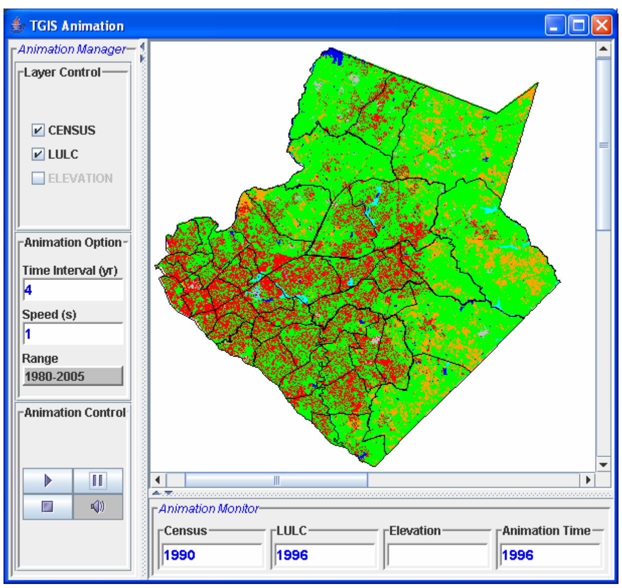


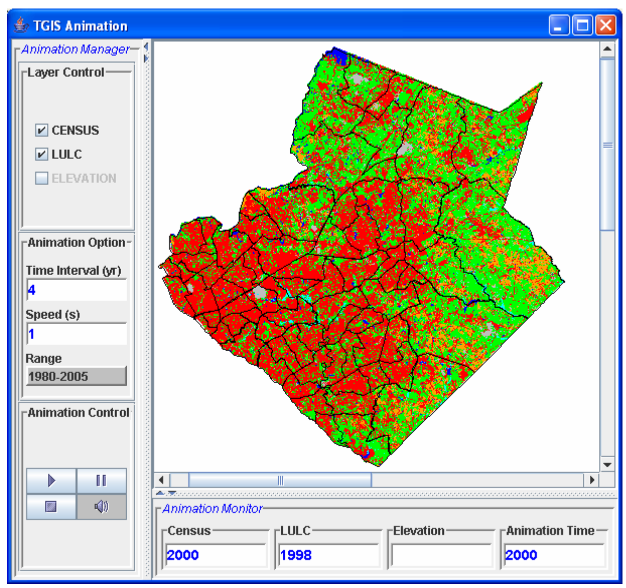
a) 1980 b) 1984



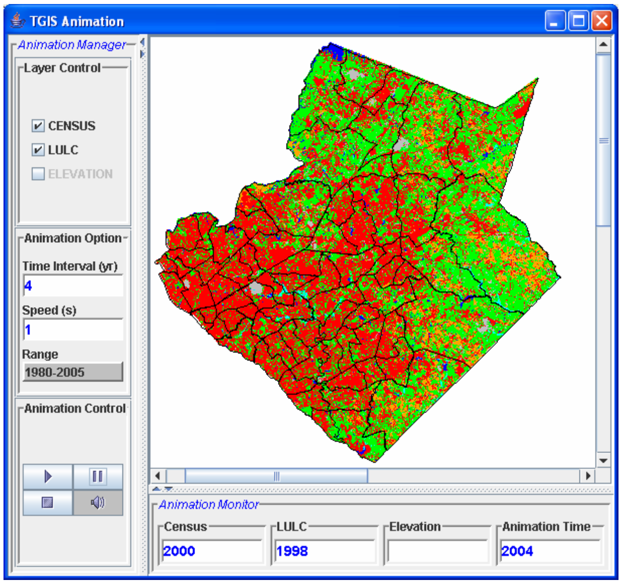


c) 1988 d) 1992





e) 1996 f) 2000



g) 2004

Figure 5.16 Seven snapshots in an animation in the prototype temporal GIS.

This case study gives examples for all four spatio-temporal queries in section 5.2.3.1. The main window of the prototype temporal GIS allows querying a snapshot at a given time, getting the history of a feature through the table, and retrieving changes of field data. The animation window can be used to replay the history during a time interval or the changes of features.

5.4 Discussion and conclusions

This paper examined temporal GIS, which is capable of integrating spatio-temporal data represented in multiple STDMs, based on common spatial and temporal reference systems. There are three major components: STDMs, interface and GUI in a temporal GIS. Each STDM must implement common editing and query interfaces, and may have its own optional interface. The system development strategies and database design are highly dependent upon the STDMs with which temporal GIS aims to work.

