Temporal Maps and Temporal Geographical Information Systems (Review of Research)

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Abstract

The need to record the history of and the ability to reason about changes in the world has lead to a new field of research within the community of Geographical Information Systems (GIS). Recently a lot of new theory and concepts have emerged and a number of spatiotemporal data models have been presented. In this review we will have a closer look at the most important issues such as bitemporality, temporal topology, visualization, and different types data models such as the snapshot model, the time-stamping method and event-oriented models. Finally, suggestions for future work will be made.

1 Introduction

Most current Geographical Information Systems (GIS) and Digital Mapping Systems today are only capable of representing our geographical world at one single state. Recent research has focused on a new type of maps and GIS, *temporal maps* and *temporal GIS* (in the sequel called *spatiotemporal systems*). These are capable of maintaining the history of the data such that reconstruction of earlier states becomes possible.

One of the most significant contributors to this field has been *Gail Langran*. She took the personal initiative to begin this new field of research, and her final PhD thesis was later rewritten in a non-academic style and published in the book *Time in Geographic Information Systems* [Lan92]. This book is the most comprehensive work published in this field so far and covers the most basic concepts of spatiotemporal systems. However, even if Langran's work covers many of the most important issues of spatiotemporal systems, many other scientists have made significant contributions to this field as well, and a number of data models have emerged.

There are many applications in which a spatiotemporal system can be utilized. Langran gives no less than seven examples of applications in which a temporal GIS can play the lead role [Lan88, Lan92]. These are forest resource management, urban and regional management, research and development, infrastructure management, transportation, and map and chart production. Vrana gives three examples of applications where the fields of cadastral databases, and land-use planning adds to the already mentioned [Vra89]. The application of temporal management in a coastal GIS has also been discussed [Bar93].

Additionally, since the early 1970's database engineers have researched the field of temporal databases in general. Although spatiotemporal databases have been discussed, no significant results in this field have emerged. Langran has reviewed this research and discussed its application in GIS [Lan89]. The vast majority of this research focuses on the relational model and other connected issues such as indexing techniques and query languages. Such databases are interesting to GIS in terms of the storage of non-spatial data (i.e. attribute data).

2 Time as the Fourth Dimension

Most often, a spatiotemporal system is referred to as a four-dimensional system. Normally, this would mean three spatial dimensions in addition to the fourth time dimension. However, most commercial GIS today only handle 2 or 2.5 spatial dimensions, which means that the third dimension often is referred to as the *attribute* dimension leaving time invariantly as the fourth one.

On the other hand, Kadmon shows that a spatiotemporal object can be represented as a four-dimensional vector $[a_i, g_i, p_i, t_i]$ describing attributes (a_i), geometrical position (g_i), topological description (p_i), and temporal description (t_i) [Kad93]. This way of describing spatiotemporal objects has many advantages. First, it does not take the number of spatial dimensions into consideration: 2D, 2.5D or true 3D. Second, it involves topology as a separate dimension which means that systems can obtain topology directly instead of deriving it from the geometrical or temporal components. And finally, the concept of four dimensions is not violated.

2.1 Representing the Time

Accepting time as the fourth dimension, there are two ways to represent it in a temporal system. The *discrete* model which is isomorphic to the natural numbers, and the *continuous* model which is isomorphic to real numbers. Although people generally perceive time as continuous, most implementations represent time in a discrete manner [Sno92].

Based on the discrete model, the smallest unit of time, analogous to a pixel in a raster image, is called a *chronon*. Many systems may represent time parameters in the granularity of one second or finer. This is in some cases adequate, but for most applications of GIS a granularity of one day would be more appropriate.

Still, systems should provide means of representing temporal indeterminacy [Sno92]. For many events, exact times cannot be determined. For example, it can be hard to define the exact time of which a building came into existence, compared to the opening time of a new road segment which can be scheduled to a certain time of a particular day. Another example is when a temporal map has been subjected to cartographic generalization. A new area of settlement is generalized from the set of houses comprising the area. Even if the whole settlement emerged in a limited period of time, setting an exact time for the single object representing the whole area might be impossible [Ren].

