It's About Time: A Conceptual Framework for the Representation of Temporal Dynamics in Geographic Information Systems

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The concept of time is intuitive. We use it in many ways in our daily lives. The passage of time is normally understood via changes we perceive occurring to objects in space—their transformations over time and their movements in relation to one another. The scientific study of the spatial processes that influence these changes is also impossible without considering both space and time. Whatever the spatial process under scrutiny, inclusion of the temporal element in the data is required so that change can be represented, cause and effect relationships can be derived from the observational data, and ultimately understanding of the nature and structure of the processes involved can be advanced (Gregory 1982).

Geography's study of processes over space and time is neither new nor unique. Since the passage from the paradigm of "Geography-as-chorology" in the 1950s, a variety of approaches for studying space-time phenomena has evolved. Andrew Clark's early work in historical geography demonstrated that changing spatial patterns could be studied as "geographical change" (Clark 1959; 1962). Cliff and Ord (1981) later examined change through time by scanning a sequence of maps, searching for systematic autocorrelation structures in space-time in order to specify "active" and "interactive" processes. Perhaps the best-known efforts within the field of geography that made explicit use of time as a variable in the study of spatial processes are Hägerstrand's models of diffusion and time geography (Hägerstrand 1967; Pred 1977; Parkes and Thrift 1980). Diffusion models focus on the overall pattern of specific natural or cultural phenomena as change spreads through space over the passage of time. The "theory of diffusion" has been applied to a diverse range of topics, including agricultural innovation, the spread of political unrest, and the spread of AIDS (Parkes and Thrift 1980; Gould 1993). Time geography deals with complex space-time phenomena by reducing space-time patterns to the individual level, observing paths of individuals through space and time and their interactions. In contrast, the importance of (and emphasis upon) the complex interwoven relationships of activities set within a hierarchical social structure of functional rules, power relations, and space-time constraints was recognized by Giddens and other sociologists in what became known as the Structuration school (Giddens 1981). When Pred adapted the structuration approach to human geography, he effectively integrated the concepts of time geography with Giddens' complex multiscalar social structures (Pred 1984).

In addition to continuing examination of social processes such as daily activity patterns and urban growth, the need to advance understanding of the effects of human activities on the natural environment is now being viewed with increasing urgency. Computerized databases are being used to study ecological phenomena such as climate dynamics, ocean dynamics and global warming, changes in animal habitat, and the effects of water pollution on aquatic life. Moreover, researchers in natural resource management are shifting their atten-

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tion from resource inventory and exploitation toward integrated and normative approaches that seek to maintain diversity or to maximize long-term environmental productivity. The advent of remotely-sensed satellite data and the exponential accumulation of other spatiotemporal data has recently enabled researchers to undertake detailed empirical studies of complex spatiotemporal processes at multiple geographic scales.

Although geographic information systems (GIS) provide, in principle, an integrated and flexible set of tools for analyzing large volumes of geographic data, such systems have only recently begun to fulfill this promise. GIS are still most often used in an exploratory mode. In the past, the conceptual and practical difficulties in representing[1] and analyzing complex spatial patterns within GIS have caused the representation and analysis of the temporal dynamics of those spatial patterns to be ignored. The full potential of space-time models for empirical spatial analysis thus remains unrealized because the paradigm for representing data temporally in the manner required does not yet exist (Miller 1991).

Enhancement of the spatiotemporal capabilities of geographic information systems is an issue that has been receiving attention recently, although most of the work to-date has primarily served to reveal that the representation of phenomena in time as well as space is significantly more complex and more difficult than their representation in space alone (Hazelton 1991; Kelmelis 1991; Langran 1992). The spatiotemporal data representations that have been put forward are extensions of traditional GIS representations. These traditional representations are, in turn, based on a visually-oriented cartographic representational paradigm. In other words, they are based on the concepts of points, lines, areas, locational grids, and other primitive elements of a static map display.

This paper proposes a new approach to the representation of spatiotemporal information that incorporates concepts from perceptual psychology, artificial intelligence, and related fields. It is an "approach" in the truest sense of that word. The representational framework described is less a definitive solution for representing spatiotemporal information so much as an attempt to apply a more encompassing perspective. This paper also attempts to look beyond prevailing approaches and to explicitly recognize a much needed distinction between *representation* in an abstract conceptual sense and visual *presentation,* given the additional constraints that the latter imposes.

