A GENERAL OBJECT-ORIENTED SPATIAL TEMPORAL DATA MODEL

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ABSTRACT

Current research on spatial temporal data modelling meets many problems, such as the separation of space and time, application-driven, not incorporating human cognition and confusing of representation for discrete and continuous spatial change. This paper proposes a general object-oriented model that tries to overcome above problems. The model is directed by human cognition on spatial object that each object have what/where/when attributes. Attributes of theme, space, and time are tightly linked to each other in a unified object class. The precise and flexible structure of this model supports multi-semantics of space and time. Besides complex spatial relationships, it is also capable of modelling linear/branch/cyclic time order, various spatial change, and complex temporal relationships. Verified by different spatial temporal scenarios, this model is proven to be extendable to different spatial temporal applications.

1. INTRODUCTION

Space and time are most important and basic information in the real world. Many applications demand for spatial temporal support (Spaccapietra 2001), such as cadastral systems that capture the histories of land parcels, traffic management systems computing traffic network and traffic volume at different time, forecast-prediction systems recording weather change process, etc. But existing database techniques couldn't support spatial temporal information management well (Tryfona and Jensen 1999). After almost 20 years' research, representation of space and time in databases and functional applications are still problematic (Peuquet 2001). This paper presents a universal object-oriented framework for spatial temporal data modelling. Spatial temporal data modelling aims to extend the existing data models to include space and time in order to better describe our dynamic real world.

One problem with previous data models is that spatial and temporal aspects of databases are modelled separately (Sellis 1999) (Martin Erwig 1999). Spatial database focuses on supporting geometries (Guting 1994), while temporal databases focus on the past state (Tansel and Clifford 1993). But in many circumstances, such as environmental monitoring, resource management, transportation scheduling, etc, spatial and temporal attributes should be connected together. Many current systems can handle only one aspect of space and time. Spatial systems always fail to cater for many temporal aspects in a dynamic environment (Abraham and Roddick 1999). Though many people have found the necessity of integration of space and time in one environment, by far, little such work has been done.

Application-driven is another problem. Many database systems concentrate on the definition of a particular spatial temporal model that is related to certain application. The result is that more and more different models appeared. Each model focuses on a specific set of spatial temporal features (Goralwalla, Ozsu et al. 1998). When encountering other features and applications, the model doesn't work. So what we should do is to build an overall framework that can be extended to various applications, not driven by various applications generating different models (Mennis, Peuquet et al. 2000). Furthermore, application specific modelling will be more efficient if it is based on a generic model (Raza and Kainz 1999).

The third challenge for spatial temporal modelling is on the discrete representation of continuous phenomena. Many temporal systems can only capture discrete snapshot of real world (Hornsby and Egenhofer 2000), and hence couldn't model continuously changing object. But many temporal phenomena in nature are continuous, such as the clouds, rainfall, etc. Designing new model that can represent continuous process is one aspect, the other aspect is that the computer always records data in a discrete way (Peuquet 2001). How to mediate the discrete and continuous view is really a big problem when building the data model.

The fourth problem is representation of data should be natural to human. The structures of space and time are identified as essential for the realization of cognitive systems (Freksa 1998). According to Donna J. Peuquet and her group (Mennis, Peuquet et al. 2000), models of spatial temporal data in geographical database representations must incorporate human cognitive principles. Human knowledge of the dynamic geographical world comprises of three different (and interrelated) subsystems that handle *what*, *where* and *when* aspects of object properties (Mennis, Peuquet et al. 2000) (Sinto 1978). Theme-based model, location-based model and time-based model separately describe one subsystem. From this view, these 3 kinds of model are all single semantic models. According to human cognitive principle, the model we build should cover all of these 3 subsystems. Donna J. Peuquet and her group's pyramid framework show how to incorporate three subsystems of human cognition into data modelling.

From above analysis, we should build a unified infrastructure that integrate space and time, mediate discrete and continuous representation, describe when/where/what systematically, and be extensible to various applications. A multi-semantic model cannot ultimately be generated from extension of current single semantic models such as ER model and location/time/theme-based model. Object-oriented approach with its characteristic of inheritance and aggregation is capable of capturing the various notions of space and time and reflecting them into a single framework extensible to different applications.

This paper focuses on the unified models of space and time using object-oriented approach. In particular, we propose a conceptual, object-oriented spatial temporal data model based on Donna J. Peuquet's pyramid framework. Section 2 presents a unified object-oriented spatial temporal framework. Section 3 verifies the model using different spatial temporal scenarios, and discusses the advantages and disadvantages of this model. Section 4 gives a conclusion and discusses future research in this area.

