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Temporal GIS and Spatio-Temporal Modeling

Abstract

This paper investigates the development of temporal GIS and its applicability to support spatio-temporal modeling. Many GIS data models have been proposed to incorporate temporal information into spatial databases. Their general frameworks, with littl e considerations on data needs for spatio-temporal modeling, use a set of geometry-based spatial objects to represent reality. Thematic characteristics are represented as attributes of spatial objects. Temporal information is either associated with time-s tamped individual layers, such as the Snapshot Model (Armstrong, 1988), or individual spatial objects, such as the Space-Time Composite Model (Langran and Chrisman, 1988). The snapshot approach usually results in significant data redundancy. The space-tim e composite approach requires re-construction of thematic and temporal attribute tables whenever operations involve any changes in spatial objects (shape, size, or configuration). Consequently, geographic entities tend to be decomposed into fragments of s patial objects. For example, a wildfire event can be represented by a set of polygons with descriptions of burn severity and burn time. Problems appear, however, in representing phenomena like front lines, re-ignition, and spotting. The lack of direct map pings from GIS data to model input hampers GIS capabilities of spatio-temporal analysis, such as calculating periodicity, rate of movement, and process. Further attempts have been made to provide such direct mappings by event-based (Peuquet and Duan, 1995) or object-oriented data models (Worboys, 1992, Raper and Livingstone, 1995). This paper aims to (1) examine these typical temporal GIS data models, (2) discuss their applicability to facilitate spatio-temporal analytical modeling, (3) provide examples o f spatio-temporal analytical models and phenomena difficult to be handled in these proposed temporal GIS data models, and (4) synthesize important data concepts in spatio-temporal analytical models to be included in temporal GIS.

I. Introduction

A temporal GIS aims to process, manage, and analyze spatio-temporal data. However, the capabilities of any information system largely rely on the design of its data models. Data models present the conceptual core of an information system; they define data object types, relationships, operations, and rules to maintain database integrity (Date, 1995). A rigorous data model must anticipate spatiotemporal queries and analytical methods to be performed in the temporal GIS. Information about temporal constr ucts must be represented by data objects defined in data models to be stored or retrieved for analysis in a GIS. If a temporal GIS does not have a good data model, its support for temporal queries and temporal analysis of phenomena will be ineffectual.

Conventional GIS data models emphasize static representations of reality. Geographic information for a given area is decomposed into a set of single-theme layers as regular (raster) or irregular (vector) tessellation models (Frank and Mark, 1991). The se layers constrain GIS capabilities to represent dynamic information, such as transitions and motion. Raster cells encode attribute values at every given location with no considerations of the spatial characteristics of the theme they represent. Geometri cally indexed vector objects, on the other hand, 'force a segmentation of the entities being represented into separate layers whenever they interact in time or space: adopting this representational method forces compromises on most environmental modeling' (Raper and Livingstone, 1995, pp. 359). GIS needs a complete and rigorous framework for geographical data modeling (Goodchild, 1992) to overcome the difficulty in handling geographic complexity, scale differences, generalization, and accuracy (Burrough a nd Frank, 1995). The lack of data representation schemata to integrate GIS data with models for spatiotemporal processes appears to be a major shortcoming in current GIS.

The paper discusses the trend of modeling temporal data in GIS. Key temporal GIS data models will be elaborated on the development of modeling spatiotemporal data. The discussion that follows provides difficult cases to be represented by the current t emporal GIS data models. To improve the capabilities of temporal GIS, the paper suggests important constructs in the representation of spatiotemporal phenomena.

II. The Trend of Temporal Data Modeling in GIS

The development of temporal data modeling in GIS parallels to the progress of temporal data modeling in the computer science (CS). The incorporation of temporal components has been implemented with the relational model and then with the object-oriente d data models in CS. The trend of temporal data modeling in GIS is moving from time-stamping layers (similar to relational tables) to time-stamping events or processes (similar to objects). Data semantics is a key issue in data modeling and the fundamenta l idea is to raise the level of abstraction in the transition from layers/tables to events/objects.

II.1. Representing spatiotemporal information by time-stamping spatial objects

In the last decade considerable research effort has been directed to temporal databases and temporal query languages (Tansel et al., 1993). Computer scientists have proposed methods to incorporate temporal information into a relational database by tim e-stamping a relation (a table, Gadia and Vaishnav, 1985), individual tuples (ungrouped relations, Snodgrass and Ahn, 1985), or individual cells (grouped relations, Gadia and Yeung, 1988). In GIS, Langran and Chrisman (1988) and Langran (1988) explore the idea of temporal GIS to outline a framework for conceptual design and implementation of incorporating temporal information in GIS. As Snodgrass (1992) summarizes the progress on the support for time-varying information in database management systems, Lan gran (1993) provides a comprehensive and compelling synthesis of temporal research in GIS. Parallel to the three relational database approaches, temporal information has been incorporated into GIS spatial data models by time-stamping layers (the snapshot models, Armstrong, 1988), attributes (space-time composites, Langran and Chrisman, 1988), and spatial objects (spatiotemporal objects, Worboys, 1992).

In the snapshot model, every layer is a collection of temporally homogeneous units of one theme (Figure 1). It shows the states of a geographic distribution at different times without explicit temporal relations among layers. Time intervals between an y two layers may vary and there is no implication for whether changes occur within the time lag of any two layers. The Temporal Map Sets (TMS, Beller et al., 1991) model can be seen as extensions of the snapshot model. The design of TMS purports to model geographic events in a defined area (Figure 2). Events are defined as binary TMSs, specifying whether each cell is in or out of the event. These snapshot approaches always result in a large amount of data duplication with unchanged properties in space and time. The major drawback is data redundancy and the risk of data inconsistency.

