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Time in GIS and geographical databases

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Although GIS and geographical databases have existed for over 30 years, it has only been within the past few that the addition of the temporal dimension has gained a significant amount of attention. This has been driven by the need to analyse how spatial patterns change over time (in order to better understand large-scale Earth processes) and by the availability of the data and computing power required by that space–time analysis. This chapter reviews the basic representational and analytical approaches currently being investigated.

1 INTRODUCTION

Representations used historically within GIS assume a world that exists only in the present. Information contained within a spatial database may be added to or modified over time, but a sense of change or dynamics through time is not maintained. This limitation of current GIS capabilities has been receiving substantial attention recently, and the impetus for this attention has occurred on both a theoretical and a practical level.

On a theoretical level GIS are intended to provide an integrated and flexible tool for investigating geographical phenomena. The world never stands still. This means that GIS should be able to represent these phenomena in both space and time (see also Veregin, Chapter 12). If GIS are to fulfil their envisioned role as decision-making tools, they will need to represent information in a manner that more closely approximates human representation of geographical space. An important element of human representation of the world around us is the retention of information relating to past events. Cognitive science has shown that the retention and accumulation of such information is essential to deriving more generalised concepts, and of learning in general (Mark, Chapter 7).

On a practical level, as a result of widespread use of GIS over the past 15 years and increasing reliance on GIS in everyday applications, users are increasingly encountering the issue of how to keep a geographical database current without overwriting outdated information. This problem has come to be known as 'the agony of delete' (Copeland 1982; Langran 1992). The rapidly decreasing cost of memory and the availability of larger memory capacities of all types is also eliminating the need to throw away information as a practical necessity. In addition, the need within governmental policy-making organisations (and subsequently in science) to understand the effects of human activities better on the natural environment at all geographical scales is now viewed with increasing urgency. The emphasis is shifting in natural resource management within the developed world from inventory and exploitation toward maintaining the long-term productivity of the environment. This task requires integrated and broad-scale process analysis in order to understand natural and human processes better and how they are interrelated. Global Circulation Models (GCMs) are currently being used to study climate dynamics, ocean dynamics, and global warming (Simmons and Bengtsson 1988).

The need for a more detailed examination and understanding of the dynamics of human–environment interactions at urban and regional scales is also a continuing priority (Hunter and Williamson 1990; Vrana 1989). Diffusion theory (Hägerstrand 1970) has been applied to a diverse range of topics including agricultural innovation, the spread of political unrest, and the spread of AIDS (Gould 1993a; Parkes and Thrift 1980).

All of these require the analysis of change through time and of patterns of change through time, with the goal of gaining insights about cause-and-effect relationships. The advent of remotely-sensed satellite data in addition to the accumulation of other spatio-temporal observational data has made the empirical study of large-scale, complex spatio-temporal processes possible – further increasing the demand for integrated computer-based tools for this task (see Barnsley, Chapter 32; Estes and Loveland, Chapter 48). The extension of GIS and geographical database capabilities in order to provide efficient and flexible data storage and access has therefore attracted much attention within the GIS research community within the past few years.

2 ISSUES OF REPRESENTATION

In order to understand and compare approaches to space–time representations for GIS and geographical databases in general, a number of preliminary concepts and definitions are necessary.

2.1 Form vs function in space–time representation

There are two basic types of questions that can be asked using a space–time model: those concerning the 'world state' at a given time and those concerned with change in the properties of locations or spatial entities over time. These can be interpreted respectively as relating to static and dynamic views in time. Based on these two types of questions, the following generalised types of queries can be defined:

1. *World state*; what was/is/will be the spatial distribution of a given phenomenon at a given time? (e.g. where were the locations devoted to recreational land use in 1993? What was the spatial configuration of the 42nd Congressional District in the last election?)
2. *Change*; which elements changed/are changing/will change during a given time span? (e.g. where has growth in recreational land-use occurred between 1988 and 1998? Which congressional districts have shown an increase in unemployment over the past four years?)

The capability to ask change-related questions requires a dynamic view of the relevant phenomena. With this in mind, work toward providing temporal capabilities in a GIS context must include the development of methods for representing spatial change as it occurs through time in an explicit way, as well as 'states' at given times. Similarly, there must also be methods allowing direct manipulation and comparison of simulated and observational data in the temporal as well as the spatial dimension.

Any representational scheme is inextricably linked with specific types of questions or uses. This is why a strip map or route map is more easily used for travelling from one place to another than an overall areal map, whereas a route map is virtually useless for showing the overall distribution of various geographical entities within a given area. Thus, if change-related questions are to be addressed, it is necessary to utilise a type of representation that is specifically suited to that type of application.

