SPATIO-TEMPORAL KNOWLEDGE REPRESENTATION

A wide range of spatial knowledge representations based on two-dimensional ontologies have been developed from cognitive analyses and from *a priori* schemes (see chapter 2). However, these two-dimensional ontologies explicitly excluded time, seeing it as conceptually distinct from space and unnecessary in spatial knowledge representations. Langran (1988, 1992) was among the first to explore spatio-temporal knowledge representation, defining the concept of 'dimensional dominance' to describe how spatio-temporal information is usually dominated in display and query terms by either the space or time dimension. This situation is a function of the fact that uses of spatio-temporal information tend towards interest in space as an ordering (maps) or time as an ordering (case histories) rather than both. However, spatio-temporal knowledge representations need to express a unified spatial and temporal approach.

There have been far fewer attempts to define spatio-temporal knowledge representations, as there are correspondingly fewer spatio-temporal ontologies available. Possible spatio-temporal ontologies divide into those based on absolute time and space and those based on relative time and space (Wachowicz 1999). Ontologies are defined by the spatial and temporal boundaries of events in the absolute approaches, and by the relationships between the geo-phenomena in the relative ones. These alternatives mark out different approaches to the definition of identity, and, therefore, different approaches to change. Peuquet (1994) proposed the TRIAD scheme where all geo-phenomena are defined by attribute, spatial and temporal references ('what, where, when') to form a 'world history model'. This is an absolute time and space view that is equivalent to the ontological argument of attribute 'bundles'. By contrast, Roshannejad and Kainz (1995) argued that while all multidimensional geo-phenomena need to be referenced by what, where, when information, object identity must be independent of referencing. This is a relative time and space view that is equivalent to the ontological argument of 'essences'.

In a formal approach to spatio-temporal knowledge representation, Claramunt and Thériault (1996) presented a typology of spatio-temporal processes from an absolute time and space perspective, based on the TRIAD scheme of Peuquet (1994). Claramunt and Thériault argue that there are three main types of spatio-temporal processes: the evolution of a single entity such as changes, transformations and movements; the functional relationships among multiple entities such as replacement and diffusion; and, the evolution of spatial structures involving several entities. On the basis of this typology they introduce an Event Pattern Language (EPL) which can describe the spatio-temporal evolution of a set of objects in terms of processes and operators. Although this is a useful and expressive formalism it cannot handle non-discrete geo-phenomena or gradual object identity change. The semantics of Claramunt and Thériault have recently been extended by Shu, Chen and Gold (2000).

Hornsby and Egenhofer (2000) presented a formal scheme for spatio-temporal knowledge representation, based on possible changes to geo-phenomena, modelled as discrete objects at a high level of abstraction. In the Hornsby and Egenhofer (2000) Change Description Language (CDL), objects can be in the following states: existing; not existing with no history of a previous existence; or, not existing but with a history of previous existence. Changes from one state to

another are defined as 'transitions', which in total allows nine combinations: continue existence without history; create; recall; destroy; continue existence; eliminate; forget; reincarnate; and continue non-existence with history. This scheme is an axiomatic system for the exploration of change semantics that produces a classification of the changes to an object identity defined in this way. The constitutive nature of 'transitions' (object inter-relationships) in the scheme implies that this approach is a relative time and space view.

An alternative conceptualisation of change might be based on a psychological concept of 'difference' that is independent of referencing and representation. The set of all possible forms of change defined as difference, with the human construction placed on these scenarios is:

- Same place, same geo-phenomena, different time (progression of geo-phenomena)
- Different place, same geo-phenomena, different time (geo-phenomena that have moved)
- Same place, different geo-phenomena, different time (monitoring place)
- Different place, different geo-phenomena, different time (elsewhere)
- Same place, same geo-phenomena, same time (real time feedback)
- Different place, same geo-phenomena, same time (contemporaneous monitoring).

This schema classifies difference, and, by implication the scope of multidimensional identity.