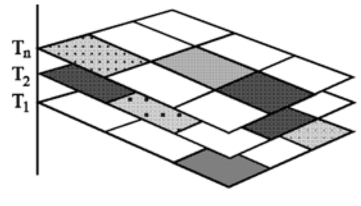


Fig.1: An example of the snapshot model (Armstrong, 1988)

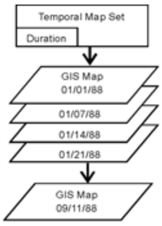


Fig.2: An example of a TMS (Beller et al., 1991)

The model Space-Time Composites (STC) represents the world as a set of spatially homogenous and temporally uniform objects in a 2D space (a layer, Figure 3). Every space-time composite has its unique temporal course of changes in attributes. Apparentl y, space-time composites can be derived by temporal overlays of time-stamped layers (snapshots). A space-time composite conceptually describes the change of a spatial object through a period of time. Attribute changes are recorded at discrete times, altho ugh its temporal resolution is not necessarily accurate. The STC model is able to record temporality within the largest common units of attribute, space, and time (i.e. change in situ), but it fails to capture temporality among attributes across space (i. e. motion or movement). In addition, updating a database of STC requires reconstruction of STC units. Consequently, geometrical and topological relationships among STC units change and the whole database, both spatial objects and attribute tables, needs t o be re-organized.

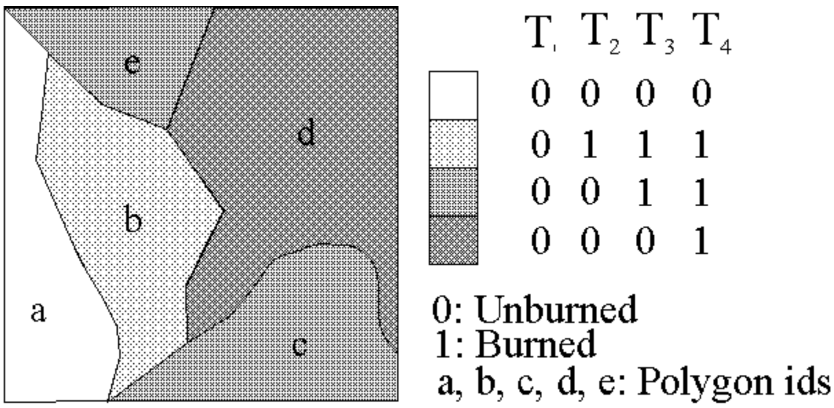
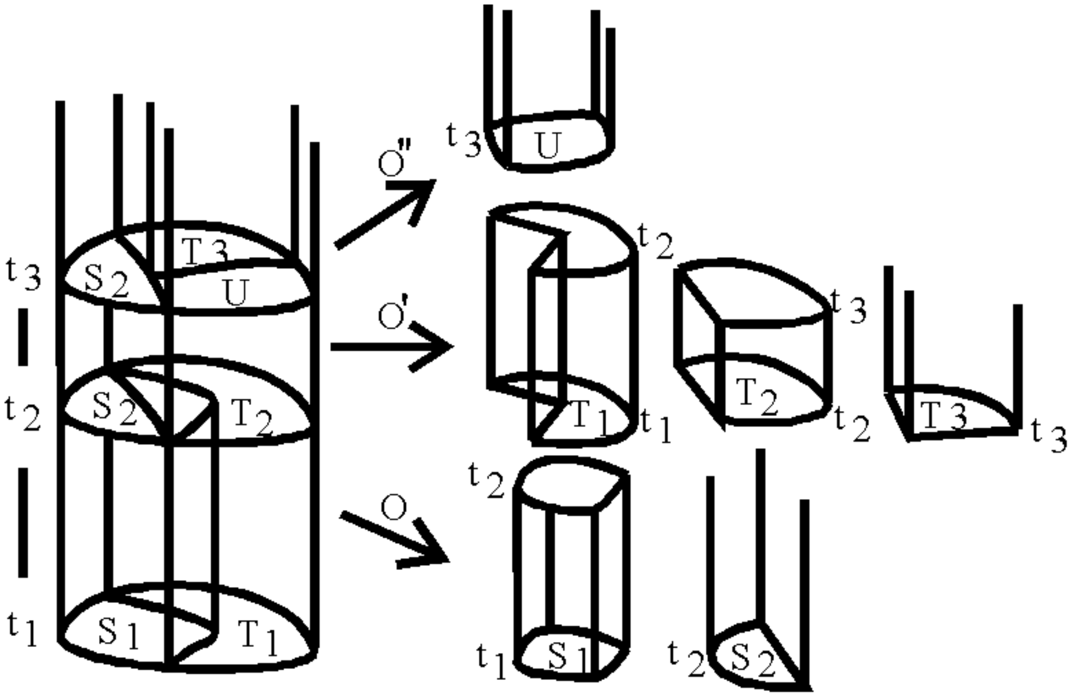


Fig.3: An example of an STC layer for burns (Modified from Langran and Chrisman, 1988)

The spatiotemporal object model (ST-Object model) represents the world as a set of discrete objects consisting of spatiotemporal atoms by incorporating a temporal dimension orthogonal to the 2D space (Figure 4). Spatiotemporal atoms are the largest ho mogeneous units in which certain properties hold in both space and time. A spatiotemporal object can possess changes in both space and time, although there is no change occurring within each of its spatiotemporal atoms. Therefore, the ST Object model is a ble to record changes in attributes of a ST-object in both spatial and temporal dimensions, together or separately, by projecting its ST-atoms to the spatial and/or temporal space. However, gradual changes in space through time are unable to be represente d in the ST Object model since its ST-atoms are discrete. Though the ST Object model is similar to the snapshot model and STC model, it only represents sudden changes upon an independent, discrete, and linear time structure. None of them are able to portr ay the concepts about transition, process, or motion.