2.2 The Nature of Changes

Changes on spatiotemporal objects may occur along all the three non-temporal axes described above (geometry, topology and attribute). Most commonly, changes on man-made structures are looked upon as events. A new road is opened, a new building is finished, or an area of forest is chopped down. Even if such events have duration, intuition tells us to associate one single time or date with the event.

Additionally, many of the changes in the real world are results of continuous processes such as the melting process of glaciers, expansion of desserts, or erosion of rivers. Although some changes are of a sudden nature and others are results of continuous processes, most changes fall in category between the two.

With respect to different behaviour in time, entities can be divided into several categories according to their temporal behaviour or change patterns (figure 1). *Stable values* are exposed to events of a sudden nature and have stepwise constant values. *Continuous changing values* can be divided into three sub-categories according to change patterns: *Uniformly*, *Smoothly* and *Irregular* changes. A third type of entities exists in the form of *discrete values* which are collected on a regular or irregular basis [SS93, MP93]. Additionally some entities are static and never change while other entities may be measured or depend on the time itself [Lan92].

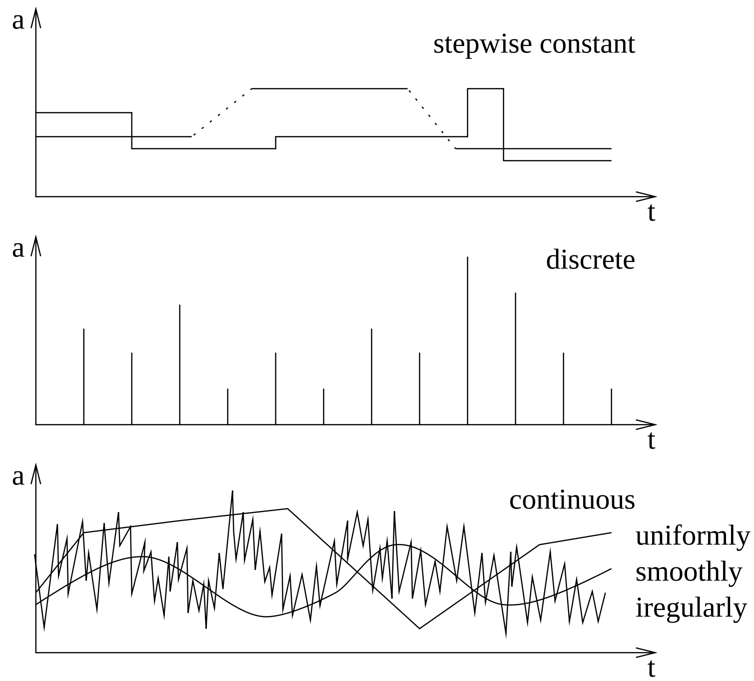

Figure 1: Types of changes of an attribute.

In principle, any temporal system can implement changes completely with two operators: *addition* and *deactivation* [GV94]. This approach is based on time-stamping where every object are validated in time by a pair of time-stamps indicating addition- and deactivation time. A change to an object is then performed by first deactivating the current version and then adding the new version of the object to the database.

However, there is a problem with identification. In many database systems, every object (i.e. tuple) must have a unique identifier. Using tuple level versioning, two tuples that are two versions of the same object cannot be related to each other by their identification [Lan89]. The ability to trace the history of an object is critical in many applications and the problem can be solved in more than one way. One method would be to establish a successor - predecessor relation explicitly for each tuple [Pri89, WD93]. Another method could be to provide means of configuration management applying composite identifiers to each object giving information about object type, ID, and version number. In this way, identifying change propagation in the data becomes possible as well.