In the case study, we develop a prototype temporal GIS for three STDMs: the feature-based temporal model, the CSC, and the sequential snapshots approach. The example, with three datasets represented in these three STDMs, shows that the prototype temporal GIS is capable of integrating all three STDMs. The prototype temporal GIS implements all four spatio-temporal queries identified in this paper. Another finding in this case study is that the CSC is better for fields with little change such as elevation, while the sequential snapshots approach is better for fields with much more change such as LULC.

The most difficult problem encountered in this research was how to obtain spatio-temporal data. For example, we planned to incorporate transportation in the case study, but found it hard to get relevant data. With three transportation datasets: 1995 Tiger, 1997 DOT and 1998 Tiger data available from the Georgia GIS Clearinghouse, comparisons among them show: 1) there is almost no spatial change in highway/state owned roads during 1995-1998; and 2) although some roads have different names in different datasets, we cannot tell for sure it results from a change in name because in reality many roads do have multiple names and it is possible that different datasets use different names. Therefore, it is difficult to find spatio-temporal change only with historical data in snapshots. At the end, we decided to exclude the highway data in this case study.

The prototype temporal GIS introduced in this paper is rudimentary. In the future, we plan to 1) improve thematic mapping; and 2) provide more temporal query capabilities. In addition, we wish to: 1) conduct spatio-temporal data analysis using the prototype temporal GIS; and 2) change detection to support spatio-temporal data.

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CHAPTER 6

CONCLUSIONS

The purpose of this dissertation research is to incorporate time into base geographic data. Different from most other spatio-temporal models, the representations of time proposed in this research are not specified for a single application such as cadastre or transportation, and not only for spatial data in field or object form. This dissertation models time for base geographic data, represented as fields or objects, which are used commonly for many GIS applications. The representations introduced in this research are not constrained to base geographic data, but can also be applied to other types of data.

This research question can be divided into three sub-questions: 1) how to represent time in base geographic data, 2) how to implement the STDM(s) and 3) how to develop a temporal system to work with spatio-temporal data represented in the data models? The answer to the first question influences the study of the others.

In order to represent time appropriately, this dissertation first examined the ontological commitment for time in base geographic date. For base geographic data, the main characteristics of time are absolute and linear. Although base geographic phenomena can change discretely, stepwise, or continuously, all of them are simplified as discrete in this dissertation. With this simplification, a change takes place at a point time, and a world status is valid during a time interval. World time is more important to base geographic data, but it is not always available and data collection or database time is often used as a substitute. Temporal granularity is coarse and can be different for different types of base geographic data.

Currently, there are two major spatial representations, objects and fields, and a layer-based temporal framework for base geographic data. Review of literature shows most spatio-temporal approaches can only work with one spatial representation, either field or object form. Although there are a few frameworks able to work with both, they are usually not suitable for both.

Because space can be represented differently in existing GIS and there are similarities between space and time, this dissertation argues time does not have to been represented using a single framework, but can be in different approaches. According to the object-field dichotomy, this dissertation identifies two combinations for time in base geographic data: continuous space with discrete time and discrete space with discrete time. This dissertation proposes the layer-based for the former and a feature-based temporal model for the latter. The layer-based approach can be further classified into CSC to model change, and sequential snapshots to model status.

In the feature-based temporal model for objects, time is represented using different states of a feature. A temporal feature is a basic element in this model. It can have multiple temporal spaces and multiple temporal themes during different time periods. All of them are functions of time. Since time and change are treated as discrete, these temporal functions can be simplified as constants during corresponding time intervals. This makes it possible to model a feature history with several time intervals and corresponding states. There exist "Was/Became" temporal relationships between temporal features, between temporal spaces, and between temporal themes.

In the CSC approach, discrete change in fields is modeled using the current state and a series of spatio-temporal changes. The current not the original state is considered as the base state because the current data are the most frequently used and need to be accessed efficiently.

The sequential snapshots approach is recommended for fields where space is frequently fragmented through time. However, there is no strict distinction between CSC and sequential snapshots, and each type of field data could be represented in either way.

With these temporal models, this dissertation discusses temporal query capabilities, including four elemental temporal queries and one complex spatial-temporal analysis. The data model determines the way and efficiency that each type of temporal query is solved.