ST-objects modeling regional change

Decomposition of ST-objects into ST-atoms

Fig.5: An example of a spatiotemporal object model with spatiotemporal atoms (Worboys, 1992)

II.2. Representing spatiotemporal information by events or processes

Computer scientists have developed temporal data models based on the concepts of time sequences (STC: temporal sequence collection, Segev and Shoshani, 1993), and time objects (OODAPLEX, Wuu and Dayal, 1992). These models are comparable to the recent studies of temporal information modeling by events or processes, such as the event-based spatio-temporal data model (ESTDM, Peuquet and Duan, 1995), and the geomorphologic spatial model (OOgeomorph, Raper and Livingstone, 1995).

Peuquet and Duan (1995) proposed a new raster-based data model (ESTDM) to organize spatiotemporal information about locational changes (Figure 5). Both ESTDM and TMS models group time-stamped layers to show temporal observations of a single event in a temporal sequence. However, ESTDM outperforms TMS in terms of data efficiency and support for analysis of temporal patterns and relationships, since the ESTDM stores 'changes' in relation to a previous state rather than a snapshot of an instance. A heade r file contains information about its thematic domain, pointer to a base map, and pointers to the first and last event lists. The base map shows an initial snapshot of a single theme of interest in a geographic area. An event-based series (EST series) con sists of the spatiotemporal dynamics of the thematic domain in that geographic area. Every event is time-stamped and associated with a list of event components to indicate where changes have occurred. An event component shows changes to a pre-defined loca tion (a raster cell) at a particular point in time. The ESTDM has shown its capabilities and efficiency to support both spatial and temporal queries. However, the adoption of the ESTDM model to a vector-based system requires a substantial redesign of even t components. Historical or transitional information of an entity or a process will be fragmented if changes occur to spatial objects or their topology. Mechanisms are needed to allow event components to keep track of their pre-defined entities and locati ons.

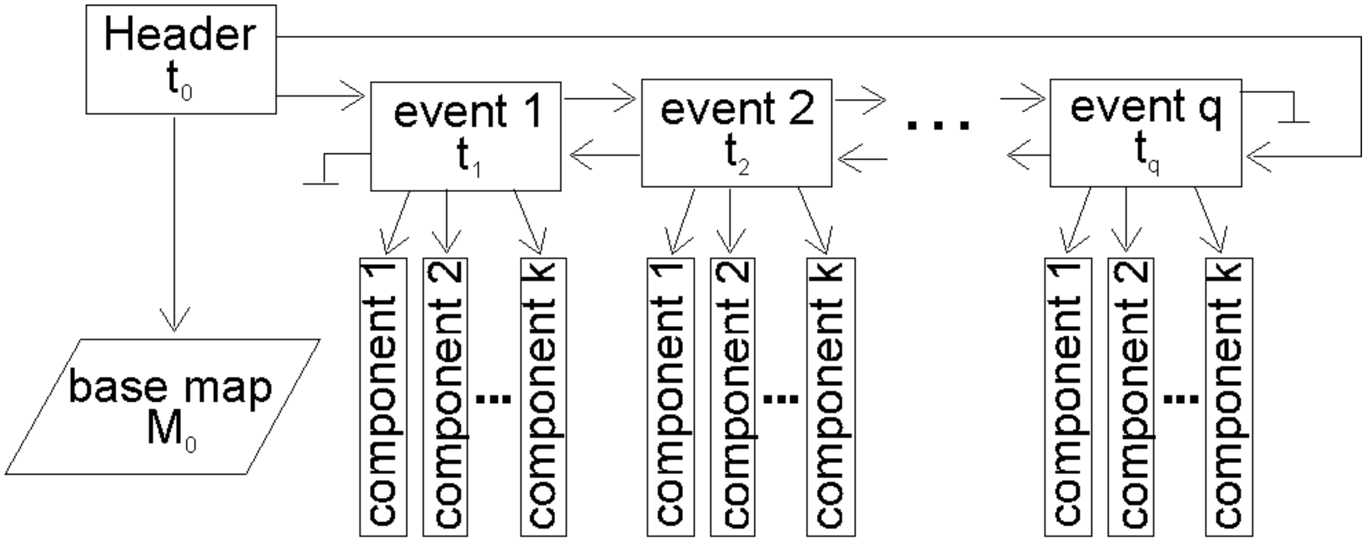


Fig.5: Primary elements and the pointer structure of an ESTDM (Peuquet and Duan, 1995).

While the ESTDM stores changes of a single theme at pre-defined locations, the design of OOgeomorph attempts to incorporate geomorphologic processes and theories with classes in an object-oriented representation (Figure 6, Raper and Livingstone, 1995) . A geomorph_info module models geomorphologic data from a geomorphologic spatial database to the data representation to be used in a geomorph_system module. A geomorph_system module represents the dynamics of a geomorphologic system, such as a coastal sy stem or a fluvial system, and includes associated geomorphologic theories. A set of CASE tools, mform, mprocess, and mmaterial, associate attribute data about geomorphologic forms, processes, or materials. Data input from the geomorph_info are used to ini tiate geomorphologic objects based on structures defined in classes of form, process, or material. As such, every geomorphologic phenomenon is represented by a set of form, process, and material objects, and every of these objects is, in turn, represented by a set of attribute objects. Three-dimensional location (x, y, z) and one-dimensional time (t) are referenced to objects in attribute classes (att). This approach is similar to Worboy's space-time object model of space-time objects and space-time atoms , but OOgeomorph stresses the importance of a physical system and processes within the system. Space-time objects and atoms are formed by their spatiotemporal associations, but objects in the OOgeomorph are linked by their relationships defined in a geomo rphologic system. While OOgeomorph can handle point-based locational information well, it has difficulty in manipulating area data and topological relationships.