The overall goal is to represent stored spatiotemporal data in a way that conforms both to human conceptualizations of the world in space-time and geographic theory and to technical demands for accuracy and flexibility in computer-based analysis and visual presentation. This is not to say that cartographic traditions, developed over decades and even centuries, should be discarded; nor should what has been called the "cartographic metaphor" be abandoned (Downs 1981; Hazelton 1991). What is proposed here, instead, is an interrelated set of alternative and mostly non-visual "mappings" of reality that organize information in different ways thereby facilitating solutions to differing questions, as well as offering an integration with more traditional cartographic representations.

The remainder of this paper is divided into four parts. Part one describes various queries that might be posed given a satisfactory spatiotemporal representation, examines the fundamental properties of time and space that must be taken into account in order to answer even the most basic of queries, and reviews the current representational approaches for both spatial and spatiotemporal data. Part two introduces a more robust representational framework that incorporates time, location, and object-based views in a Triad framework. Part three discusses some of the conceptual issues involved in extending any database of observational values (observed facts) that could be built upon this Triad framework to one that incorporates and uses derived information on spatiotemporal pattern and processes. Part four considers some implications of a Triad framework for spatiotemporal analysis and notes the continuing research needs in this domain.

Examining and Analyzing Spatiotemporal Data

A Typology of Queries Involving Time and Change

Queries of a spatiotemporal database may take various forms. One class of query addresses changes in an *object* or *feature* (Langran 1989):

(a) Has this object moved in the last two years?
(b) Where was this object two years ago?
(c) How has this object changed over the last five years?

A second class of query addresses changes in the *spatial distribution* of an object or set of objects:

(d) What areas of agricultural land use in January 1, 1980 have changed to residential land-use as of December 31, 1989?
(e) Did any land use changes occur in this drainage basin between January 1, 1980 and December 31, 1989?
(f) What was the distribution of commercial land use 15 years ago?
(g) What areas have changed from predominantly agricultural land use to urban land-use over the last 50 years?

A third class of query addresses the temporal relationships among *multiple geographic phenomena:*

(h) Which areas experienced a landslide within one week of a major storm event?
(i) Which areas within one-half mile of the new urban bypass road have changed from agricultural land uses to other land uses since completion of that road?

All of these examples incorporate time in the implied underlying conceptual representation of the phenomena as well as in the questions themselves. Some questions (a, b, and c) refer to spatial objects relative to space and time or just to time. Others (d, e, f, and g) refer to locations relative to time; and still others (h and i) refer to time relative to the attributes of specific locations or specific objects. Each of these classes of queries imposes somewhat different demands on the temporal element, but in each case the inclusion of time in the observational data allows the examination of change in the spatial configuration of natural, social, or economic patterns.

Current GIS are limited to queries that perform straightforward retrieval of observational data based on relational constraints. This is the type of query that the list above represents, with the addition of the temporal dimension. Although such retrieval operations are essential for analyzing spatiotemporal data, the true power and utility of GIS lay in the ability to perform spatial analysis. Similarly, the greater promise of spatiotemporal GIS resides ultimately in their capacity to examine causal relationships and their effects in any of four modes of inquiry:

(1) *Exploration:* What patterns of vegetation change are evident when moving through a sequence of photographs taken in 1890, 1909, 1927, 1945, 1968, and 1990?
(2) *Explanation:* What factors would account for the change in vegetation distribution between that which is observed in 100-year old photographs and contemporary photographs?
(3) *Prediction:* If a given plot is clearcut next year, what changes in species mix of flora/fauna on the plot will occur in one year? in ten years? in thirty years?
(4) *Planning:* What are the optimal vegetation age/species mix and spatial distributions for maintaining a stable Spotted Owl population in an area while simultaneously conforming to governmental regulations and specific economic goals?

The first set of queries is clearly exploratory in nature and can be answered on the basis of stored observational data alone. In order to examine the causes of occurrences and their effects in the explanatory, predictive or planning mode, however, the storage of derived information (or higher-level knowledge) regarding phenomenological relationships is needed in addition to observational data. The addition of derived knowledge transforms what may be termed a "world history model" (i.e., an organized collection of observed values over space and time) into what may be called a "process model."

In order to appreciate this most critical transformation, certain preliminary comments on time and space are necessary.