Temporal GIS

Temporal GIS are systems for representing the temporal behaviour of geo-phenomena when they have been projected from four dimensions to two spatial plus one temporal. Early approaches were based on the extension of commercial two-dimensional GIS to handle time with the attributes, which Langran (1992) classified into three types: sequent 'snapshots'; 'base state with amendments'; and, 'space-time composites'. These designs mirrored the early approaches to developing temporal relational databases to handle change in the stored entities (Snodgrass 1992). Here, 'snapshots' are equivalent to the addition of new tables to the database; 'base state with amendments' is equivalent to the addition of tuples to a table; and 'space-time composites' are the equivalent of adding new items to an attribute. Snodgrass (1995) developed a temporal version of SQL TSQL2 to support temporal queries in relational databases, but this has not been widely adopted pending progress on the ISO standard SQL/MM.

In both GIS and relational database, Langran (1992) showed that the creation of temporal 'versions' at relation, record or attribute level leads to unacceptable extra data volume and violations of integrity in the tables. Violating integrity rules, for example, by adding extra items to an attribute, meant that the standard query tools would not give valid results, requiring further potentially non-standard extensions to the system. Several alternative theoretical schemes for spatio-temporal data storage and access using GIS were evaluated by Langran (1992). These ranged from the insertion of objects into a versioned grid index (which expanded the number of objects unacceptably) to approaches using versioned map partitions based on R-tree indexing (which reduced the efficiency of searches due to the overlapping partitions). Xu, Han and Lu (1990) showed how to extend the R-tree to handle changing spatio-temporal data by adding nodes to the tree as change occurs to the spatial objects. Abraham and Roddick (1999) have surveyed and synthesised work in this area.

Subsequent innovations in temporal GIS involved further extensions to geo-relational GIS designs. Raafat, Yang and Gauthier (1994) proposed a system in which temporal behaviour leading to changes is stored by the addition of tuples in the database. However, unlike the earlier users of this technique they propose a two-tier system in which only a master relation has the 'essential property' attribute conferring identity on an entity, while 'slave' relations contain all other data. This allows the temporal change to be stored as additional tuples at the level of entity identity, without expansion in all other tables – except where new geometric data is required to create the new spatial configuration. Although data volumes do increase, the system supports temporal queries on vector geometric entities using standard SQL and no extensions to the relational model are needed.

Peuquet and Duan (1995) proposed an event-based approach to temporal change in raster geometric maps called the Event-based Spatio-Temporal Data Model (ESDTM). In ESDTM temporal behaviour is stored by recording changes to an initial raster map in an event list in the form of a sets of changed raster grid cells. In a more sophisticated design, Peuquet and Qian (1996) used the TRIAD scheme to define the TEMPEST temporal GIS in which all changes to the stored spatial entities are referenced to a set of unequal ordered temporal intervals. To capture the semantics of the change TEMPEST stored change to the extent and type of objects in a feature view, the times and locations that had changed in a time view, and the changes at-a-location in a location view. Mennis, Peuquet and Qian (2000) have developed the Pyramid scheme to add the semantics of object identity to TRIAD.

These GIS-based or GIS-like approaches to storing temporal behaviour are really only suitable for a coarse temporal granularity of change which takes place in discrete ways, for example, changes in ownership or dimensions of an urban land parcel. In environmental applications highly dynamic phenomena change at a fine temporal resolution (minutes to weeks) in a continuous way, for example, in the seasonal migration patterns of animals or the hourly change of the tides in the coastal zone. Morris, Hill and Moore (1999) outline the Water Information System database design of the Spatio-Time Environmental Mapper (STEM), which uses a relational database to store what, where, when information in an optimised record-versioned data model.

Recently, Yuan (1999) has argued that what temporal GIS have lacked is a means to handle spatio-temporal identity through semantic links between spatial and temporal information. She presents a three-domain model in which snapshot, space-time composite and spatio-temporal object approaches are fused by linking the storage of data in the semantic, temporal and spatial domains. The three-domain model allows efficient entity-based and location-based queries by storing the semantic associations and temporal transitions in a 'space graph' that indexes all the stored discrete spatio-temporal entities. In effect, the georelational

implementation Yuan presents is a normalisation of the snapshot, space-time composite and spatio-temporal object models.