2.2 Representing time and change

Conceptually, the basic objective of any temporal database is to record or portray change over time. Change is normally described as an event or collection of events. Perhaps the most encompassing definition of an event is 'something of significance that happens' (Mackaness 1993). For the purpose of space–time modelling a better definition might be 'a change in state of one or more locations, entities, or both'. For example, a change in the dominant species within a forest, a forest fire, change of ownership of the land, or building of a road would all be events. Change, and therefore also events, can be distinguished in terms of their temporal pattern into four types:

- *continuous* – going on throughout some interval of time
- *majorative* – going on most of the time
- *sporadic* – occurring some of the time
- *unique* – occurring only once.

This means that duration and frequency become important characteristics in describing temporal pattern.

These patterns can be very complex: just as a spatial distribution can be random, uniform, or clustered a temporal distribution can be chaotic, steady state, or cyclic. Similarity of states of locations or entities through time can also be converging, diverging, or combinations such as a dampened oscillation. Individual events can be characterised as clustered, forming *episodes*, that perhaps can be further grouped into cycles. Perfectly cyclical distributions are an important form of steady-state behaviour over longer temporal intervals. Thus a series of dry years in California can be grouped as a drought episode. This drought episode may in turn be part of the El Niño cycle. Variations in the length of El Niño cycles may be seen as chaotic, as may governmental response to various economic and social repercussions of such climatic cycles.

Change relating to entities or locations can be sudden or gradual. Entities appear, progress through various changes, then disappear over time. They may also change in complex ways. A critical issue is maintaining or changing the identity of entities: how are various states of the same entity, such as a stand of trees or a town, maintained as it changes through time? What kinds of change denote a change in the identity of an entity? Spatially, an entity may move, expand, shrink, change shape, split in two, or merge with an adjoining entity.

Change of some sort is always occurring. Change also occurs at different rates for various entities and locations. Since it is impossible to go back to a location in time as one can go back to a location in space, some events will inevitably be observed after-the-fact (or after the onset), with the exact time, duration, and nature of the events inferred. Some events will simply go unrecorded or be obliterated within a series of unobserved events. This translates to some level of inherent error and incompleteness in space–time data.

Although space and time are continuous, they are conventionally broken into discrete units of uniform or variable length for purposes of objective measurement. Time is divided into units that are necessarily different from those of space (we cannot measure time in metres or feet). Temporal units can be seconds, minutes, days, seasons, political administrations, or other units that may be convenient. Whether a single temporal scale or a hierarchy of scales is used, the smallest unit of recorded time is called a *chronon* (Jensen et al 1993).

An important capability for geographical modelling applications is to be able to represent alternative versions of the same reality. The idea of multiple realities over time is called *branching* (Langran 1993; Lester 1990). The idea of branching time is that of independent, yet synchronous states. This allows various model simulation results to be compared or to compare simulation results to observed data. As such, branching time is an integral notion as part of process model calibration and validation – regardless of whether the model is of mesoscale climate change or urban growth.

Given this general review of the nature of time and the representational issues that must be taken into account our focus now turns to the more concrete issue of present cartographic and GIS approaches for representing space–time information.

3 APPROACHES FOR REPRESENTING SPATIO-TEMPORAL DATA IN GIS

3.1 Location-based representations for spatio-temporal data

The only data model available within existing GIS that can be viewed as a spatio-temporal representation is a temporal series of spatially-registered 'snapshots', as shown graphically in Figure 1. This is not an intended representation but is rather a convenient redefinition within a standard GIS database organisation of what is stored in the

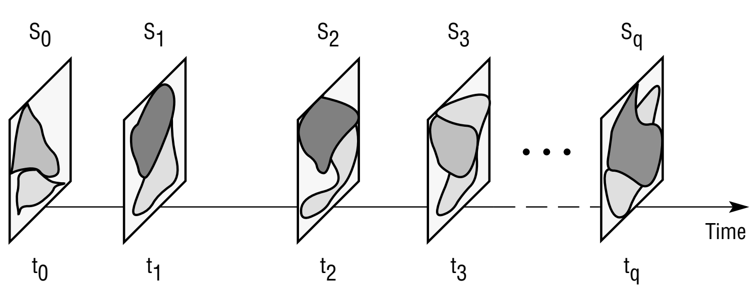

Fig 1. The 'snapshot' approach for representing spatio-temporal data: each 'snapshot', S_i, represents the state for a given point in time, t_i.
Source: Peuquet and Duan 1995

individual thematic layers. The ‘snapshot’ approach for space–time representation usually employs a grid data model, although a vector model can also be used (Pigot and Hazelton 1992). Instead of storing all information relating to a given thematic domain (e.g. elevation or land-use) within a single layer, a layer holds information relating to a single thematic domain at a single known time. Data are thus recorded over a series of discrete temporal intervals. The distinguishing feature of the snapshot representation is that a ‘world state map’ S_i at each given point in time t_i is stored as a complete image or snapshot. Everything is included regardless of what has or has not changed since the previous snapshot, and the temporal distance between snapshots is not necessarily uniform.