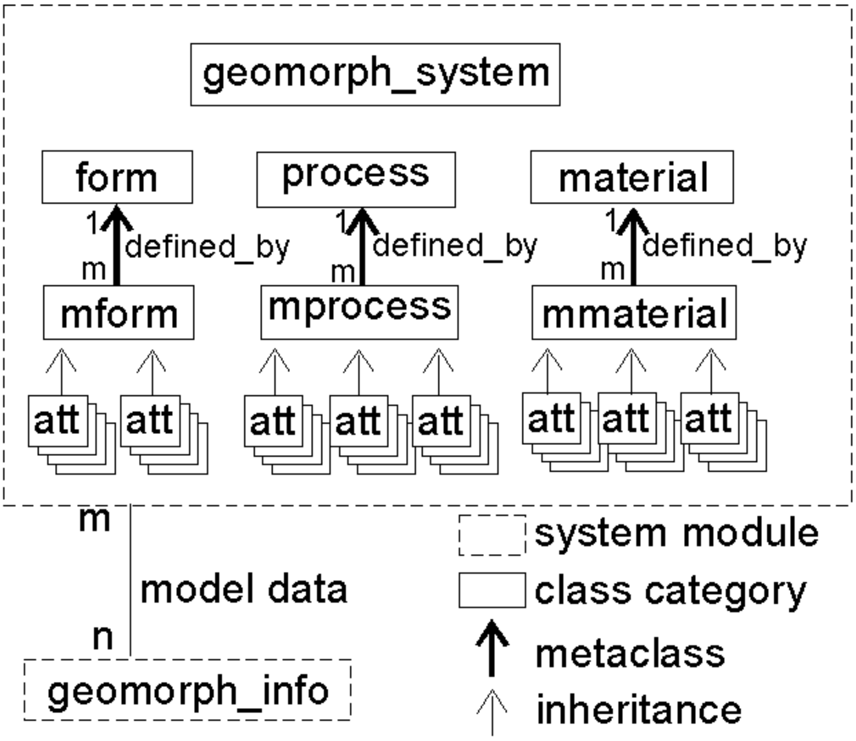


Fig.6: The design of OOgeomorph: an object-oriented data system (Raper and Livingstone, 1995).

However, the real challenge in GIS temporal modeling is to maintain spatial objects' identities throughout the evolution in geometrical properties and topological relationships. This is unimportant for aspatial databases or raster/point-based GIS data bases. Raster or point-based spatial objects are stationary in space and temporal information can be associated with spatial object identifiers and therefore can be handled mainly as an aspatial database. Line- or polygon-based GIS are very likely involve d in changes to geometry and topology of spatial objects. Domain-oriented data models are proposed to manage complex changes of spatial objects and maintain object identities.

The three domain model is developed by analyzing spatiotemporal information needs for wildfire studies and representational requirements to facilitate these studies in a GIS environment. A wildfire information cycle shows the needs of four data schema ta. Snapshots represent states, fire entities represent processes, entity snapshots represent changes, and fire mosaics represent history. These representational schemata are designed to support spatiotemporal data for wildfire studies of fire forecasting , fire behavior, fire impacts, and fire history. A separation of semantical1, spatial, and temporal information is necessary in order to dynamically support all four schemata. The three domain model defines semantical, temporal, and spatial objects in thr ee separate domains. Time is modeled as an independent concept in the three domain model, instead of being an attribute of location as in the snapshot model or being an integral part of spatial entities as in the space-time composites and spatiotemporal o bjects. Geographic concepts and entities are represented by dynamically linking the three types of objects from a layer or object perspective (Figure 7). The data model is able to represent reality from locational-centered, entity-centered, and time-cente red perspectives with six basic types of changes in geographic information: attribute changes, static spatial distribution, static spatial changes, dynamic spatial changes, mutation of a process, and movement of an entity (Yuan, 1995). The major advantage of the three domain model is that there is no pre-defined data schemata; rather the model will dynamically link relevant objects from the three domains to represent a geographic entity or concept. Linkages among these objects can be numerical or fuzzy me mbership functions. These functions are useful to represent dynamic boundaries such as transitions of soil distributions, seasonal changes in lake boundaries, or diurnal changes in shorelines.

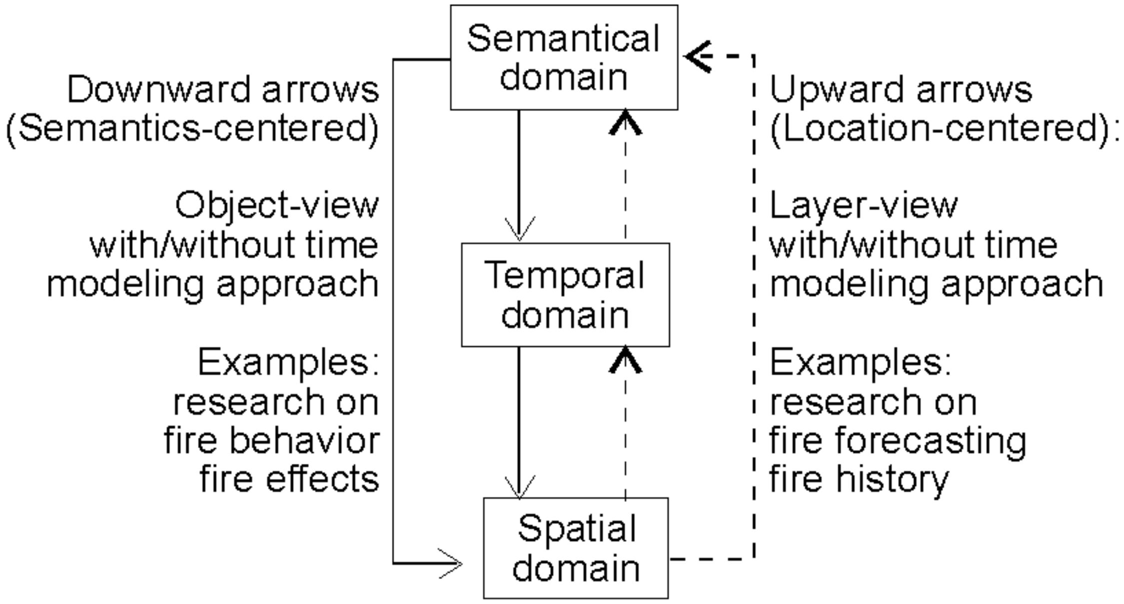


Fig. 7: An conceptual framework of the three domain model (Yuan, 1994b).