Object-oriented spatio-temporal GIS

In a search for more flexible and expressive forms of geo-representation to handle temporal change, a number of authors have developed object-oriented spatio-temporal GIS. The key design issue in object-oriented approaches to handling spatio-temporal behaviour is how to structure the object classes and attributes to handle temporal change, when projected from four dimensions to two spatial plus one temporal. This in turn depends on the temporal and spatial ontologies that are to be used, and in the case of time, whether the time used will be world time (valid time), database time (transaction time) or both together (Worboys 1998b).

In the 'absolute space and time' approach objects are made within a space and time referencing system, and are bounded by events (ontologically, an 'endurantist' approach). 'Events' are defined as 'instants in time' when objects were extended in the third dimension in proportion to their temporal duration to create spatio-temporal (ST-) objects with individual identities. ST-objects can be decomposed into right prisms bounded by spatial boundaries and temporal events, called ST-atoms, each with its own identity. Worboys (1992) suggested ST-atoms could be implemented using zero-, one- and two-dimensional simplices. Spatio-temporal queries could be evaluated by exploring the space-time intersections of ST-atoms.

Yeh and de Cambray (1996) proposed a similar approach to spatio-temporal representation called the Behavioural Time Sequence (BTS) in which a three-dimensional B-rep scheme is used to represent temporal change of two-dimensional vector geometric objects. The BTS system can handle the gradual and discrete evolution of objects through time, as the change is defined using behavioural functions. Wachowicz and Healey (1994) suggested a design in which 'events affecting objects' created 'versioned objects' such that new and temporally different versions of an object would exist on either side of an event. This approach to spatio-temporal representation was implemented in the Spatio-Temporal Data Model (STDM) approach of Wachowicz (1999), developed for the mapping of public boundaries. Ultimately spatio-temporal identity is a function of the boundary/event bounding.

In the 'relative space and time' approach time is a property of the objects. Space-time is made of objects with a spatial and temporal extent, and where there are no spatio-temporal objects there is no space or time (ontologically, a 'perdurantist' approach). In most 'relative space and time' systems using object-oriented techniques, the objects are time stamped to create temporal versions of the original object. Kemp and Kowalczyk (1994) used the 'Zenith' object management system to develop a spatio-temporal data store capable of storing 'has_version' relationships for geometric objects. Events, therefore, do not force any change in the identity of the object or instance. Kemp and Kowalczyk point out that it is possible to divide attributes between levels in the object class hierarchy such that the time invariant attributes are stored at a higher level than the time variant attributes. The key question of implementation concerns the appropriate identity criterion to use, since all the attributes of an object may eventually change.

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Ramachandran, McLeod and Dowers (1994) proposed a design called TCObject in which objects with geometric and non-geometric attributes are given past, present and future states: the temporal reference is established using dates of birth and death for the object. In a similar approach, Hamre (1994) proposes a design based upon OMT (Rumbaugh *et al.* 1991) where a 'four-dimensional dataset' object is composed of a spatio-temporal component (including a 'time of creation' temporal reference) and a non-spatiotemporal component. Voigtmann, Becker and Hinrichs (1996) develop a timestamped attribute approach by extending their Object-Oriented Geodata Model (OOGDM) to form the T/OOGDM that can be queried using the T/OOGQL query language.

El-Geresy and Jones (2000) have presented a typology of spatio-temporal representational architectures and the queries they can each support. They distinguish three state-oriented spatio-temporal models: the 'where' view of changes at a location (e.g. the Langran 1992 raster change model), the 'what' view of changes to objects (e.g. Raafat, Yang and Gauthier 1994), and the 'snapshot' view of change (e.g. Peuquet and Qian 1996). They recognise three change-oriented spatio-temporal models: the 'when' view of temporal relations between events (e.g. Peuquet and Duan 1995), the integrated event view of changes in location, object and sequence, and the 'space composite' view in which relations between successive states are recorded in a single geometric layer. El-Geresy and Jones (2000) argue that these event and change models are limited by their descriptive capacities: new advanced models of change are now focussing on process (the 'how' view) and causality (the 'why' view).