With this conceptually straightforward approach the state of any location or entity at a given time can be easily retrieved. This is also an obvious representation for data that are similarly collected as exhaustive coverages at discrete intervals, such as the decennial Census. There are, however, three drawbacks inherent in this approach.

1 The data volume increases enormously when the number of snapshots increases since each snapshot is a complete map of the entire region. This necessitates storage of a significant amount of redundant data since in most cases the spatial changes in two consecutive snapshots are only a small portion of the total data volume.

2 The changes of spatial entities that accumulate between two points in time are stored implicitly in the snapshots and can only be retrieved via a cell-by-cell (or vector-by-vector) comparison of adjacent snapshots. This process can be very time consuming. More importantly, however, some critical yet short-lived change at some location may occur between two consecutive snapshots and thus may not be represented.

3 Exactly when any individual change occurred cannot be determined. Chrisman warned against the use of snapshots on the basis of these last two characteristics alone since volume problems can be overcome with greater hardware storage capacity (Chrisman 1994).

A modification of the grid model that allows the time and place of individual changes (i.e. events) to be recorded was proposed within a GIS context by Langran (1990) and has been implemented on a prototype basis (Peuquet and Qian 1996). This model is also used in electronic circuitry design analysis (Fujimoto 1990). Instead of recording only a single value for a single pixel a variable-length list is associated with each pixel. Each entry in the list records a change at that specific location denoted by the new value and the time at which the change occurred. This is shown in Figure 2 in which each new change for a given location is added to the beginning of the list for that location. The result is a set of variable-length lists referenced to grid cells. Each list represents the event history for that cell location sorted in temporal order. The present (i.e. most recently recorded) world state for the entire area is easily retrieved as the first value stored in all of the locationally-referenced lists. In contrast to the snapshot representation, this representation stores only the changes related to specific locations and avoids storing redundant information (i.e. values for locations which remain unchanged).

3.2 Entity-based representations for spatio-temporal data

Several spatio-temporal models have also been proposed that explicitly record spatial changes through time as they relate to specific geographical entities instead of locations (Hazelton 1991; Kelmelis 1991; Langran 1992). On a broad conceptual level, all of these proposed models represent extensions of the topological vector approach. As such, they track changes in the geometry of entities through time. These spatio-temporal models rely on the concept of

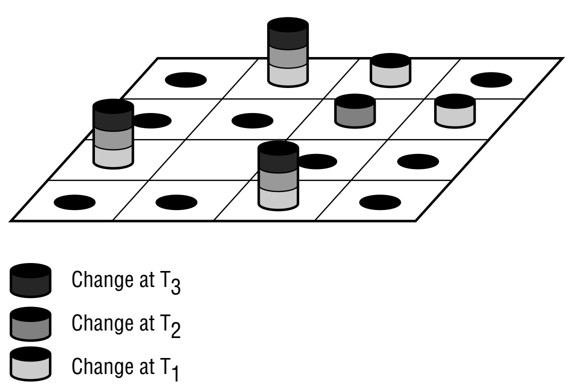

Fig 2. The temporal grid approach for representing spatio-temporal data.
Source: Langran 1992

amendments, where any changes subsequent to some initial point in time in the configuration of polygonal or linear entities are incrementally recorded. The first of these models was proposed by Langran (1989b) and relies on what she describes as 'amendment vectors'. As a simple graphic example Figure 3 shows the historical sequence for a small portion of the roadways in a growing urbanised area. The thin black line shows the original configuration of a road at time t_1. At some later time, t_2, the route of the original road was straightened. Note that this modification required cutting the original line at two points, designating the piece of the original route between those two points as obsolete, and inserting a new line segment between the same two points to represent the new portion of the road. This results in four line segments where there was only one before the update. At some still later time, t_3, a new road is built and entered into the database which has an intersection point along the realigned segment of the first road. The time, t_n, when the change occurred is recorded as an attribute of each vector. This organisation allows the integrity of individual entities (e.g. lakes, roads, etc.), components of those entities (e.g. boundary lines), and the vector topology to be explicitly maintained over time.