Intrinsic Properties of Time and Space

Any effective spatiotemporal representation must take the special properties of space and time into account, yet space and time can be viewed in many ways. This is the central problem in deriving a single representational approach that can accommodate a range of applications. At the most fundamental level, representations of time and space have been historically divided into *absolute* and *relative* views (Chrisman 1977; Sack 1980). The nature of time and space and the differences between these two views have been debated since the ancient Greeks. Absolute space-time was initially described by the Greek atomists who reduced everything to bodies adrift in space, with space itself being the container of these objects—the Void. From this arose the notion of space and time espoused by Newton, with space being composed of points, time being composed of instants, and both existing independently of the bodies that occupy this space-time. Within Newton's space-time framework, the movement of a body changes the position of that body, but that movement changes neither the framework itself nor the relationship of other objects to that framework. Leibniz, a contemporary of Newton, subscribed to the quite different notion of relative space-time. Nevertheless, Newton's absolute view of space-time predominated in science until the beginning of this century when the relative view was adopted by Einstein as a central theme of his work. According to the relative view, both space and time are positional qualities that are attached to each object. Objects are located relative to other objects. The relative view of space-time continues to dominate modern physics, in particular, and twentieth-century science, in general.

Absolute and relative views of space-time are complementary, not contradictory. The absolute view focuses on space-time as the subject matter. Objects are located within an unchanging geometry defined by a space-time matrix. The relative view, in contrast, focuses on objects as the subject matter. Space and time are measured as relationships between objects. Absolute space-time is thus *objective:* This view assumes an immutable structure that is rigid, purely geometric, and serves as the backcloth upon which objects may or may not occur. Relative space-time is *subjective:* This view assumes a flexible structure that is more topological in the sense that it is defined in terms of relationships between and among objects. In the relative view, neither space nor time exists independently. These two views of space-time are thus complementary. On one hand, the objective view involves measurement referenced to some constant base, implying non-judgmental observation. The *relative* view, on the other, involves interpretation of process and the flux of changing pattern and process within specific phenomenological contexts.

It seems essential to store observations utilizing an objective view of both space and time if the patterns and processes within observational data are to be subsequently interpreted, tested, and verified. This becomes increasingly important as geographers and other earth-scientists gain access to shared collections of observational data that have been collected via satellite and other automated devices. Such data are more exhaustive than selective, inferred, or interpolated. We therefore have an opportunity to "let the data speak for themselves" (Gould 1981) in the absence of preconceived notions that could obscure previously undisclosed patterns. The same observations can potentially be interpreted in different ways depending upon the purpose of the investigation. Spatiotemporal analysis thereby involves, at a fundamental level, going from the objective to the subjective; superimposing various subjective views onto a single, objectively measured and stored observational database. While attempting to avoid a myriad of unresolved and perhaps unresolvable ontological issues, a number of intrinsic properties of time within this objective/subjective (absolute/relative) dichotomy must be assumed in order to develop a general spatiotemporal data representation framework.

The properties of time and space have many similarities and some important differences. In objective space-time, everything everywhere progresses inexorably forward in time. Nothing can travel backward in time, save of course in the sense of an historical retrospective. We accordingly experience absolute time as unidirectional (July 24, 1992 will never happen again). In space, by contrast, we can travel backward as well as forward. Given the forward flow of objective time, it follows that processes—spatial as well as non-spatial—are evolutionary (linear and irreversible) in nature. For example, everyone continually grows older; the map of political states continually changes. Within the subjective view, however, we can interpret patterns of occurrences through time. Four main mathematical characterizations of temporal pattern have been developed; steady state, oscillating (cycles and rhythms), chaotic, and random. The term *chaos* has been defined as "[t]he irregular, unpredictable behavior of deterministic, nonlinear dynamical systems" (Gleick 1987:306). Chaotic behavior characteristically amplifies small uncertainties through time, allowing only relatively short-term predictability within an overall random pattern of occurrences. We can also use the term chaos to describe spatial distributions that are not completely irregular and unpredictable. The steady-state, oscillating, chaotic, and random characterizations of temporal distributions also have corresponding characterizations of pattern in spatial distributions; these are regular, clustered, chaotic, and random. Identifying the type of pattern present—such as distinguishing oscillation from chaos—and examining temporal discontinuities are fundamental tasks in the study of temporal processes (Young 1988).

Both space and time are continuous, yet for purposes of objective measurement they are conventionally broken into discrete units of uniform or variable length. Time is divided into units that are necessarily different than those for space (we cannot measure time in feet or meters). Temporal units can be seconds, minutes and days, seasons, or other units that may be convenient. In the case of time, intervals of time are normally separated by events. An event represents the occurrence of some change in the phenomenon being measured.