Smith et al. (1993) and Smith (1994) also take a domain approach in the design of a modeling and database system (MDBS) to support high-level modeling of spatiotemporal phenomena. The MDBS consists of a conceptual domain (C-Domain) for abstract views of entities and transformation and a representation domain (R-Domain) for symbolic representation (Figure 8). Typical R-Domains include primitive domains (bools), purely spatial domains (polygons), non-spatial domains (rainfall), geographic domains (drain age basins), and temporal domains (hydrographs). These R-Domains can in fact be incorporated into the domains of semantics, space, and time. The two systems are compatible, and the three domain model will benefit by incorporating the theory of domains as well as the modeling and database language (MDBL) developed in the MDBS.

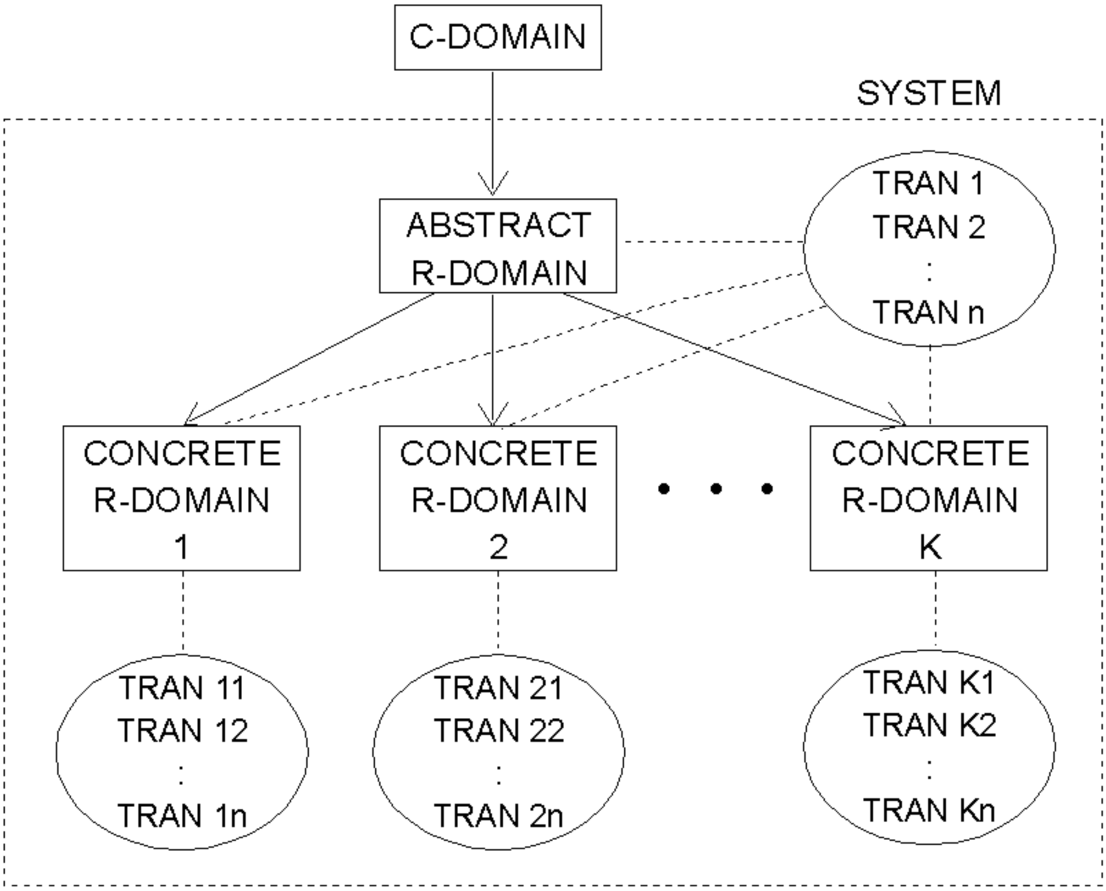


Fig.8: A C-domain, an abstract R-domain and its n concrete R-domains (Smith, 1994).

III. Examples of Difficult Cases for Temporal GIS

Changes occur to attributes of a phenomenon, environmental settings, behaviors of an event, or mechanisms of a processes. There are six major types of spatial and/or temporal changes in geographic information (Yuan, 1995):

I. For a given site where occurrences and duration of events or attributes may change from time to time, analysis is done by fixing location, controlling attribute, and measuring time.

II. For a given point in time where a certain phenomenon may change its characteristics from site to site, analysis is done by fixing time, controlling attribute, and measuring location.

III. For a given period of time where attributes may change from site to site through time, analysis is done by fixing time, controlling locations, and measuring attributes.

IV. For a given event where its characteristics or processes may change at sites through time, analysis is done by fixing attributes, controlling locations, and measuring time;

V. For a given area where attributes may change site to site and from time to time, analysis is done by fixing location, controlling time, and measuring attributes.

VI. For a given event where its location may change from time to time, analysis is done by fixing attributes, controlling time, and measuring locations.

Type I changes only involve variations in attributes over time; there is no variations in spatial properties. Therefore, this kind of data modeling and analysis can be totally handled in a semantical domain as historical transactions in a relational o r object-oriented database management system. Type II changes describe static spatial distribution of a geographic phenomenon, such as topography or air pressure. Techniques, such as contouring, choropleth mapping, and dasymetric mapping are often used to present such information, while current GIS store this kind of information in forms of vector or raster layers. Changes of Types III to VI alter geometry or topology of spatial and/or temporal properties.