Chen and Molenaar (1998) have developed a model of spatio-temporal change motivated by coastal geomorphological applications, which is focussed on process. In their 'star' model they link views of attributes, location, sequence, object and process in a single integrated approach to representing change. The processes that they define viz. shift, appear, disappear, split, merge, expand and shrink can be compared to those put forward by Claramunt and Theriault (1996) and Hornsby and Egenhofer (2000), although they are less formally based. Allen, Edwards and Bédard (1995) presented a model of change driven by causal relations among objects, based on the Bunge (1966) model of causality. In the Allen, Edwards and Bédard model, causal chains originate with intentional or non-intentional agents, which precipitate a cascade of events that change the state of objects. This model facilitates the tracing of causes and effects in time and space, at least insofar as the causal chain is well founded.

Research on spatio-temporal geo-representation is now focussed on the modelling of change rather than events. Hence, Tryfona and Jensen (1999) present a Spatio-Temporal Entity-Relationship (STER) model based on an ontology of entities in motion (e.g. a car) and discrete change in entities (e.g. land parcels). The STER model adds spatial, temporal and spatio-temporal modelling constructs to the Entity-relationship model of Chen (1976). Renolen (2000) reviews the alternative conceptual modelling frameworks for spatio-temporal information system design. These include the structural perspective of entity-relationship modelling, the functional perspective of data flow diagrams, the behavioural perspective of statecharts, rule-based approaches, object-oriented designs, action-workflow diagrams and agent models. Erwig *et al.* (1999) introduce 'moving data types' into a spatio-temporal database design using a many sorted algebra approach.

Time geography

Another context within which spatio-temporal geo-representation has been developed is 'time geography', which is the study of the spatio-temporal behaviour of individuals. The origins of time geography can be traced to Hägerstrand's (1968) work on migration, but it was codified and developed by Pred (1977). Parkes and Thrift (1980) set time geography in the context of social studies of place and time. Time geography is concerned with the space-time paths marked out by individuals, and the problem of how such paths both create and constrain the fabric of human interactions. In this formulation, 'place' can be seen as a pause in movement, while the superset of all paths form 'movement geographies' such as a commuting pattern for a city. As such, this is a relative space and time view, since the patterns created form spatio-temporal identities (Wachowicz 1999). Adams (1995) used time geography concepts to explore the 'ability of a person/group to overcome the friction of distance through transportation or communication' (p267). Adams described individuals as simultaneously points at a location, which are grounded in space-time, and as 'dendritic extensions' engaging in social and natural phenomena at various distances, which are ungrounded [spatially] as they can take place at any distance. Kwan (2000) has noted significant gender differences in space-time constraints on personal time geographies.

In order to realise time geographic concepts several distinctive spatio-temporal geo-representations have been created. In a study of urban accessibility, Lenntorp (1976) calculated the area that was reachable by a traveller from a given location, within a specified time. The zone of accessibility can be represented as cone in a three-dimensional space in which the z axis is time. The apex of the cone is at the current location and the slope of the sides is set by the attainable velocity. If the journey has to end up back at the same place by a certain time, then two identical cones of accessibility fit together to form a space-time 'prism' (Figure 4.13). Miller (1991) implemented the space-time prism concept in Arc/Info GIS as potential path areas (PPAs) by identifying which links in a road network were 'reachable' in the time interval available.

Forer (1998) reviews time geographic concepts and applications and argues that it is time to re-evaluate the possibilities of this form of representation. He argues that the greatest potential lies in the implementation of space-time prisms in raster representations (Angel and Hyman 1976), rather than in vector representations as used by Jânelle (1968) and Miller (1991). Forer (1998) proposes a novel voxel-based spatio-temporal geo-representation called a 'taxel' referenced by two dimensions of space and one of time. Using the taxel representation Forer defined four kinds of spatio-temporal volumes: space-time prisms, space-time paths (lifelines), and both static and mobile facilities. Spatio-temporal queries can be implemented as masks excluding taxels that are either not reachable or denied access. The intersection of a space-time prism with the available facilities defines spatio-temporal opportunities. Forer suggested the use of octree encoding to compress the vast amounts of data that would be required to implement realistic

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spatio-temporal volumes. He calculated that the city of Christchurch, New Zealand (300,000 people and $180km^2$) would require 1100 million taxels to represent at 10 metre and 5 minute resolution.