2. THEORETICAL FRAMEWORK

2.1 Ontology of Space and Time

A uniform spatial temporal data model must be based on certain ontology of space and time, which is much more important than the multi-representation. Though many models are highly expressive, they present limitations to adequately model many applications because those models do not define enough or reasonable space-time primitives that would allow for a satisfactory representation of space and time (Borges, Jr. et al. 2001).

Sinto (Sinto 1978) defines geographic information with attributes as theme/location/time. He believes no geographic data should be entered into an information system without all three of these attributes present. Sinto further divides spatial data into geometric information and spatial relationship descriptions (topological, metric and algebraic relationship). Peuquet (Peuquet 1994) and Yuan (Yuan 1994) suggest a what/where/when structure. They argued that any spatial object has theme/space/time attributes. Goralwalla (Goralwalla, Ozsu et al. 1998) defines temporal primitives in a temporal object-oriented data model as combination of instant/interval/span and discrete/continuous domain and determinacy/indeterminacy. In this model, the author also defines linear/sub-linear/branching time order and valid/transaction/event time history. Wang (Wang and Cheng 2001) defines spatio-temporal behavior as continuous/discrete/stepwise change. Tryfona (Tryfona and Jensen 1999) divides spatial temporal applications into 1) objects with continuous motion, such as a moving car. 2) Discrete changes of and among object. In this type of applications, the characteristics of objects, such as shape, position may change discretely in time. 3) Continuous motion as well as changes of shape. That means a moving object with changing properties. He also divides spatial relationships into topological/directional/metric subsets. Temporal aspects in his model are valid/transaction/existence time. Raza and Kainz (Raza and Kainz 1999) defined time aspects in his model as linear/branching/cyclic subclasses and temporal operations as before/after/during/meets.

There are also many other papers and models define their ontological framework of space and time. But the main contents are same to literatures listed above. One problem of those models is they do not support a whole spatial temporal structure. Some of them support only space, some of them support only time, some of them support incomplete primitives of space and time.

Having identified the ontological structure of space and time, the next task is to model these spatial temporal primitives.

2.2 Data Modelling Approaches

Popular data modelling approaches include extending relational models, extending vector/raster models, time-based models and object-oriented models.

Driven by applications, much of the research on spatial temporal data models focus on extension to relational models (Renolen 2000), such as EER (extended entity-relation model) (Wang and Cheng 2001), STER (spatial temporal entity-relationship model) (Tryfona and Jensen 1999), ERT (entity-relationship with time model) (Renolen 2000), STSQL (Bohlen and Jensen 1998), etc. These models generalize new relations to manipulate multiple temporal as well as spatial attributes.

Extending vector/raster models are conceptually location/theme-based models. Within existing GIS, available such models include snapshot and update models (Li 2001) (Peuquet and Duan 1995). These two models are all based on a time sequence that is evenly divided. Snapshot records complete static maps at each time, while update model records complete initial map, then only changed information will be recorded at each time. This approach is straightforward. Nevertheless, because the locations are recorded in same interval, those locations where no change occurred result in the storage of redundant information, meanwhile, change occurred between two locations are not explicitly stored (Hornsby and Egenhofer 2000) (Peuquet and Duan 1995).

Time-based model records the timestamp for any change and associated details describing each specific change in temporal order, such as ESTDM (event-based spatial temporal data model) (Peuquet and Duan 1995). With certain time granularity, temporal locations will be recorded only when changes occur. For successive or continuous change, recording timestamp can be determined by certain rule or when the change accumulates to a meaningful status. So the distance between two timestamps can be different.

Object-oriented approaches originated in programming languages (Worboys and Hearnshaw 1990). In object-oriented data modelling, all conceptual entities are modelled as objects. Object class, generalization, specialization, aggregation, and association are the well-known concepts of object-oriented approach (Renolen 2000) (Guting 2000). Each class has a class ID, a list of attributes and a list of behaviours. Object is the realization of abstract class. Each object has certain attributes and performs according to certain operations. Inheritance of class includes two concepts: generalization and specialization. A class may be specialized into many sub classes, or a super class may be generalized from some classes with similar attributes and behaviours. A set of homogeneous classes can be associated to form a higher-level class, while a set of different classes can be aggregated to form a higher-level class. Not like above data modelling approach, though object-oriented approach has certain rules, object-oriented data models are largely different with each other, such as IFO (Is-a relationships, Functional relationships, complex Objects) (Worboys and Hearnshaw 1990), TOODM (Temporal Object-Oriented Data Model) (Goralwalla, Ozsu et al. 1998), MADS (Modelling for Application Data with Spatio-temporal features) (Parent, Spaccapietra et al. 1999), etc.