III.1. Spatial Changes

Spatial changes refer to variations across space at a given time or in a period, in which comparisons are made between two or more sites according to data of the same vintage. Spatial changes can be classified as static (Type III) or transitional (Typ e IV). Static spatial changes concern variations of a geographic phenomenon at a snapshot, whereas transitional spatial changes compare states of an event or a process at different sites (Figure 9) . For example, we can compare vegetation successions at Site A and Site B to examine the ecological impact of air pollution. As another example, central and western India experience heavy rainfalls in El Nino years, while the northern India usually has deficit of precipitation during these periods. Type IV tra nsitional changes describe variations of spatial properties for a given event or process in a time series (Figure 10). Such changes can be shown by linkages from a set of temporal objects to a set of spatial objects. Three basic parameters in measuring sp atial changes are attribute, duration, and continuity of a phenomenon, event, or process. For example, we can compare transitional changes of landuse types at Site A with what has occurred at Site B from T1 to T2. Or, we can compare impact of the monsoon trough on rainfall processes in El Ni(o years at these two sites.

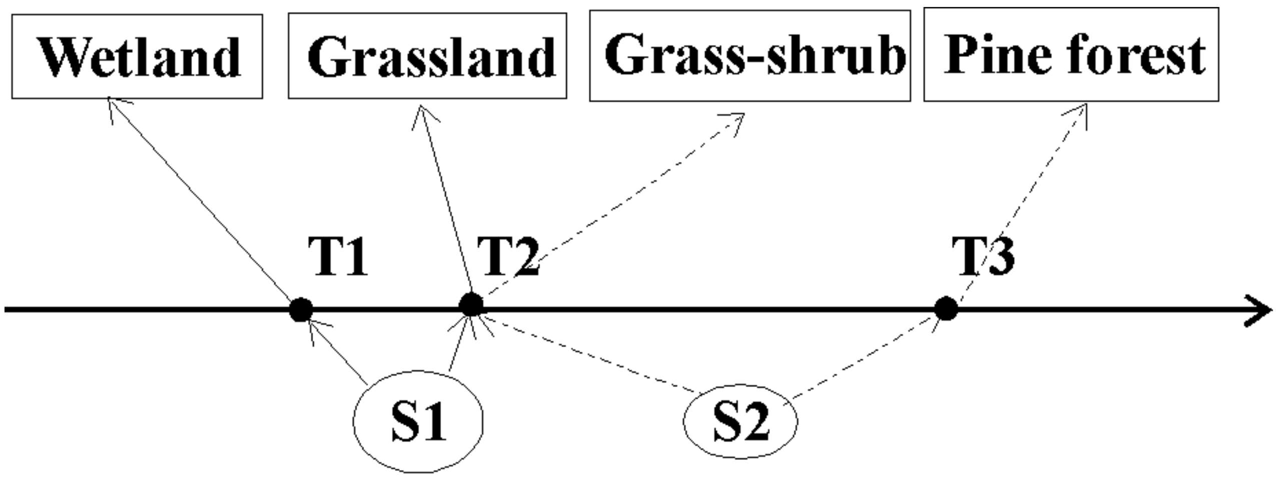


Figure 9: An example of static change (Type III Change).

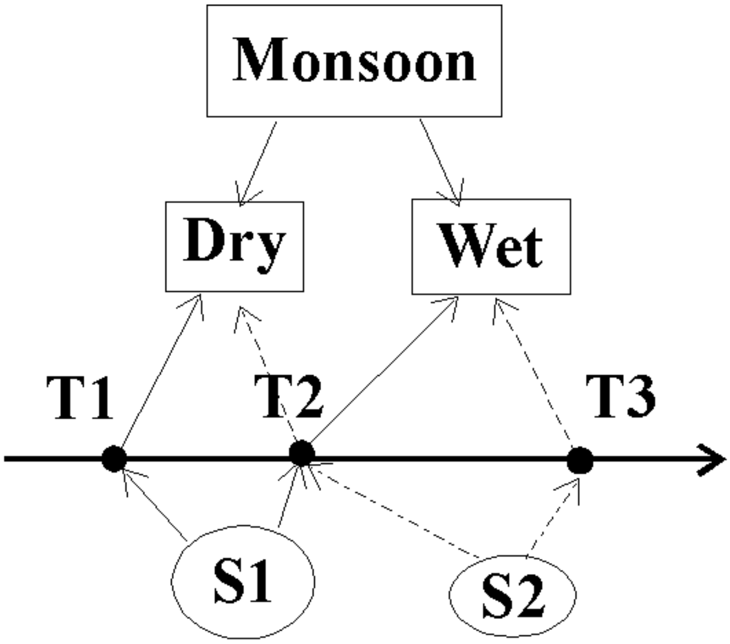


Figure 10: An example of transitional change (Type IV Change).

II.2. Temporal Changes

Temporal changes are changes occurring at different points or periods in time, and they are recognized by changes in spatial properties and/or locations from time to time. Two types of temporal changes are identified in this research: mutation (Type V) or movement (Type VI).

Mutation refers to changes occurring to the internal mechanisms of an event or a process, or to the interactions between events/processes and their environments. For example, a thunderstorm and a tornado may develop in a county and progress to other c ounties (Figure11). A practice of artificial rainfall in a region may mutate the patterns of precipitation and water resources in its surrounding area. Type V changes describe the mutation of a type of processes or events (semantical objects) by two sets of temporal objects; each of them is linked to a set of spatial objects. Comparisons are made between the two sets of spatial and temporal objects to show how a process mutates its attributes, temporal properties, and spatial characteristics in the two se ts of time series. Therefore, a comparison of frequency, period, and severity of an event in an area at different periods of time may suggest Type V temporal changes in the area.