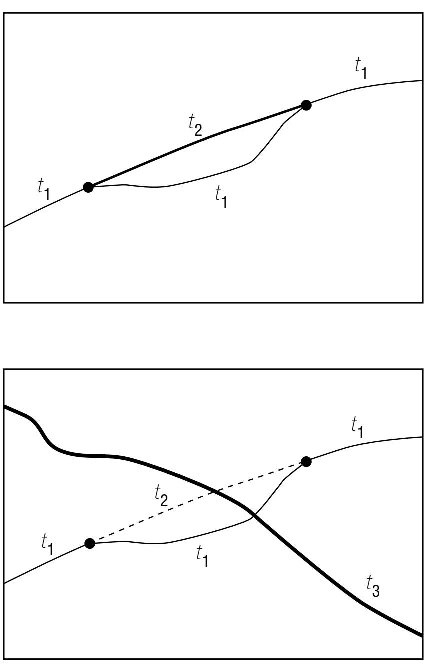

Fig 3. The 'amendment vector' approach.

Hazelton utilised this basic idea within a 4-dimensional Cartesian space-time and proposed an extended hierarchy comprised of nodes, lines, polygons, polyhedra, polytopes, and polytope families as the conceptual organisational basis (Hazelton et al 1990). Kelmelis proposed a similar hierarchy of nodes, lines, surfaces, and volumes within a 4-dimensional Cartesian space–time coordinate space as an extension of the DLG-3 data model (Guptill 1990; Kelmelis 1991).

Besides explicitly maintaining the integrity of individual entities and their changing topology through time, the amendment vector approach also has the advantage of being able to represent asynchronous changes to entity geometries. This capability, however, comes at significant cost: as time progresses and the number of amendment vectors accumulate, the space–time topology of these vectors becomes increasingly complex.

There are many aspatial entity attributes that can also change over time. To track the history of aspatial attributes a separate relational database representation can also be used where an entity is represented as a tuple, composed of a unique identifier and a sequence of attribute values. This is an extension of the separation of spatial/non-spatial attribute storage commonly used in current GIS. However if the components that make up the spatial and aspatial aspects of any given entity are changing at different times and at different rates, as would commonly happen, maintaining the identity of individual entities in such a disjoint representation becomes difficult. Accurately maintaining identities becomes particularly complex when entities split or merge through time: which components carry which identifiers?

The object-oriented approach to representation has been proposed by a number of researchers as a means of handling this problem (Kucera and Sondheim 1992; Ramachandran et al 1994; Roshannejad and Kainz 1995; Worboys 1994; see also Worboys, Chapter 26). The object-oriented approach was originally developed as a generally applicable data representation method for software design and implementation (Booch 1994). The key to the object-oriented approach is the idea of storing, as an integral unit, all components that define a particular 'thing', as a *concept* (e.g. a single bank transaction, geographical entity, etc.). This is known as *encapsulation*. Another basic element of the object-oriented approach is *inheritance*: the explicit linkage of objects to a taxonomic hierarchy identifying object types. For the case of geographical entities Lake Erie *is a* lake would be an example of an inheritance relation. Figure 4 gives a conceptual schematic of how an entity might be represented using this approach. This conceptual example includes aspatial, spatial, temporal, and taxonomic components. The object-oriented approach thus provides a cohesive representation that allows the identity of objects, as well as complex interrelationships, to be maintained through time. Rules for determining how to split or merge entities can be stored as part of the entity and entity class definitions. Perhaps the most mature implementation so far of an object-oriented spatio-temporal model is the Spatial Archive and Interchange Format (SAIF). Version 1 of this format was adopted in 1991 by the Canadian General Standards Board Committee on Geomatics as the Canadian standard for the exchange of geographical data (Kucera and Sondheim 1992).

3.3 Time-based representations for spatio-temporal data

Spatio-temporal representations that use time as the organisational basis have also been proposed recently (Peuquet and Duan 1995; Peuquet and Wentz 1994). These also suggest maintaining the explicit storage of temporal topology as an adjunct to location- and entity-based representations in a temporal GIS. In the time-based representation proposed by Peuquet and Duan, shown diagrammatically in Figure 5, all changes are stored as a sequence of events through time. The time associated with each change is stored in increasing temporal order from an initial, stored 'world state' (see Figure 5a). Differences between stored times denote the temporal intervals between successive events. Changes stored within this timeline or 'temporal vector' can relate to locations, entities, or to both (see Figure 5b). Such a timeline, then, represents an ordered progression through time of known changes from some known starting date or moment (t_0) to some other known, later point in time (t_n). Each location in time along the timeline (with its temporal location noted as t_0, t_1,..., t_n) can have associated with it a particular set of locations and entities in space-time that changed (or were observed as having changed) at that particular time and a notation of the specific changes.