2.3 Bitemporality

The fact that maps are abstract representations of the real world means that events that occur in the real world are recorded into the database at a different time than the actual event. Normally, there is a delay between the actual event and the registration of it in the database. But, some changes can be made *on-line* while others changes that are anticipated can be registered in prospectus. For example, entrepreneurs often schedule the opening of a new road segment a long time in advance. This clearly shows that time in the context of maps, has dual characteristics, and therefore has to be treated carefully to obtain consistence and integrity.

Particularly if the database is subject to decision making, it is critical that users can reconstruct and compare the state of the database to the state of the real world at the actual time (obtained at a later time). Therefore, it is important to associate both the transaction time and the real world time with each event. In literature these two times have been given many names, and a brief overview can be found in [Lan89] or [Lan92]. In this article however, these two times will be termed *transaction time* and *real time*.

Based on the ability to track both transaction and real time, temporal databases can be classified according what time they support. A database supporting only the transaction time is called a *roll-back* database while a database supporting only the valid time is called *historical*. Databases that support both transaction and valid time are called *bitemporal databases* while databases that support neither of the times are called *snapshot databases* [Sno92]. Note that many erroneously state that snapshot databases are not temporal databases. Indeed they are, but they cannot identify individual changes. Although supporting only one time is sufficient in many applications of GIS, supporting both is the ultimate solution. Therefore, one should obtain a thorough understanding of bitemporality before implementing a robust support for it.

2.4 Temporal Topology

Topology is the study of those properties of geometrical forms that remain invariant under certain transformations, as bending, stretching, etc. (Webster's dictionary). In other words, we are speaking of relationships between objects such as neighbour of, overlap, disjointness, and insideness. A similar theory can be developed including the temporal dimension. Temporal relations includes predecessors, successors, various forms of coexistence, and others [Lor93].

Langran distinguishes between versions of objects and states of the map [Lan88]. Events occur at map level while mutations occur at object level (figure 2). This model suggests that every object can have only one preceding and one succeeding version. However, for some types of spatial objects this is a too simplistic view. In a cadastral map for instance, a lot may be subdivided in two or more lots, or a lot may annex parts of another lot into its extent [Ren96].

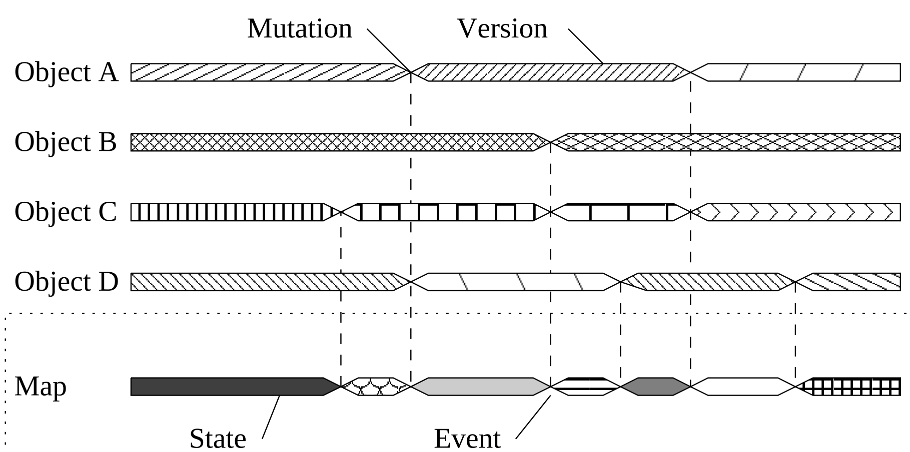

Figure 2: The relationship between object versions and the map and between mutations and events.

Many types of changes also results in a change in topology. A glacier may expand one of its arms into a lake, changing the topology between the two. Egenhofer and Al-Taha

[EAT92] have developed a theory based on the *9-intersection* model where topological change patterns can help determine the type of transformation applied to planar objects. Similar change patterns have been developed for lines, points, and combinations between these [VR96].

3 Visualization and Animated Maps

Visualizing the temporal dimension on maps can be achieved in three ways: As one single map with symbology indicating change patterns, as a series of static maps displaying states of a changing phenomena (strip maps), or as an animation sequence [KM94].