Movement concerns the travel of an event or an entity from one place to another, and the event or entity may or may not involve changes in spatial properties other than location. Examples of movement include spread of wildfire, insect infestation, and animal movement (Figure12). The changes denote a single event or process and can be represented by linking a semantical object to a series of temporal objects and then to a set of spatial objects to show the movement of this event during the period const ituted of these temporal objects. Eight subtypes of temporal changes result from combinations of changes in attributes, morphology, and topology (Armstrong, 1988).

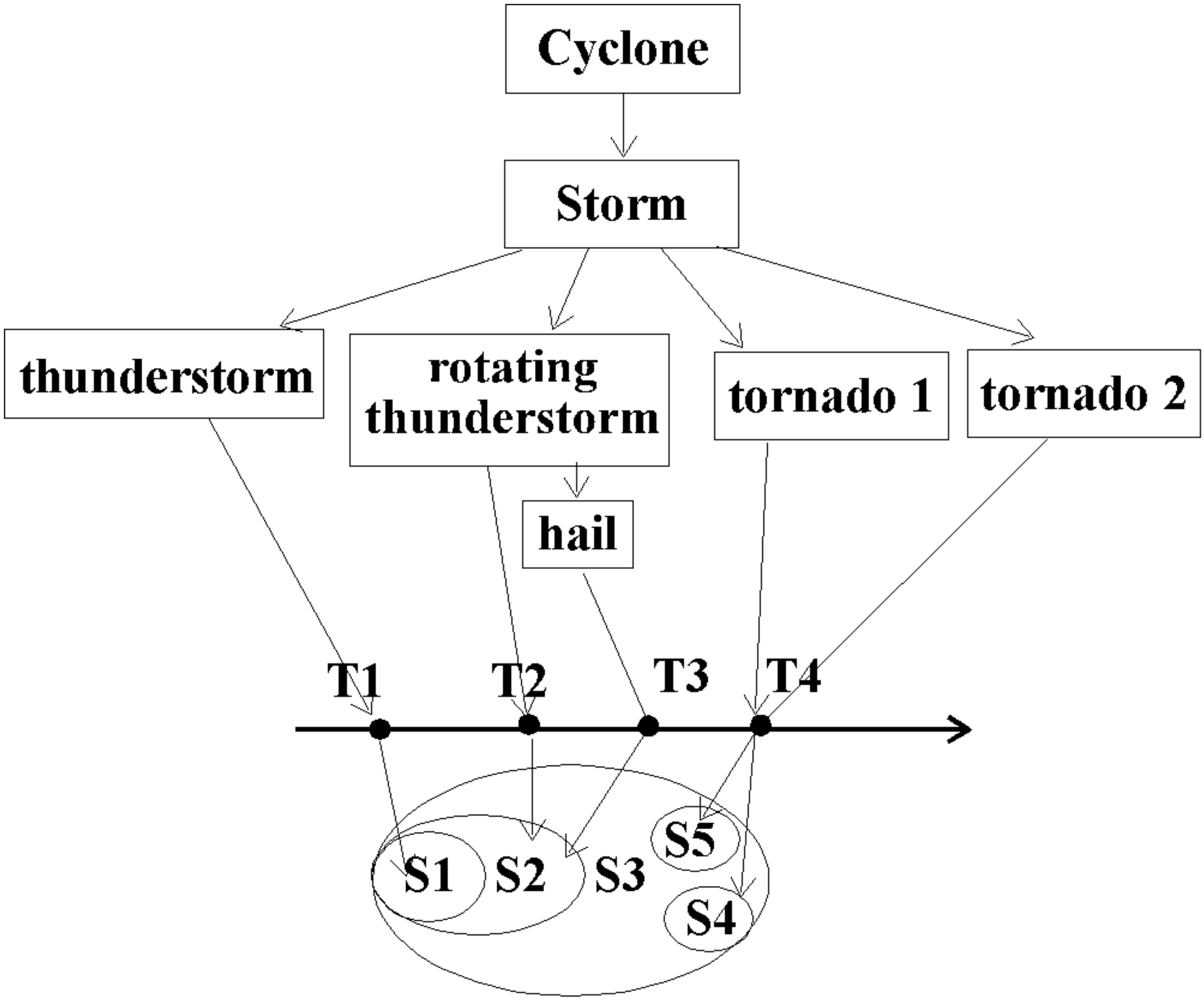


Fig. 11: An example of mutation (Type VI Change).

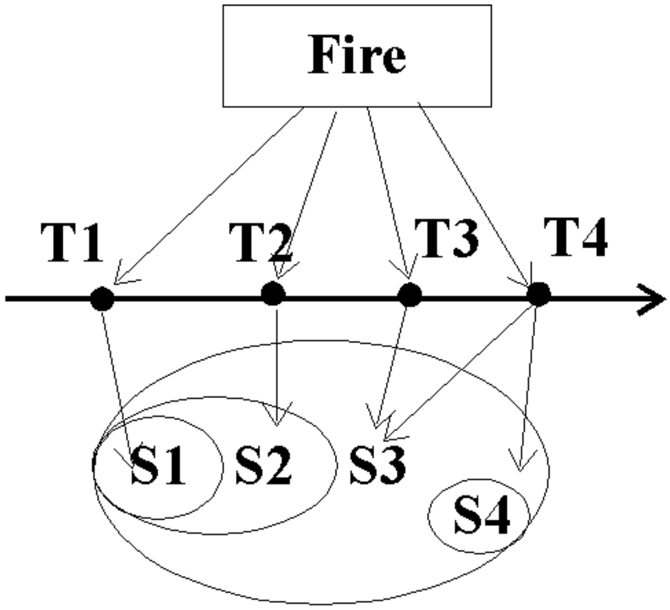


Figure 12: An example of movement (Type VI Change).

The incorporation of temporal elements into databases itself is a nontrivial task, and it becomes even more complicated when we try to model spatiotemporal data in GIS. The current temporal GIS data models lack of capabilities to represent Type III to Type VI changes. The following section discusses important spatiotemporal concepts to be considered in GIS data modeling to improve GIS's representativity by including important spatiotemporal concepts in its data models.