The segmentation of time and space into discrete units of measurement leads in turn to the question of resolution and scale: How large or small should these units be? Ideally the answer is that the resolution (as well as the units of measurement) should always be related to the phenomenon under observation and the problems or questions being posed about it. It is not always possible to determine this "ideal," nor is a single scale sufficient for phenomena that are inherently multiscalar in time and space. A distinct spatiotemporal pattern at one temporal resolution may disappear into chaos at another. Progressively finer or coarser temporal resolutions may also reveal distinct spatiotemporal patterns of change.

Given this theoretical/philosophical background, our focus narrows to the more concrete issue of current cartographic and GIS approaches for representing time in order to provide a context for discussing a new representational approach. Following this, a new and integrated spatiotemporal framework for GIS will be presented.

Cartographic Approaches for Representing Time

Although maps may be used to depict change or movement, they have mainly been used to present a static view of the world. One of two basic strategies have been employed by cartographers to represent spatiotemporal dynamics (MacEachren et al. 1992). The first manipulates the symbology (e.g., line width) within a single visual display. These maps, though often clever, focus on the visual presentation of very specific types of information and are intended to convey specific messages to the reader (Tufte 1990). The second strategy uses a sequence of static maps that represent discrete "snapshots" at sequential moments in time. These "chess maps" are so-called because of their resemblance to newspaper reports of chess games depicting a sequence of board configurations over a series of moves (Monmonier 1990).

Computer-based cartographic animation and visualization techniques rely on three strategies for depicting change. The first presents a sequence of discrete displays ("stills" or "snapshots") at various speeds and is analogous to the frames of a movie. The transitions between the discrete images may be either abrupt or smoothly faded in and out. The second strategy dynamically modifies display elements via program or interactive control. Perhaps the best-known example of this strategy is the television weather map that commonly includes lines, arrows, and other symbology with oscillating colors intended to simulate airmass movement. The third strategy augments a static map display with supplementary graphs or charts depicting the change in a specific variable in specific locations or over the entire region.

Current cartographic approaches thus are able to incorporate temporal as well as spatial characteristics, even though the primary basis of the representation is spatial. The techniques mentioned above (oscillating colors, temporal sequences of static maps, and supplementary graphs) each successfully portray continuous forward movement in time using appropriate temporal measurement units. Nevertheless, all of the current cartographic approaches for depicting change over time have a critical shortcoming with respect to multipurpose spatiotemporal representation: Namely, these approaches all adhere to the cartographic tradition of conveying a specific and limited (and intentionally subjective) message.

Current GIS Approaches for Representing Time

Current geographic information systems also represent a static view of the world. Change in geographic phenomena over time is recorded as a series of "snapshot" images in a manner analogous to the "chess map." These "snapshot" images entail use of a grid (or raster) data model with a sequence of spatially-registered grids. Each sequential grid represents a "world state" at a particular moment. This approach is conceptually straightforward, and the "world state" for any stored time can be retrieved directly. Nevertheless, the changes that occur between "world states" are not explicitly stored. These must be calculated by comparing the spatial patterns of two successive "world states."

The other basic representational approach for computer storage of geographic data, in addition to the grid (or raster) data model, is the vector data model. In contrast with the grid data model, the vector representation is based on the map line or vector delineating individual point, linear, and polygonal map features. Extending the vector approach to incorporate temporal dynamics has been proposed by Hazelton (1991), Kelmelis (1991), and Langran (1992). These models rely on the concept of "amendment vectors"; changes in an initial location and the time at which they occur are recorded as amendments (additions) to the original recorded map vectors, thereby maintaining the temporal continuity of individual spatial objects. In practice, however, storage of these "amendment vectors" becomes unwieldy as individual geographic objects evolve over time since each change alters the topology of connected map vectors. The problem is compounded when various new objects come into existence, disappear and then reappear.

The incorporation of time into raster and vector data models is seen by many as the obvious solution for the representation of spatial change within GIS. Moreover, such an approach appears to be supported by the mathematical tradition of the Minkowski framework in which time is represented as an additional dimension or axis in a 4-D space-time visual geometric, that is, x, y, z, t, with t representing time in a hypercube coordinate volume space (Galison 1985). The combined treatment of space and time also seems to be supported by natural language (at least in the case of English), in which time tends to be expressed in spatial terms (Lakoff 1990), e.g., the phrases: "We are *close* to Christmas" or "There is going to be trouble *down the road.*" It is not surprising, therefore, that the problem of representing spatiotemporal data in GIS has been regarded as one of implementation and, in turn, of how to efficiently handle the increased data volume.