MacEachren introduces time as a cartographic variable [Mac94] which gives new opportunities to the cartographer when displaying both static and temporal phenomena on dynamical displays. In addition to Bertin's seven visual variables [Ber81], MacEachren added four new *dynamic variables*: *duration*, *rate of change*, *order*, and *phase*. Another two variables, *display date* and *synchronization* can be found in [D^+92].

3.1 Involving Time on Static maps

Static maps are maps that are displayed on media not capable of animating geometrical changes over time. This doesn't mean that dynamical symbols cannot be applied. Blinking lights, rotating wheels and other wizards can all be applied in an otherwise static environment to achieve certain effects.

One can classify static maps along two axes. The first axis is the number of maps: One single map or series of successive maps displaying snapshots of a changing phenomena (strip maps). The second axis indicates the application of dynamical symbols on the map. On traditional hard-copy maps such as paper maps, only static symbols can be printed, while on TV screens, computer screens, and other types of boards and models are good subjects for *dynamical symbols* that are controlled by parameters of time.

Monmonier has given a good overview of the means of presenting temporal processes on static maps [Mon90]. For single static maps several presentation alternatives are discussed. These include the use of temporal glyphs (clock faces, calendar symbols, time graphs etc.), isochrones, arrows, printed dates, and change maps to mention some of them. Displaying several maps in chronological order in a strip map is possibly the best way to display a temporal process on printed maps. Monmonier also suggests that variables should be separated so that the maps are displayed in a *cross classification array*, one strip map for each variable.

When static maps are presented on media providing dynamical facilities such as blinking lights or pixels on a computer screen, MacEachren's dynamical variables mentioned above may be applied in different ways, for example to emphasize existence, uncertainty, or importance. In addition, depicting movements, changes, or particular trends becomes easier [Mac94].

3.2 Animated Maps

The animated map would typically consist of a map window and five push buttons. Two buttons for running the map forwards and backwards, two buttons for fast winding and rewinding, and one stop button. The analogy to the VCR is obvious, but instead of the winding buttons, there should be one *jump* or *go to* button for a quick jump to another time. Additionally there should be one button or slider to adjust the animation pace (temporal scale).

One would intuitively suggest that animated maps would be far more powerful than map strips. However, Koussoulakou and Kraak tested a group of 39 geodesy students displaying one series of static maps and one animated map [KK92]. They found that the correctness of answers were not influenced by the type of map, but the students answered more quickly when they studied the animated map. Even if the individuals in this test group are likely to be good map readers, the test clearly indicates that map strips are sufficient in many cases.

However, with the help of animation techniques, many secrets of the world can be revealed. A documentary series that recently went on TV in Norway, clearly showed the behaviour of plants when one day was scaled down to a few seconds. This example indicates that new knowledge about processes in the world caused by man or by nature itself can be obtained with animated maps. In fact, there are many examples of animated maps available over the Internet. Many weather stations provide web pages containing animations sequences displaying the last 30 or 60 frames of weather satellite images over an area [suUcg, Sta].

4 Spatiotemporal Data Models

Since the beginning if research in this area, an abundance of data models have been presented. Some of these are based on the raster approach, others on the vector approach and yet other concepts can be applied to both vector and raster data. Some of the models are based on the object-oriented paradigm, an approach that has proven to be capable of integrating both vector and raster data into one data model.

However, commercial GIS today often separate attribute data and spatial data into two databases. The spatial database is often a custom database designed by the manufacturer of the system, while the attribute data are stored in a standard relational database with object ID's associating entities in the two databases together.

4.1 The Snapshot Model

One of the simplest spatiotemporal models is the snapshot model (figure 3). The state of the world is given at regular or irregular intervals in different maps, one separate map for each state. The drawback with this model is that two snapshots contain much of the same data and that changes do not exist as explicit entities [Lan88, PD95]. This is indeed the case for vector models, but for raster models based on remotely sensed images the approach can be useful as well. Hamre has implemented a temporal GIS which integrates such images with other temporal information [Ham95].