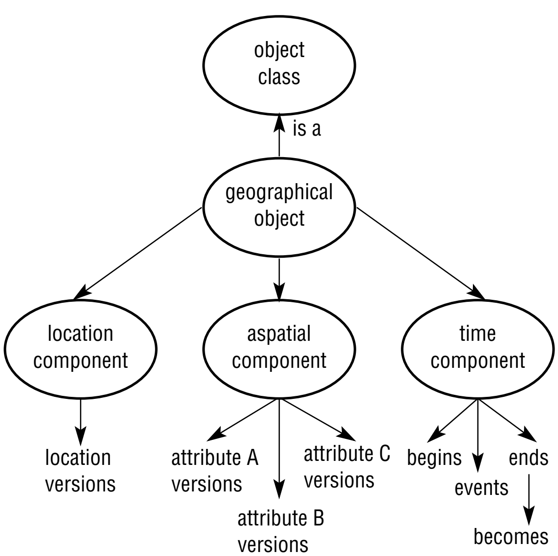

Fig 4. The object-oriented approach.

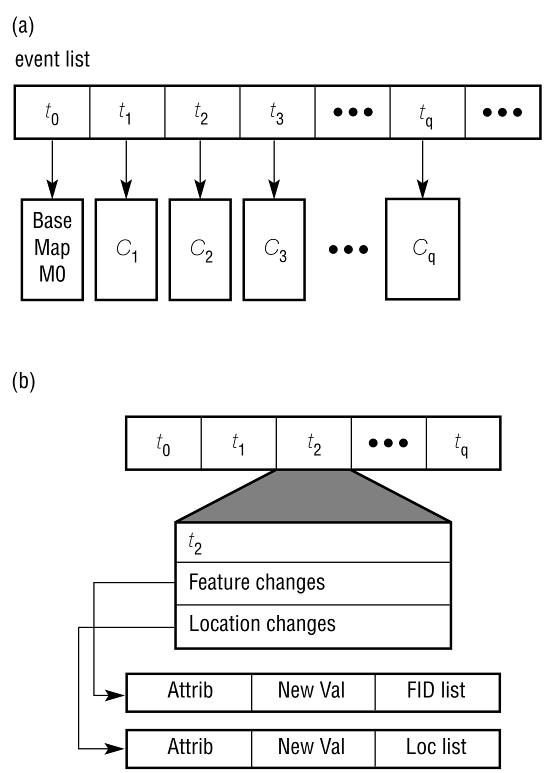

Fig 5. A time-line, or 'temporal vector'.
Sources: Peuquet and Duan 1995; Peuquet and Qian 1996

Besides sudden change as might be caused by some catastrophic event such as a forest fire or industrial plant closing, change can also be gradual such as the amount of rainfall or income level associated with a particular location, drainage basin, county, etc. For such instances of gradual change a change 'event' is recorded at the time when the amount of accumulated change since the last recorded change is considered to be significant or by some other domain-specific rule. It would also be possible to extend this basic model to denote explicitly and separately the start and end of gradual or longer-term changes as specific event types. Mackaness (1993) has called these longer-term changes *episodes* in order to distinguish them from shorter-term 'events'.

With this type of time-based representation, the changes relating to times are explicitly stored. This type of representation has the unique advantage of facilitating time-based queries (e.g. retrieve all events that occurred between January 1 and March 30, 1995). Adding new events as time progresses is also straightforward; they are simply added to the end of the timeline.

Similar timeline approaches have been proposed by Lester (1990) and by Frank (1994). In these approaches the timeline is strictly an ordinal model where the precise dates of events are unknown. A strictly ordinal timeline facilitates the representation of *branching* time in order to represent alternative or parallel sequences of events resulting from specific occurrences. Limitation to the temporal ordering of events is encountered in application domains such as archaeology, urban history, and ecology.

3.4 A combined approach for spatio-temporal representation

Associating additional temporal information with individual entities provides a means of recording entity histories, and thereby allows histories of entities and types of entities to be easily traced and compared. Similarly, associating temporal information with locations allows the history of individual locations and sets of locations to be traced and compared. Locational overlay operations can also be used in a location-based spatio-temporal representation to characterise locations on the basis or colocation of multiple changes or types of change. Since these different types of representation provide differing perspectives of the data, each facilitates a different class of queries. This is precisely the reason why the current trend to provide both location-based and entity-based representations within current GIS is being extended to temporal GIS as well (Peuquet 1988, 1994; Yuan 1994).