3. A GENERAL OBJECT-ORIENTED SPATIAL TEMPORAL DATA MODEL

The purpose of data modelling is to bring about the design of a database that performs efficiently, contains correct information, whose logical structure is natural enough to be understood by users, and is as easy as possible to maintain and extend. Based on above analysis and former work, this paper proposes an object-oriented spatial temporal data model, which is extended from Peuquet's what/where/when triad structure. Following OMT standard, this model adopted classification/specialization/association/generalization/aggregation strategy.

3.1 Class Structure

3.1.1 Super Class: Super-class of the model is shown as below. It's a void class that defines classID and basic attributes and behaviours of any object located in spatial and temporal dimension. A superclass can be inherited by subclasses in different applications contexts.

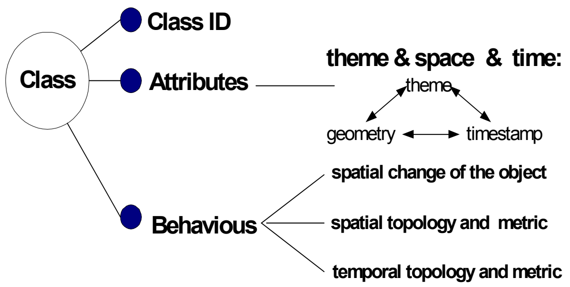

Figure 1. Superclass structure of the model

3.1.2 Structure of Attributes: Each object has attributes of theme, space and time.

Theme attributes record the information of "what is this object" and other related property information. For example, if the theme of this object class is "city", a city must have attributes such as Nation or Province it belongs to, Population, etc. Theme can be inherited according to certain classification hierarchy. For example, theme can be classified as transportation, settlement, water system, cadastre, natural resource, etc.

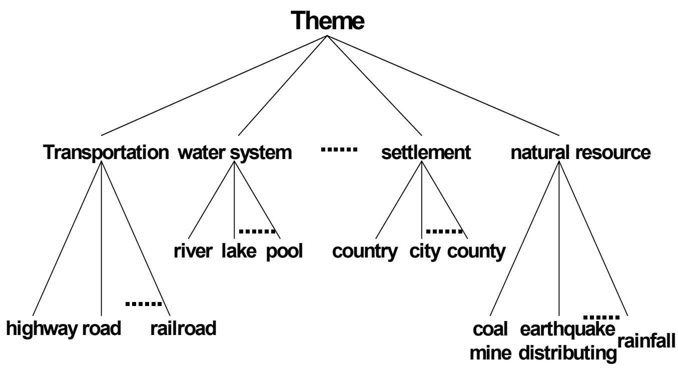

Figure 2. Theme classification hierarchy

Space attributes record geometry information of the object, such as whether it is a point, line, or polygon, and its location. Space attributes can be inherited into subclasses such as the point class, line class and polygon class.

Time attributes are represented through timestamps associated with theme and geometry information. When properties or geometry information of an object changed, a new timestamp will be recorded for that object. That means only initial information and changed information will be recorded. Each timestamp is an instant. Interval is the time between two timestamps. This model can support linear, branch and cyclic time order. The demonstration of different time order will be shown below in this paper.

In this model, theme, spatial, time attributes are recorded as 3 tables. Each attributes use one list. For example, a lake object has theme attributes as *"name"*, *"volume"* and spatial attributes as *"border"*. During different season and time of a year, the volume of the lake will change, and the border of the lake expands or contracts. Whenever the volume or the border of the lake changes, a timestamp will be recorded. Thus, as shown in fig. 3, each lake object has a name list, a volume list (*v1, v2, v3*), a border list (*b1, b2, b3*) and a timestamp list (*Jan, Mar, Apr, Jun, July, Sep, Oct, Dec*). Name list has only one element. It points to all border elements and timestamps. Each record of volume relates to a record of border and a timestamp; each record of border relates to a record of volume and a timestamp; each timestamp relates to a record of volume and border. In winter (*January*), the lake has the smallest volume and border (*v1 and b1*). It lasts for 2 months. From March to April, the volume and border change from *v1*, *b1* to *v2*, *b2*. After 2 months, it changes to *v3*, *b3*. From Sep., it goes down to *v2*, *b2*. Then, in next January, it is down to the smallest volume *v1* and border *b1*.