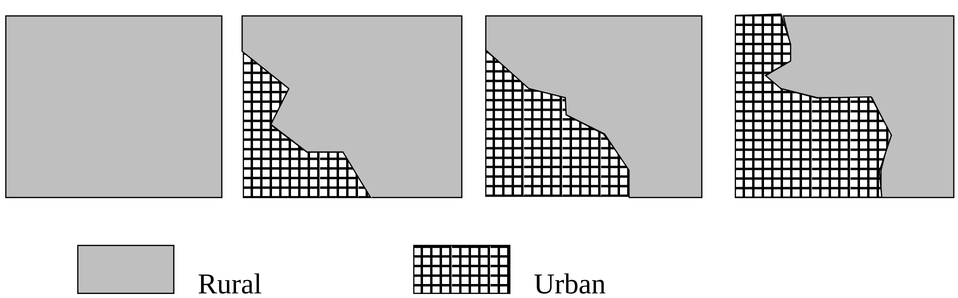

Figure 3: The snapshot model.

However, it is relatively straightforward to implement a model based on raster snapshots using currently available software. In a GIS that provides layers, it is possible to put one snapshot into each layer while animation software can be deployed to create animated maps consisting of densely sampled snapshots of the area of interest.

4.2 Data Models Based on Simple Time-stamping

Another simple approach is to tag every object with a pair of time stamps, one for the time of creation and one for the time of cessation. Current objects have their cessation time given by a special value 'NOW', 'CURRENT' or 'NULL'.

Hunter and Williamson [HW90] and Galetto and Viola [GV94] have implemented such an approach and show that time slices can easily be retrieved by simple queries. However, such a model spreads the different versions of the same object over several non-related tuples around the same table. This makes it hard to trace the history of one single object [Mon95].

This deficiency can be resolved by adding explicit references to preceding and succeeding versions of the objects. Ramachandran, MacLeod and Dowers [RMD94] deal with this issue in an object-oriented model, implementing a *Temporal Change Object* (TCObject) which is an object consisting of set of references to past (historic), future (scheduled), and the current version.

Another approach is to organize the object versions into *time sequences*. Although Segev and Soshani's implementation of time sequences are designed for single value sequences [SS93] it should be possible to implement the approach on abstract types as well.

4.3 The Space-time Composite Data Model

This vector model has been suggested by Gail Langran [Lan88]. It is based on the principle that every line in space and time is projected down to the spatial plane and intersected with each other creating a polygon mesh. Each polygon in this mesh has its own attribute history associated with it (figure 4). Each new amendment is intersected with the already existing lines, and new polygons are formed with individual histories. The model has been tested with a number of indexing methods [Lan92]. The results that were obtained looked promising, but only smaller data sets were tested.

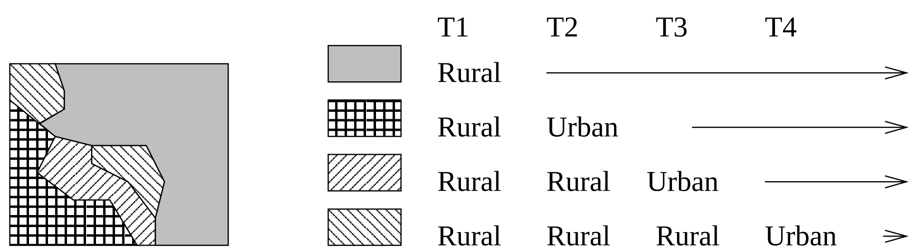

Figure 4: The Space time composite data model.

However, this data model will also have some redundancy since two contiguous objects may have full or partial common history as they are parts of the same semantical object. Moreover, the number of polygons does not grow linearly with time, which can be a serious problem. Saafeld has made a study of the result of overlaying two polygon meshes and shows that there is no limit on the number of resulting polygons in a worst case. In practice, the number of resulting polygons seem to exhibit a more linear behaviour [Saa91]. Migrating this with Langran's model we can say that the Space Composite model is the result of overlaying every amendment into one polygon mesh and the number of polygons must grow with an exponential patterns since every new amendment must be intersected with an increasing number of non-current lines.