4 TEMPORAL RELATIONS

In using a spatio-temporal GIS to analyse processes it is essential to be able to examine change on the basis of time, retrieving locations and entities on the basis of the temporal relationships of a specified event and, moreover, to be able to examine overall patterns of temporal relationships. Within an automated database context relationships act as *operators* on stored observational values. These relational operators may be implemented algorithmically or stored as explicit links. As operators, they enable the analyst to select and manipulate stored data in an ad hoc manner. Three basic types of temporal relationships have been defined (Peuquet 1994):

- association between elements within a given temporal distribution at a given temporal scale;
- combination of elements from different temporal distributions;
- transformations between temporal scales.

Selective retrieval and manipulation of data on the basis of these basic temporal relationships is particularly important from an analytical perspective because it allows the examination and derivation of cause and effect as well as overall temporal patterns (i.e. temporal *cycles* and rhythms).

The first type of basic temporal relationship includes metric and topological relations. Given that time is 1-dimensional there is only a single temporal metric, namely temporal distance. Temporal distance is the quantitative measurement of the interval between any two given points in time. Temporal distance can be used to denote the length of an event (i.e. its duration), the duration between two events, or the duration of some continuous state.

Temporal topology is the expression of relationships between events strictly in an ordering sense. In this type of relation the timeline itself can be viewed as elastic with events recorded upon it as knots or singularities. In terms of analysis this also allows for examination of different sequences of events that may occur at varying time scales.

Temporal topology has been studied in a number of fields including philosophy, mathematics, linguistics, and artificial intelligence (Allen 1984; Davis 1990; Shoham and McDermott 1988). These relationships are shown graphically in Figure 6. Note that six of the seven basic relationships have inverses so there are 13 possible temporal topological relationships in all.

The second basic type of temporal relationship includes those that combine different types of temporal distributions. These are the temporal overlay relationships that act as Boolean set operators (intersection, union, negation). This type of relationship allows temporal co-occurrence (or non co-occurrence) of different states or events over specific temporal intervals to be examined.

The third basic type of temporal relationship, temporal scale change, includes generalisation and extrapolation over a specific temporal distribution. This type of relationship involves combining events, episodes, and states in the case of generalisation. In the case of extrapolation events, episodes, and states may be inferred in order to fill in an expanded temporal sequence. The method of temporal generalisation (or extrapolation) used is dependent upon the given temporal measurement used (e.g. four seasons, 12 months, or 365 days (usually) each equal one year). The method may also vary from scale to scale.

In addition to these basic temporal relationships there are other temporal relationships that also relate directly to specific locations or to specific entities. As such they operate respectively within location-based or entity-based temporal representations.

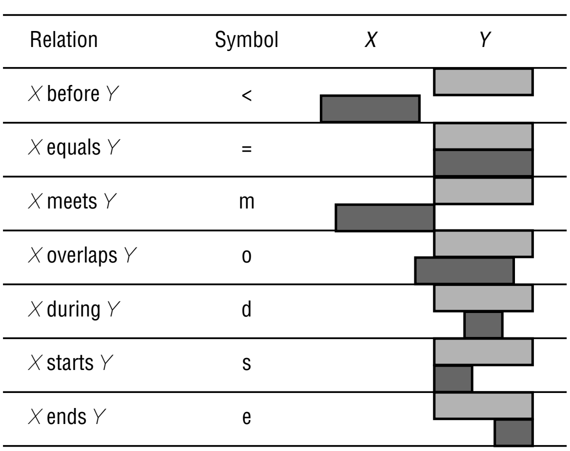

Fig 6. Allen's temporal relationships.
Source: Allen 1984

The most apparent locationally-based temporal relationship is essentially a variation of spatial overlay but in this case is used to compare change or similarity of state at a specific location or set of locations at differing times. This is the temporal operation that can already be performed in existing GIS utilising temporal snapshots. This differs from the temporally-based overlay relationships described above in that the comparison is tied to specific locations over specific temporal intervals. In contrast, the basic temporal overlay relationship previously described is tied to specific times but not to specific locations.

Cause-and-effect is an entity-based temporal relationship relation. This relationship is certainly the most important but also the most complex of the temporal relationships to determine. Establishing a cause-and-effect relationship is usually the final goal of most spatio-temporal analyses. One-to-one cause-and-effect relationships may be derived from *a priori* knowledge or direct observation of before/after states. As such these are most often explicitly stored as causes/caused-by or becomes/precedes links within an entity-based temporal representation.

5 METHODS OF SPATIO-TEMPORAL ANALYSIS

The ability to retrieve data in an ad hoc manner is a very basic and fundamental form of qualitative analysis. For the full analytical power of any modern GIS, temporal or otherwise, to be realised, all three types of analysis should be present: qualitative, quantitative (numerical), and visual.