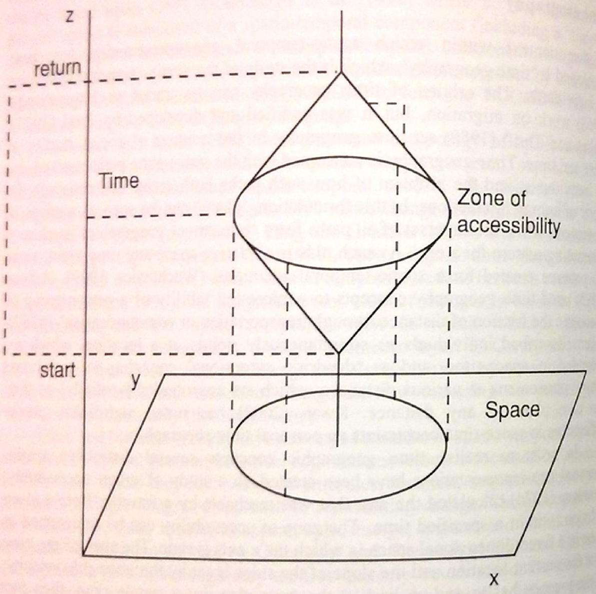

Figure 4.13 Space-time prism

Four-dimensional GIS

While spatio-temporal geo-representations can handle two dimensions of space and one of time, four-dimensional GIS are designed for three dimensions of space and one of time. A small number of fully four-dimensional systems have been designed to represent the forms, structures and properties of geo-phenomena and dynamic physical processes. Pigot and Hazelton (1992) showed that four-dimensional geo-representations for non-branching time could be based on topological cellular complexes if snapshots of discrete configurations (for example in B-rep form) were available. Since algebraic topological theory can be extended to k-dimensions (Massey 1967), connected, homogenous and bounded k-manifolds can be defined with a k-cell geometric identity, when k = 4. Pigot and Hazelton (1992) show that four-dimensional operations are equivalent to assembling and

disassembling the k-cell complexes corresponding to the time between the snapshot representations. Hazelton, Leahy and Williamson (1990) developed a database design for a four-dimensional GIS based on simplices aggregated into temporally extended polytopes.

Other approaches to four-dimensional representation have focussed on the indexing of hypercubes where data is referenced to three dimensions of space and one of time. Mason, O'Conaill and Bell (1994) developed a four-dimensional bintree to index a temporally extended three-dimensional ocean temperature grid. The bintree consisted of two 32 bit words, one for the four-dimensional location and one for the attribute field and object membership in terms of volume boundaries. The storage was not efficient compared to the raw data storage, however, the geo-representation offered rapid querying, interpolation and generalisation tools.

A method based on Riemannian Helical Hyperspatial indexing called the HHCode was described by Varma (1999). The HHCode is a transformation of the geometric into the topological and can be used to break down an n-dimensional space into storage buckets of user-defined size with very high levels of compression. Since the HHCode implicitly stores the neighbourhood of the bucket and since it can be dynamically resized, it is a flexible representational tool and an efficiently queried index. The HHCode can be used to index temporally extended three-dimensional volumes that Varma terms 'toxels', which can then be 'fused' in an operation conceptually similar to a two-dimensional overlay.

Raper and Livingstone (1995a) presented an object-oriented four-dimensional geo-representation called OOgeomorph, which assigned four-dimensional referencing to every attribute of every 'observable' stored. The set of 'observable' attributes is then assembled into a 'phenomenon' class based on application needs. This design makes it likely that the attributes of the 'phenomenon' class stored will be spatially and temporally heterogeneous, ranging from highly observation-dependent forms ('over this space at this time' attributes) to infinite steady forms ('always, everywhere' attributes). The approach forces the user to create phenomena with a functional identity as the phenomena will have multiple spatio-temporal identities needing rationalisation, i.e. an ontology is generated from phenomena rather than imposed onto it through a space and time framework. Since data storage is atomic at the scale of 'observable' data points, data storage is highly compressible and accessible through four-dimensional range queries (see chapter 10).