All in all, Langran's space time composite model have many interesting properties. But the question is whether the model will give too fragmented data sets, and whether the indexing techniques are able to cope with the large data sets in the long run.

4.4 Event-oriented or Time-based Approaches

As mentioned above the snapshot model cannot identify individual changes or events to the data set. One way to overcome this is to represent the events explicitly. Imagine a traditional GIS, if all changes that were made to each data set were logged into a transaction log, that log itself would provide all the information needed in a spatiotemporal system. The actual database would then act as a current state database, and in order to obtain historical states of the map, a 'rewind' can be obtained by tracing the transaction log backwards. Thus, the transaction log itself truly is a temporal database.

Langran briefly discusses the amendment vector approach (figure 5) where the current state can be found by applying amendments from a base map or current state map [Lan88]. Despite some of the advantages this model has, (such as redundancy and consistency) the approach has not been investigated further.

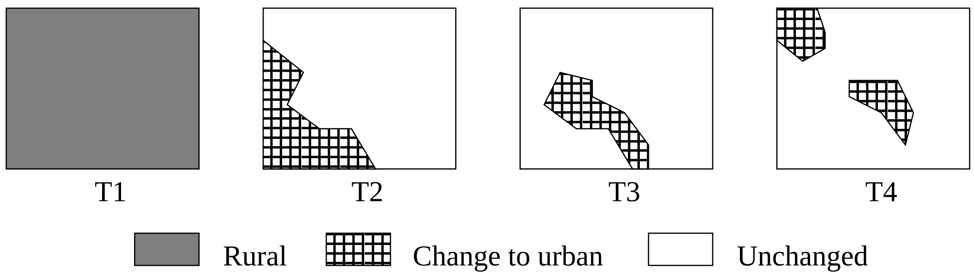

Figure 5: The amendment vector model.

On the other hand, Peuquet and Duan have implemented a raster-based event-oriented approach called the *Event-oriented Spatiotemporal Data Model* (ESTDM) [PD95]. This model consists a base state database and one compactly stored change image for each event. Peuquet shows that the model is space saving compared to the snapshot model and efficient in terms of common query types.

However, in most applications the current or the most recent state of the map will be accessed much more frequently than non-current historical states. It is therefore a better idea to have a current state map as the base map so that historical states can be obtained by applying the amendments in a backward manner [Lan92]. For rollback databases, the base state should be empty anyway. For optimization, intermediate states (i.e. snapshots) could be saved to get shorter reckoning paths to the desired states.

The advantage with the event-oriented models is that they are well suited for queries such as "*what has happened in the area in this period*". Another advantage is consistency and redundancy. There are no false objects that result from recording events in the wrong order, and two objects that share the same history are not represented with two sets of historical objects.

4.5 Abstract and Object-oriented Data models

The object-oriented data models are based on the object-oriented paradigm which includes objects, classes, encapsulation, inheritance, and polymorphism. This concept has in recent years shown its applicability in most types of programming and development projects, also within the GIS community. This makes it possible to embed all historical versions of the same object into one single entity [Mon95]. However, most object-oriented approaches to a spatiotemporal system is based on building an abstract structure in 3D or 4D space where time is one of the dimensions.

Worboys has already contributed to the subject of object-oriented GIS [WHM90]. His recent contributions to the design of an object-oriented spatiotemporal system are based on a three-dimensional space-time approach (x, y and t) [Wor92]. The objects are modelled as translational sweeps along the time axes, and put together constructively in a three dimensional structure (figure 6). Even if this model is designed to model changes as discrete events, it can be augmented to handle gradual changes as well.