This dissertation does not only seek a conceptual framework for time, but also studies questions of how to store and manage the spatio-temporal data in a computer system and how to query and visualize them in a GIS. The layer-based temporal framework is relatively easy and has been studied in other research, so this dissertation only discusses the implementation of the feature-based temporal model.

The feature-based temporal model, which is proposed in this dissertation, can be best implemented in ORDBMS, which supports ADT and fits the data model very well. For example, the nested table data type can be applied for the 1-m 'Has' relationship between a temporal feature and its temporal spaces or themes. Timestamps can be added at record-, attribute- and attribute-group levels. In the OR feature table, one record models one temporal feature, and all historical information about the feature is included.

From a system view, this dissertation designs and develops a prototype temporal GIS. This dissertation studies temporal GIS, which is capable of integrating spatio-temporal data represented in multiple STDMs, because different spatio-temporal approaches are used for different types of spatio-temporal data in base geographic phenomena and they are often used together in GIS applications. The integration is based on common spatial and temporal reference systems. There are three major components: STDMs, interface and GUI in a temporal GIS. Each STDM must implement a common editing and query interface, and may have its own optional interface. The system development strategies and database design are highly dependent upon the STDMs with which the temporal GIS works.

In order to visualize spatio-temporal data organized in OR tables for temporal features, this dissertation suggests development of a new temporal GIS rather than extending an existing one, because the existing GIS environment limits the advantages of the OR schema. However, there is much work to develop a new system.

In the case study, a prototype temporal GIS is developed for three STDMs: the feature-based temporal model, CSC, and sequential snapshots. An example, with three datasets represented in these three STDMs, shows the prototype temporal GIS is capable of integrating all three STDMs. Another finding in this case study is that CSC is better for fields with little change such as elevation, while the sequential snapshots approach is better for fields with much more change such as LULC.

In addition to the main research objectives, this dissertation also finds that one feature class can be spatially represented as different spatial types such as point and polygon, and this can benefit the spatial representation of base geographic data in visualization as well as spatio-temporal change between different spatial types. In other words, spatial geometry can be defined not only at feature class or layer level, but also at feature instance level. Currently, one feature class can only be defined as point, line, or polygon in existing GIS. However, features of one class may be required to represent as different spatial types. For example, in the 1:24,000-scale topographic maps, small buildings are represented as a point while large ones represented as a polygon. This is possible in the database because the spatial geometry type of a feature is defined at the record rather than table level. The original GIS spatial data are organized using simple file, such as .shp in Shapefile. Its spatial geometry type is defined at the head of the file, or file level. With developments in computer science, especially databases, it is possible to define a column in a table for the shape of features. Although the spatial data type allows spatially geometry types at the record level, this advantage over the simple file has never been used.

The prototype temporal GIS introduced in this dissertation can not only work with the three STDMs, but also can integrate other models. In other words, the prototype temporal GIS developed in this dissertation is open and extendable. For each additional STDM, a corresponding program module to implement the interfaces can be added.

The most difficult problem in this research was obtaining spatio-temporal data. For example, transportation in the case study showed: 1) there is almost no spatial change in highway/state owned roads during 1995-1998; and 2) although some roads have different names in different datasets, one cannot tell for sure whether it results from a change in name or a real change in data. Therefore, it is difficult to find spatio-temporal change only with historical data in snapshots.

This dissertation is limited in two areas: 1) stepwise and continuous time in base geographic data is simplified as discrete; 2) the prototype temporal GIS introduced in this paper is rudimentary. In the future, I plan to 1) represent stepwise and continuous time in base geographic data; 2) improve thematic mapping; and 3) provide more temporal query capabilities for spatio-temporal analysis.

In conclusion, this dissertation presents a representation of time in base geographic data using different temporal approaches, introduces a feature-based temporal model for objects changing discretely, and develops a prototype temporal GIS to integrate spatio-temporal data modeled in three different approaches. McMaster and Usery (2004) identified two short, four medium, and three long term research objectives in the area of extending geographic representations. Compared with these research objectives, this dissertation contributes in three areas, including one short, one medium, and one long term. 1) The main idea, representing time in base geographic data with different approach, reflects human cognition. 2) The research used new DBMS techniques, ADT, to model spatio-temporal changes in objects. Each nested table models time like a Type 2 Slowly Changing data type. 3) The research also developed a feature-based temporal model, and integrated it with existing temporal approaches in a prototype temporal GIS. By doing so, this dissertation contributes in moving the traditional static GIS towards temporal GIS.

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