Four-dimensional geo-representation can also be achieved by interpolation (Zhang and Hunter 2000). Hence, Mitasova *et al.* (1996) use a minimum tension approach to interpolate hypersurfaces of time series environmental data in the GRASS GIS environment. Shibasaki and Huang (1996) generate a set of voxels representing a spatio-temporal domain by optimising likelihood using a genetic algorithm to search the solution space. Miller (1997) developed a four-dimensional kriging approach (Deutsch and Journel 1992) based on a spatio-temporal semivariogram to estimate variable values at unknown spatio-temporal locations.

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Multidimensional process modelling

While four-dimensional GIS aim to represent the forms, structures and properties of geo-phenomena, dynamic multidimensional process modelling aims to develop functional models of behaviour for systems with a spatio-temporal expression. Despite the fact that such processes surround us in society and the environment there are few multidimensional geo-representations of this kind. Watney, Rankey and Harbaugh (1999) note that this shortfall derives both from computational limitations and from the lack of knowledge of the dynamic systems concerned.

A small number of multidimensional process models have been developed for geomorphological and geological environments. Tzetlaff and Harbaugh (1989) pioneered the SEDimentary SIMulation model ('SEDSIM') to represent the processes of erosion and deposition by numerically approximating the differential equations that model flow. They implemented a hybrid 'marker in cell' approach to unify the Lagrangian fluid element flow representation with the grid-based Eulerian representation within a 3D+T implementation. Martinez and Harbaugh (1993) extended SEDSIM with the WAVE model to represent incident waves, wave breaking, surf zone radiation stress, longshore currents, wave-current interaction and nearshore sediment transport over three-dimensional deformable sea bed surfaces. Since computation limitations do not allow the modelling of realistic populations of fluid elements and sedimentary particles, SEDSIM calculates representative behaviour and scales the changes to user-defined intervals and spaces.

Raper *et al.* (1999) modified SEDSIM/WAVE to grow coastal spit landforms through time given incident waves, an estuarine setting and a sediment supply. This study showed that a physically-based multidimensional process model could generate dynamic three-dimensional forms that resemble those empirically observed (see chapter 10). Tuttle and Wendebourg (1999) also used SEDSIM to simulate a glacier ice-marginal deltaic environment in order to explore the spatio-temporal distribution of sedimentation and its likely influence on the hydraulic conductivity of the resultant deposits. Both these models used a procedure referred to as inverse modelling by Cowell, Roy and Jones (1991), who argued that the only way to develop an understanding of such environments is to 'reverse engineer' the processes responsible for the generation of forms by trial and error. The results of such modelling can then inform the ontologies and the behaviour of subsequent modelling efforts.

In a distinctive approach, Penn and Harbaugh (1999) developed the 'DYNASED' model to explore the interdependencies among the coupled variables of land elevation, sea level and sediment transfer rate that DYNASED uses to model continental shelf deposition. Since DYNASED employs the logistic equation in its state equations, the results ranged from the cyclic through quasi-cyclic to chaotic depending upon input. Penn and Harbaugh point out that coupling is a fundamental feature of multidimensional processes and models, yet little is known about its sensitivity.

THE POTENTIAL FOR MULTIDIMENSIONAL GEO-REPRESENTATION

This chapter has explored three- and four-dimensional conceptual modelling and geo-representation in depth in order to evaluate their potential to realise the opportunities of multidimensional geographic information science. The evidence suggests that when conceptual modelling is coupled with geo-representation in a multidimensional framework, then powerful new insights can be obtained and fed back into concepts. The benefits of such a view are manifesting themselves in many different fields ranging from hydrocarbon exploration to urban planning and from water management to the mapping of time geographies.

Insisting that multidimensional geo-representation always moves from concepts to tools and never the other way around means that the concepts of identity, change and spatio-temporality have become more important. Before the design of the current generation of multidimensional tools, representation was frequently driven by implementation, which often led to the destruction of spatio-temporal identity as it was divided up into the formats the system supported. With the emergence of systems that deal with change by updating identity in a four-dimensional framework, we see new possibilities for realist representations in explanation.

While this chapter dealt with the representations that can be built from geometric foundations, the next chapter explores the potential of spatial multimedia and virtual reality systems to represent in a more direct fashion. Rather than representing through geometry, chapter 5 examines the direct spatio-temporal exploration of spatial multimedia and virtual reality geo-representations.

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