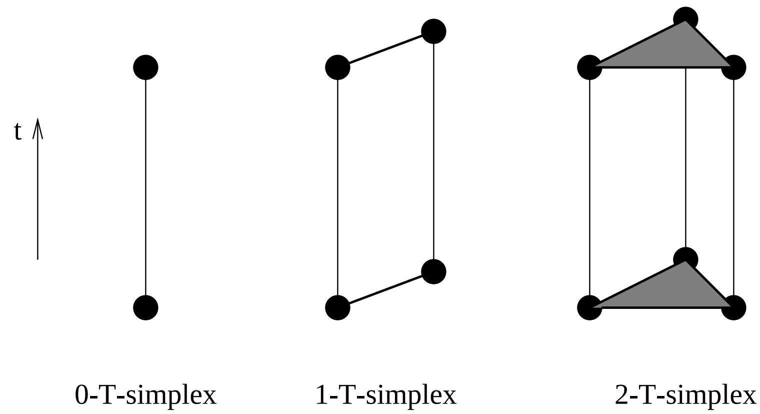

Figure 6: Basic spatiotemporal objects (ST-objects).

Another interesting approach to the modelling of an object-oriented spatiotemporal model has been made by Hamre [Ham95, Ham94]. Her model is based on a four-dimensional space consisting of points, lines (point series), surfaces, volumes and temporal volumes (hyper volumes) in a four dimensional space. The four classes of objects are defined in a class-hierarchy where sub-types of the four classes have been designed for the various needs. In her implementation, Hamre has shown it is possible to integrate both vector, and raster data (sensor images) along with non-spatial data in one spatiotemporal model.

5 Suggestions for future work

Until now, most research has focused on data models and applications of a spatiotemporal system. The diversity of the models and applications presented clearly indicates that there are many aspects of a spatiotemporal system to consider. One approach aimed at solving one problem can be more or less useless in solving another. All approaches have their strengths and weaknesses. It is also clear that there are many spatiotemporal problems yet to be solved. Langran discusses a few issues for implementing a future temporal GIS [Lan93]. These include representational issues, issues of incremental updates, and longevity of data and procedures.

We suggest that future research continue to focus both on conceptual and practical issues of temporal cartography. We need to understand the temporal processes in the real world better, and addressing practical problems with specialized models is a good way to learn more about them. Map animation is also a field where research has been scarce. Inevitably, research in map animation will emerge, if not otherwise, as a consequence of the development on the more basic issues. Besides, research into virtual reality have reached far with similar problems.

At present, generalization of spatiotemporal data sets is under consideration; A topic that can be linked to both data retirement and display issues. Another related issue to be considered is updating of multiple scale map bases. Many organizations today maintain multiple data sets at different levels of generalization (abstraction), where one data set is derived and generalized from the more detailed data set at a lower level. When these data sets are temporal, propagation of updates becomes a critical issue.

Also, more research should be done concerning the issue of bitemporality. Timestamping of data is a commonly used approach, but what if two events on the same object are recorded in reverse order? And how can we distinguish objects that results from erroneous updates. The solution is to let the database keep track of two orthogonal versions of the same object. One *false object* reflecting a state of an object that never occurred in the real world but in the database. And the *true object* which reflects the state in the real world which was corrected at a later time.

In general, there are still many problems that researchers within the GIS community must solve. In the future we can therefore expect an increasing focus on spatiotemporal issues amongst cartographers.

6 Conclusion

The need for spatiotemporal systems in various organizations has been documented and many applications have been outlined. We have seen that the research within spatiotemporal systems has come up with a lot of theory, data models and more problems to be solved. Nonetheless, it is doubtful whether the ultimate spatiotemporal system or the temporal GIS will be implemented in near future. But, systems that meet certain requirements of certain applications can be and have been implemented.

In the future, more attention should be payed to generalization issues, event-oriented modelling, update propagation and map animation. At the same time, cartographers should become more acquainted with object-oriented modelling and design techniques such that these techniques can be better exploited both when implementing traditional and temporal spatial systems.

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