The basic thesis of this paper is that this kind of homogeneous 4-D representation is not sufficient for use in GIS because time and space exhibit important differences in their properties and in their referential bases for potential queries. An alternative approach is thus required, one that incorporates distinct location-, time-, and object-based components.

An Integrated Representational Framework

Basis of an Integrated Framework

The manner in which data are represented is inextricably linked with specific analytic tasks. That is why a strip map or route map is more easily used for travelling from one place to another than an overall areal map. Conversely, a route map is essentially useless for conveying the distribution of geographical features over a given area. Similarly in GIS, grid representations are more effective than vector representations for associating multiple characteristics at specific locations (map overlay), whereas vector representations are more effective than grid representations for network routing problems. A representation that does both equally well offers the ideal solution; hence, a framework that unifies these representational schemes as it permits large, multifaceted analytical tasks (and the translation from one representation/task context to another that this implies) has significant advantages. Achieving such a representational formalism is thus essential if computer-based GIS are to serve as useful analytical tools (Peuquet 1988; Rhind 1988).

With this representation/task linkage in mind, consider the differing "world views" of the two types of representation. The vector model is object-based in the sense that all information, coordinate as well as non-spatial attribute information, is stored relative to specific geographic/cartographic objects, or features (roads, census tracts, etc.).[2] The raster or grid data model, conversely, is location-based in the sense that all other information is stored relative to specific locations. Because of these two fundamentally different orderings of stored information, the vector model is more effective for query and retrieval of information about spatial objects; the raster model more effective for query and retrieval of information about a specific location or a set of locations.

Moreover, raster and vector approaches can be interpreted as having a general correspondence to objective and subjective views of space: Objective space being measured on a rigid, purely geometric (*location*-based) structure; subjective space being defined on the basis of *objects* and relationships between objects in a largely topological structure. The location-based and object-based approaches should be regarded not as opposites, but rather as complementary and interrelated representations that are particularly suited to answering location-based and object-based queries, respectively. Their complementarity serves as the basis for the formulation of a Dual framework (Peuquet 1988). Unlike traditional raster and vector data models that are intended to be self-contained, the object-based and location-based views of the Dual framework are intended to be cooperative and interdependent.

Any conceptual representation consists of *entities, attributes,* and *relationships.* An entity in this context is any type of data element that serves as the basis of the representation. Entities have attributes, or properties, associated with them. Both entities and their associated attributes are stored as observed values. Relationships act as operators on those entities and attributes. In the Dual representation scheme shown in Figure 1, the object-based representation appears on the right side of the diagram. An object is a thing that exists and can be seen (a road, a mountain, a building) or is purely conceptual (a census tract). By extension, our definition of object may also include "derived objects"—those entities whose meaning depends upon a particular analytical context (e.g., an undeveloped parcel of land that is within one kilometer of an interstate highway, zoned light-industrial, and flat). Objects have attributes such as size, shape and location.

The location-based representation appears on the left-hand side of Figure 1. In this case, the basic entity is a location: an elemental unit of discretized, two-dimensional or three-dimensional space. Depending on the fineness of resolution, a location can be defined as a point with no area or volume or as an areal cell or pixel in a gridded data structure. Locations possess attributes that may include the objects therein (e.g., elevation, soil type, or housing density).

When both views are used in concert, only generalized locational indicators need to be stored as object attributes in the object-based representational view. These generalized locational indicators reference related information within the location-based view which contains the complete locational definitions of objects. Similarly, only generalized information identifying objects needs to be stored within the location-based view. This integration constitutes the key difference between the object- and location-based view in the Dual framework and the traditional vector and raster data models.

Relationships act as operators defined within the query language and can be combined to form complex retrieval criteria. Examples in the location-based view include distance and direction (e.g., *north* of State College or *within five miles* of the airport). In the object-based view, operators include taxonomic relationships (e.g., Oak is a *kind of* tree.). Thematic relationships associate specific attributes to specific types of objects (e.g., all forest stands *greater than 100 years old*).

Overview of the Triad Framework

Given the representation/task linkage as described for object-based and location-based representations, it follows that neither can answer time-based queries as effectively as a time-based representation.