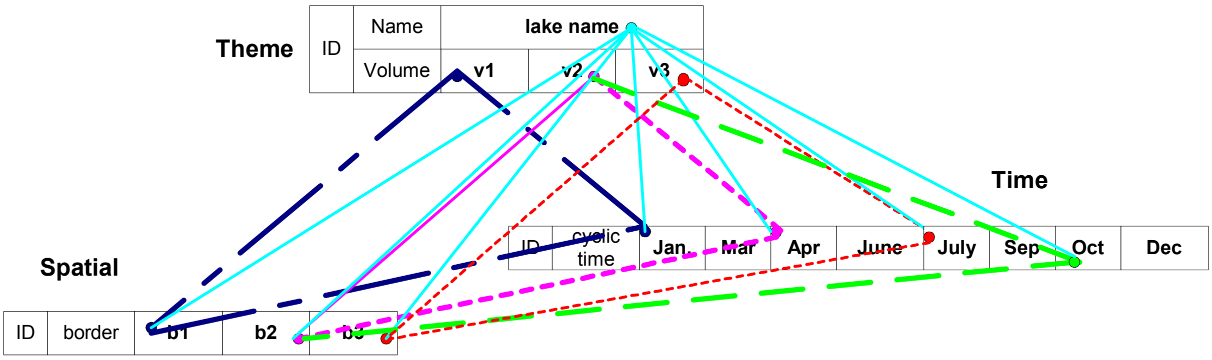

Figure 3. Relationship between theme, space and time

There are 3 kinds of relationships among theme, space and time: one-one, one-many, and many-many. In a one-one relationship, theme, space and time all changed, such as *v1-border1-Jan* and *v3-border3-July* in last example. In one-many relationship, one theme attribute may be related to more spatial attributes and many timestamps. That means that theme attribute doesn't change during this interval while the spatial attributes changed, such as the attribute "*name*". Also, in some circumstances, spatial attributes of an object are static while theme attributes change. Another special case is that the timestamp list may have just one element. That means this object is static.

The theme list, spatial list and time list can have multiple rows, such as the theme list in this example. The theme list includes two attributes "*name*" and "*volume*". If an object is made up of many spatial elements such as a river has many parts (*p1, p2, p3*), its spatial list will have 3 rows to record these 3 part's spatial information.

3.1.3 Behaviours: This model defines three kinds of behaviours. They are spatial change of the object, spatial relationship (topology and metric) with other objects, temporal relationship with other objects.

Spatial change of the object includes: 1) Stay-in: object stay-in one status (location & properties) during certain time; 2) Transform-between: object transform from one status to another during certain time; 3) Appear/disappear; 4) Increase/decrease; 5) Splitting; 6) Moving; etc.

Spatial relationship between two objects includes topology relationship (such as intersection, inclusion, adjacency, disjunction, equality, merging, etc.) and metric relationship (such as the distance of two points).

Temporal relationship between two objects also includes topology and metric relationship, such as before, overlap, finish, equal, during, meet, start, etc.

3.2 Generalization, Specialization, Association and Aggregation

This model supports generalization, specialization, association and aggregation to define relationships among objects.

Generalization and specialization are contrary constructs. Generalization extracts similar properties of different classes into a super-class, while specialization extends a class to some sub-classes. Each sub-class has same properties as well as special properties. For example, in Fig.2, transportation is a super-class, which can be specialized into highway, road, railroad, etc. In the contrary, highway, road, and railroad can be generalized into transportation.

Association can also be called grouping which enables some objects of same type to form an object of higher-level type. For example, line is the association of many points.
Aggregation is a construct that enables different objects to be amalgamated into a higher-level object. The higher-level object has all of the attributes of those different objects. For example, the water system in a country is the aggregation of many rivers, lakes, and pools.

The super class mentioned above defines basic void attributes and behaviours of a spatial temporal object. This super class can be specialized into sub-classes. Each sub-class inherits the basic void attributes and behaviours from the super-class, and realizes the attributes and behaviours with special content. Each sub-class can also have its own sub-classes. With this class hierarchy and the aggregation and association of different classes, multi-semantic space and time can be expressed.

3.3 Demonstration

There exist various spatial temporal phenomena, such as "stay-in", "transform-between", "appear/disappear", "splitting", etc. In this section, we will demonstrate how our model captures some spatial changes inside an object or among objects, and temporal changes in different time orders: linear, cycle, or branching.