One method of spatio-temporal analysis within a GIS is the use of the basic temporal relationships and space–time overlay in conjunction with visualisation techniques in an exploratory mode. This is a powerful technique that employs the power of the human visual system to detect pattern in an intuitive and ad hoc manner and has been proposed by a number of researchers within the cartographic community (Dorling 1992; Kraak and MacEachren 1994; Monmonier 1990).

As reported by Kucera (1996), experiments with visualisation of space–time dynamics of geographical phenomena have led to some startling results in uncovering patterns that are not otherwise evident. Relatively early investigation by Dorling revealed a space–time association between pub closing times, football matches, and telephone calls to emergency services (Dorling 1992). Dorling and Openshaw (1992) and Gould (1993a) have applied dynamic visualisation to the understanding of how disease spreads. Others have applied visualisation techniques to the space–time analysis of traffic patterns (Ganter and Cashwell 1994); other applications include climate change, regional groundwater pollution analysis, and crop prediction (Mitasova et al 1995).

Dorling and Openshaw (1992) have also demonstrated that direct user manipulation of temporal scale and other graphic variables for dynamic display can enhance the discriminatory power of visualisation. MacEachren has elaborated upon the potential of independently manipulating spatial and temporal scales in order to 'bring the phenomena to human scale (both spatially and temporally) so that we can examine them using a sensory system particularly adapted to this scale. To be able to see (and hear, and manipulate) "objects" as if they were a flower, or rock, or bird in our hand...' (MacEachren 1995: 159). Kraak and MacEachren (1994) also reviewed some general issues that need to be addressed towards the development of a different kind of cartography that is more attuned to dynamic display. Issues include ordering the display on the basis of variables other than time, synchronisation of two or more series, and duration of display time as it corresponds to both real-world time and to human perception.

A variety of quantitative methods for analysis of space–time data has been developed. Some of these are deterministic models, while others are purely descriptive. Perhaps the most generally known are the studies of diffusion which originated with Hägerstrand (1953). Methods for modelling diffusion processes have included Markovian probability sequences and gravity models. More recently, Gould (1993b) has utilised spatial adaptive filtering to study diffusion processes. With this method, the goal is to derive structure from a given space–time distribution instead of simulating the process as it unfolds from some starting point. Gould (1994) has also experimented with neural nets on temporal data. Layers of 'neurones' are interconnected using trial and error and then weighted by using training data (Fischer, Chapter 19).

Another approach that has been proposed is the use of cellular automata. An individual sequential state 'machine' is located within each cell of a regular grid. Each cell is in some individual but known state. Depending upon which protocol is used, changes in these states can be triggered by either (a) discrete temporal increments, or by (b) the occurrence of discrete events. At each temporal increment (or event occurrence), each cell determines its new state using some explicit transition rule. This rule may include the states of the neighbouring cells as well as global state changes as factors. Couclelis (1985) and Hogweg (1988) proposed the use of cellular automata for modelling environmental processes. Itami and Clark (1992) implemented a prototype version of this approach within the cell-based Map Analysis Package (MAP) originally developed by Tomlin (1983). Nevertheless, this approach has not progressed beyond these tentative and very preliminary proposals.

As theories of frequency, cycle, and causality are developed there is also need for a method to express these patterns. Examples abound within various disciplines in the use of self-contained numerical models for space–time modelling. These include a large number of air and water flow models, such as stormwater runoff models, global climate models, and ocean circulation models. Some of these use gridded representations and simulate varying states at these grid points depending upon surrounding states. Others use a link–node representation. All of these are fluid dynamics models and as such are based upon the fundamental physical continuity equations for the conservation of mass, momentum, and energy (Anthes et al 1987; Orlob 1983; Sklar and Costanza 1991). Ecological models that are space–time specific focus on simulating the distribution of some phenomenon over a landscape-scale surface. These are typically specific to a given geographical context. Examples include oceanic ecosystem models, pest infestation models, and wildfire models. The model developed by Show (1979) to describe the distribution of plankton in the Gulf of Mexico is one example of an oceanic ecosystem model. Perhaps the most widely used of this type of model are wildfire models, such as the one developed by Kessel (1975). These ecological models divide space either into a rectangular grid or into contiguous polygonal units and simulate successive states within these units.

The basic difficulty of modelling natural and social processes is that they are usually very complex, involving the interplay of a wide variety of variables that differentially change over time and space. Processes are also interlinked, and at varying spatial and temporal scales. Regardless of the application domain of such models, a limiting factor in their continuing refinement and validation has historically been lack of data and lack of sufficient computing capacity to handle available data. Certainly both are being rapidly overcome with modern computing advances and the availability of large, integrated government databases. The primary issue is now becoming the lack of integration with GIS. The powerful data access and manipulation capabilities of GIS need to be linked with numerical simulation models in order to refine these models (and our general understanding of the phenomena represented) in a more interactive and incremental manner, comparing before and after states over a sequence of space-time and comparing alternative simulations.