In order to include a time-based representation, the Dual spatial representational framework must be expanded into a Triad framework in which information is stored relating to *where* (the location-based view), *what*

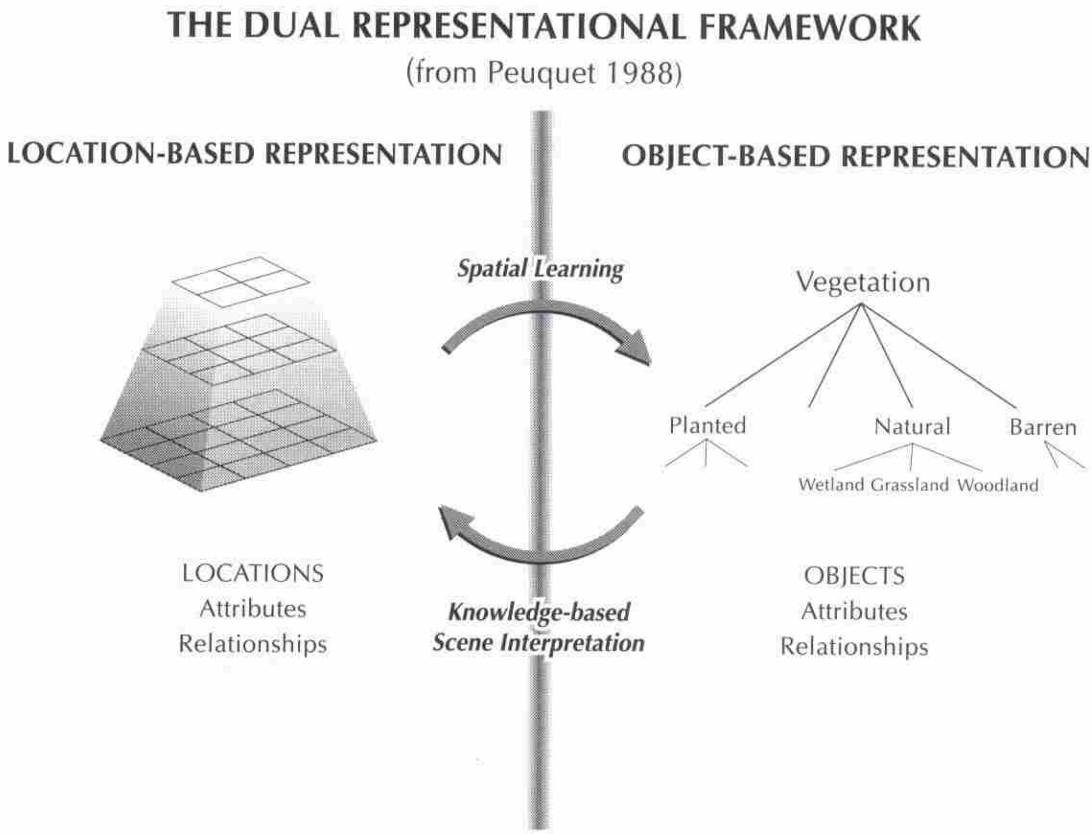

Figure 1. The Dual representational framework. Source: Peuquet 1988.

(the object-based view), and *when* (the time-based view) as shown diagrammatically in Figure 2. Locations, times, and objects thus form the three interrelated components of the Spatiotemporal Triad scheme (for more detail, see Figure 3). This scheme is not entirely new. Precedents range from the "what, when, where" interrelationship known as the "Kronecker Delta" in tensor calculus (Dodson and Poston 1977) to journalism's old axiom on what, where, and when as the most fundamental rule of reporting.

The Triad framework permits the user to pose three basic kinds of questions:

(1) *when + where → what:* Describe the objects or set of objects (what) that are present at a given location or set of locations (where) at a given time or set of times (when).
(2) *when + what → where:* Describe the location or set of locations (where) occupied by a given object or set of objects (what) at a given time or set of times (when).
(3) *where + what → when:* Describe the times or set of times (when) that a given object or set of objects (what) occupied a given location or set of locations (where).