In the lake example mentioned above, there are two kinds of spatial change inside the object: stay-in and transform-between. As shown in Fig.4, the lake stays in volume *v1* and border *b1* from the beginning of January to the end of February. From the beginning of March to the beginning of April, the lake transform from *v1* to *v2*, *b1* to *b2*. Supposing every year, the river has same changes. During one year, the change of the river border and volume is linear, while in many years change is cyclic. In fig. 3, the cyclic time order is marked in the timetable.

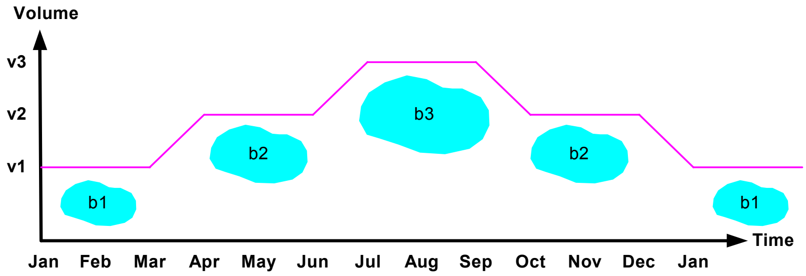

Figure 4. Volume and border change of the lake

As shown in Fig. 5, a country (*ID0*) has name *A0*, Population *P0*. It appeared at time *T0*, and split into *ID1*, *ID2* at time *T1*. "Split into" and "come from" define the relationship among these 3 instances. After splitting, *time0* branched into *time1* and *time2*. From this example, we can see, in this model, the branching time order is expressed as relationship among objects.

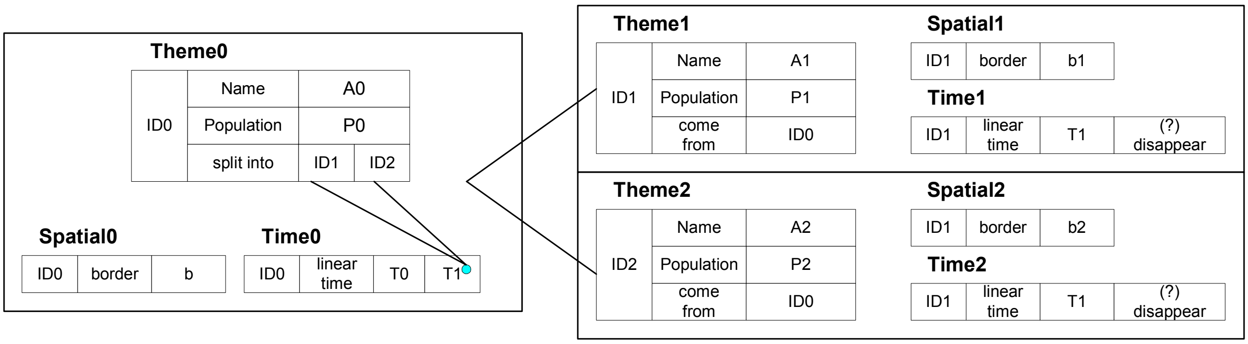

Figure 5. Splitting demonstration

4. DISCUSSION AND CONCLUSIONS

This paper reviewed current research on spatial temporal data modelling and finds some problems in this field. Then, this paper provides a unified object-oriented model that partially overcomes some problems. Based on human cognition, the model linked together theme, space and time through common object references. Such structure allows unified operations on space and time, such as navigation, tracking and query. This unification means the effectiveness both in function, consistency, and computational complexity.

Application-driven models are usually single-semantic or incompletely multi-semantic. This model is built up from the basic attributes and behaviours of spatial temporal objects. Based on the object-oriented strategy, it's extensible to any applications by generalization, specialization, association and aggregation. Thus, this model can completely support the multiple semantics of space and time.

Another advantage of this model is no matter querying time or querying space, this model has the same efficiency. Not like temporal model or spatial model. Temporal model is designed for time query. It is quite efficient when querying time through timestamp list. But when querying space, it is inefficient. Spatial model has the similar problem. In this model, each time table, each space table and each theme table has an object ID as the index. When querying time among different objects, the model will go directly to query all time tables using ID index, no need to search all objects. Things are similar when querying space and theme.

Although the research has made a progress, much work still needs to be done. Efficient implementations will be carried out in further research. Work on specification of integrating space-time query language is also under way.

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