Sophisticated qualitative approaches have been proposed as an alternative for expressing the individual elements of a process in a manner that is cognitively more straightforward than numerical models. Davis (1990) and Worboys (1990) suggested the use of rule-based temporal logics. This approach is based upon formalised rules and axioms using relationships as operators. However, temporal logics, regardless of the application context, are at a very early stage of development.

6 TIME IN ASPATIAL DATABASES

The integration of time into database management systems (DBMS) has been an active field of research for a number of years. Although DBMS technology historically emphasises the storage and handling of aspatial data, the prospect of temporal DBMS will have both a direct and indirect impact on handling time in GIS. DBMS have been used for a long time as an adjunct within GIS for handling the non-coordinate, or attribute, data within a GIS. DBMS with temporal capabilities will perform an equivalent complementary role in handling temporal attribute data within a temporal GIS. The availability of temporal DBMS will thus have a direct impact on the capabilities of temporal GIS. The development of concepts and methodologies for integrating time into DBMS will also have an indirect effect by providing insight into equivalent representational and processing issues within the spatial context. These less tangible, indirect effects are discussed in more detail below. A more thorough review of temporal DBMS research and how specific areas could be applied to GIS has been given by Langran (1989a).

Much more progress has been made in representing time within DBMS as compared to spatial databases. Within the typically aspatial context of DBMS the issues involved are not as complex because of the reduced dimensionality of the data. Perhaps at least in part because of this, progress on temporal DBMS is rapidly moving this area out of a purely research realm. Representations used for DBMS have been developed using extensions to traditional relational as well as object-oriented approaches (Ozsoyoglu and Snodgrass 1995; Snodgrass 1995). Some of this work has also been applied to the GIS context, particularly by Stonebraker and the Sequoia 2000 project (Guptill and Stonebraker 1992).

A number of query languages have also been proposed (Egenhofer and Kuhn, Chapter 28). A standard language for temporal DBMS – SQL2 – was recently adopted as the ISO standard. This language represents an extension of SQL. There are now efforts toward a further extension of SQL in a new standard (SQL/Temporal) that will also incorporate features of SQL/MM. SQL/MM was designed as an extension of SQL to address the specific needs of multimedia applications. Most importantly, in order to deal with imagery and video, SQL/MM incorporates spatial as well as temporal concepts (Kucera 1996).

Two issues uniquely related to the temporal dimension have received much attention in DBMS and seem relevant to the spatio-temporal context also. First, it is for practical purposes often impossible to enter data into a database at the moment the relevant event occurs in the real world. There is a distinction between when a state or condition is current or valid in the real world and when that state or condition was entered into the database (i.e. 'valid time' vs 'transaction time'). These are also known as 'world time' and 'database time', respectively (Jensen et al 1993). This distinction has been used for a long time in banking transaction records; for example, when a bank teller received a deposit and when that deposit was actually credited to the account. The difference between these two times is used to detect potential bookkeeping errors and to guard against fraud (e.g. to allow time for the cheque to clear before allowing withdrawals on this amount). How to effectively represent both types of information within the same database, therefore, is an important issue. This becomes an important distinction in certain GIS applications such as cadastral systems (Al-Taha 1992; Hunter and Williamson 1990; Worboys 1994).

A second major area of interest within the temporal DBMS arena is how to perform retrospective updates (i.e. inserting new information concerning past conditions or events). This issue involves how to determine which other information already in the database is affected by the new information and must therefore also be changed in order to maintain the integrity of the data. Pioneering research on this issue within the temporal DBMS community involves the use of a variety of artificial intelligence techniques and formal logics for temporal reasoning (Kowalski 1992; Maiocchi et al 1992).

Two classical and unresolvable issues in traditional GIS and cartography, which also carry over into the temporal GIS context, are being discovered anew by the temporal DBMS research community. These are temporal generalisation and temporal resolution. Temporal resolution is known as the 'granularity' of the database (Jensen et al 1993) within temporal DBMS. Many of the problems associated with resolution and discretising values for continuous phenomena as they have become known in the spatial realm are also being encountered in the aspatial realm.

7 THE FUTURE?

Much remains to be done before a true temporal GIS can be realised. As was the case in current spatial database systems, the introduction of representational power and analytical capabilities in commercial systems will itself be a temporal process. However, progress should be more rapid given the current state of knowledge and technology. This brief discussion on the related field of DBMS also provides a glimpse of how much there is to be gained from interdisciplinary research on temporal databases and temporal representation in general.

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