In the additional component included within the Triad framework, the time-based view, a single unit of time is the basic entity. A single chronologically ordered sequence of recorded times may be regarded as a time-line or "event vector" that is shown graphically in Figure 3. The arrow on the end of each event vector denotes the directionality of time as well as its open-endedness and the capacity for adding new data as new events occur. An event vector, then, represents a linear ordering of events

THE BASIC VIEW COMPONENTS OF THE TRIAD FRAMEWORK

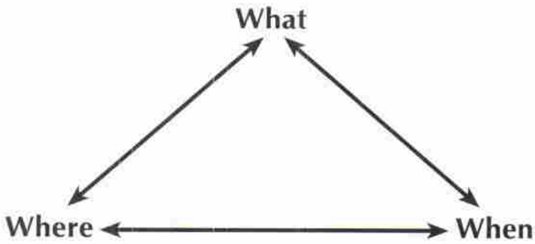

Figure 2. The basic components of the Triad framework.

from some initial moment as they occur through time. An event denotes some change in some location(s) or some object(s). Attributes of an event can include the new state of a set of objects, the new state of a set of locations for that moment, or both. Recording events with their associated attributes means that change is explicitly recorded in the time-based view and it implies that a steady-state prevails in the temporal duration between sequentially adjacent events. Each individual event vector is specific to a given phenomenon, and hence it is analogous to the locational notion of separate thematic map layers.

In the Triad framework, the location-based and time-based views each record observations as data in objective space and time. Interpretation of these observations through analysis subsequently generates information on objects in subjective space and time. Expanding the role of the subjective (and thereby interpretive) object-based view to its full extent has two advantages: 1) examples of specific object types and the relationships between them can be stored and gradually added-to; and 2) generalized rules describing the characteristics of specific objects or object-types and their interrelationships can also be stored at appropriate levels within the object hierarchy. Such stored knowledge is then used to interpret (i.e., learn from) subsequent observations as well as to retrospectively re-interpret previous observations in space-time, thereby deriving spatiotemporal relationships and patterns as new knowledge. This learning process, moreover, is consistent with theories concerning human interpretation of the experiential world (Marr 1982; McClelland et al. 1986). In a database sense, the storage of relationships and patterns means that the attributes of objects are not restricted to specific observational values.

Consider the way in which information on vegetation change would be stored utilizing the Triad framework. Using the location-based view, vegetation types for all locations in a given geographic area would be recorded. The history of vegetation types would be arranged as an ordered series of snapshots, with each snapshot representing a "world state," a complete image of vegetation types observed at a specific moment for a specific geographic area. A hierarchical representation such as a quadtree[3] could also be used as the location-based view, thereby allowing data within each "world state" to be recorded at multiple locational scales (Samet 1990).

Using the time-based view, changes in vegetation type that occur over a given time interval would be recorded. An *event* is stored as an observation in the time-based view when: 1) some sudden change occurs; or 2) the amount of accumulated change since the last change is regarded as significant. Each event and the attributes describing it are stored in their chronological order of occurrence. For example, a new event denotes some observed change in vegetation. This event constitutes a new entry that along with its attribute information is appended to the end of the event list. These attributes might include: 1) the time of the change; 2) the location(s) of the change; and 3) the new vegetation type. Additional attributes of the vegetation event may be recorded as well (for example, the causal agent of fire, logging, disease, or change in management policy). The time-based view is intended to capture all types of change in specific phenomena which are considered to be relevant.

Using the object-based view, vegetation types are stored as a taxonomic hierarchy (see Figure 3 for a simple taxonomic hierarchy; reality may be much more complex). The basic logical entity is an individual vegetation type such as "Coniferous Forest" or "Lodgepole Pine." Attributes associated with these objects are of four types. The first of these is some form of generalized locational indicator such as the coordinates of a bounding rectangle containing the specific stand of Lodgepole Pine or the coordinates of several bounding rectangles