IV. Important Spatiotemporal Concepts to be Included in a temporal GIS Data Model

Langran (1992) points out that '(p)recisely articulated information about what and where changes occurred within a geographic area is at the heart of a TGIS' (p. 419). In doing so, she suggests states, events, and evidence are the three principle ent ities of a temporal GIS. States describe the spatial distributions of a geographic phenomena. They can be represented by snapshots or space-time composites. Events cause changes of states for a given phenomena through time, such as floods or fires. Eviden ce describes how changes are discovered and measured. It provides basis for updating a state. Therefore, the combination of states, events, and evidence show what has been in an area, what has happened to the area, and how we know it has happened. The thr ee data types in fact constitute the key elements of temporal metadata in GIS.

States and changes of states are the main concern in temporal representation, although events and evidence are critical to ensure data quality and detect causal relationships. It is important to understand time when we try to record changes and associ ate aspatical and spatial objects with time. The representation of time is an important issue in the study of states and changes of states. Time can be conceptualized as instances (point-based) or intervals (Allen, 1983; Fresa, 1992). Time has multiple st ructures: linear time, cyclic time, parallel time, and branching time (Worboys, 1990). Time has multiple dimensions: valid time and transactional time, user-define time, and institutional time (Snodgrass and Ahn, 1986; Berrera et al., 1991). In order to r epresent multiple time dimensions, Worboys (1994) proposes a spatio-bitemporal model and operations to handle information about valid time and transaction time in GIS. Other important concepts about time are elaborated in Peuquet (1994) and Raper and Livi ngstone (1995).

In addition, temporal GIS data models need to incorporate the behaviors of natural phenomena as the examples given in section III. To date, the design of conventional GIS data models have neglected the physical processes of natural phenomena. The basi c concept in conventional GIS data models is "location." Basic GIS units are spatial objects (points, lines, polygons, and cells), and their static attributes. Spatial relationships or interactions are limited to being at the same location or in close pro ximity. In contrast, the basic concepts in modeling of natural processes are "system states," "mass and energy conservation," transformation and translocation," and "species and individuals' interaction and dynamics" (Fedra, 1993). GIS is, in its present state, unable to provide complete support for spatiotemporal modeling of natural processes. Temporal GIS should support both location-based analysis (Type III and Type IV Changes), such as landuse changes and ecological succession, and process-based chang es (Type V and Type VI Changes), for example fire spread and storm development. As such, locations, states, events, and processes should be handled as individual data constructs in a temporal GIS. Semantical analysis of natural phenomena on their characte ristics and behaviors is critical to determine a set of high-level spatiotemporal constructs to be modeled in a temporal GIS (Yuan, 1994b). Most of the current GIS data models, as described in section II, organize geographic information according to spati al objects. Attributes are associated with a cell, a point, a line, or a polygon. As a result, GIS does not represent Interstate 35 as a integral object, rather there are a set of independent line segments and they have an attribute value, Interstate 35. Consequently, information about changes to Interstate 35 can not be effectively represented in a temporal GIS.

It is important to understand the fundamental spatiotemporal concepts to be successful in modeling temporal data in GIS. Many GIS data models are developed from perspectives of structures in spatial data. However, a process-oriented or semantics appro aches may lead to a new direction in modeling geographic information. GIS will be more effective and precise by representing a fire, fire location, and how the fire spreads rather than burned areas at each point in time.

V. Concluding Remarks

The study of modeling temporal information in GIS started in the mid 1980s. Many data models have been proposed, and some of them have been implemented. The development of temporal data models in computer science has shown an influence on the trend of temporal modeling in GIS. However, GIS data modelers need to consider the evolution of spatial objects in addition to retroactive or postactive changes and all other issues to be considered in a non-spatial databases (Snodgrass, 1992). Geographic inform ation has three components: attributes, time, and space. While the three components can change and be analyzed independently (Berry, 1964; Sinton, 1978), the proposed temporal GIS data models, as reviewed in section II, cannot model all possible kinds of temporal information listed in section III. The Snapshot Model (Armstrong, 1988), Space-Time Model (Langran and Chrisman, 1988), Spatiotemporal Object Model (Worboys, 1992) all can represent states through time (Type I and Type II Changes). The Space-Tim e Model and Spatiotemporal Object Model can also represent state changes at locations (Type III Changes). None of them can precisely nor effectively model transitions, mutation, and movement of processes (Type IV, V, and VI Changes). While the Event-based spatiotemporal data model (ESTDM, Peuquet and Duan, 1995) and the OOgeomorph model (Raper and Livingstone, 1995) are able to show transitions, they have difficulty in handling mutation and movement. In addition, both of them are limited to raster or poin t-based GIS. Temporal GIS needs a top-down approach to modeling spatiotemporal information, because behaviors of natural phenomena need to be considered and should be considered prior to available GIS data formats and data structures in constructing tempo ral GIS representation. The process-oriented approach has been used in the development of the ESTDM, OOgeomorph, the three domain model (Yuan, 1994), and the modeling and database systems (MDBS, Smith et al., 1993) with a certain amount of success. Furthe r research still needs to incorporate spatiotemporal constructs from natural phenomena into the modeling of temporal information in GIS to fully represent Type III to Type VI changes in space and time.

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1The word 'semantics' or 'semantical' is, in the context of data modeling, the meanings of objects or concepts in the physical or abstract world (Date, 1995). It is to emphasize the meanings of geographic features and their aspatial and atemporal relation ships.

Spatialtemporal patterns are patterns that occur in a wide range of natural phenoma and are characterized by a spatial and a temporal patterning. The general rules of pattern formation hold. In contrast to "static", pure spatial patterns, the full complexity of spatiotemporal patterns can only be recognized over time. Any kind of traveling wave is a good example of a spatiotemporal pattern. Besides the shape and amplitude of the wave (spatial part), its time-varying position (and possibly shape) in