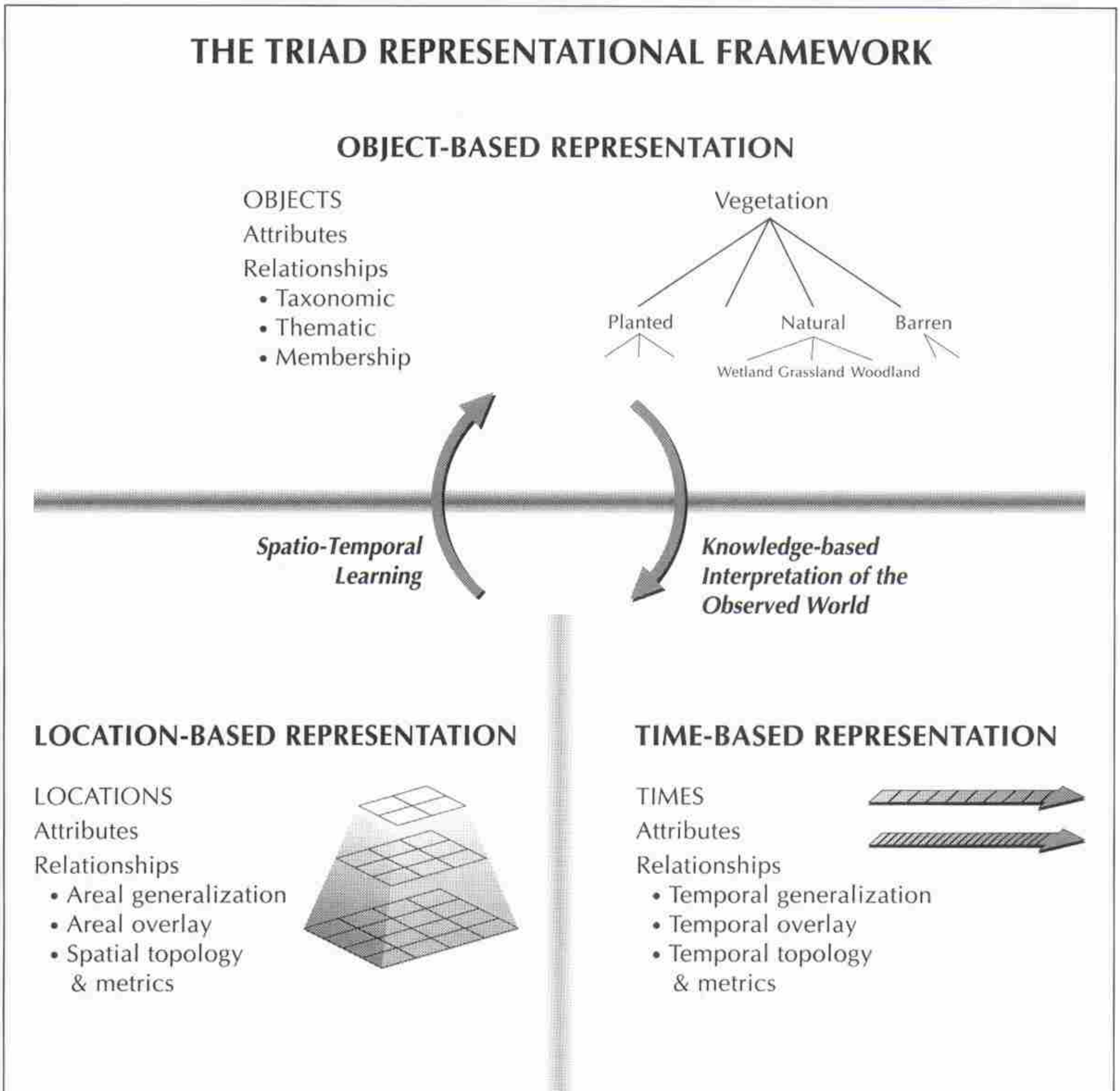

Figure 3. The Triad representational framework.

each containing the areal extent of a known example of "Coniferous Forest." These generalized locational object attributes thus serve as a search guide for the retrieval of the precise areal extent stored within the location-based view. The second type of object attribute is the temporal *interval,* that is, the length of time between events, the details of which are stored within the time-based view. Thus, the temporal extent of the existence of any given object can be expressed as a temporal interval that contains at least two events (denoting a beginning and an end). For example, times when specific forest stands were established can be stored as object attributes, while the details of these (and other) events are stored within the time-based view. A third type of object attribute is non-spatiotemporal data, e.g., a textual description of specific environmental management policies pertaining to "Coniferous Forest." A fourth type of object attribute is higher-level knowledge about known spatiotemporal relationships of specific object types, about known characteristics regarding location and times of occurrence, or about information on overall spatiotemporal patterns. One of the advantages of organizing object descriptions into taxonomies is the notion of *inheritance*. Since subtypes generally "inherit" the characteristics of the parent (e.g., tropical vegetation is generally green, thus any subtype of tropical vegetation can also be assumed to be green), there is no need to repeat the information for any of the subclasses that share a particular characteristic. When exceptions arise, however, these need to be stored.

It is the storage of higher-level knowledge in the object-based (subjective and thereby interpretive) view that provides true explanatory and predictive power and transforms what we have called a "world history model" into a true "process model."

Spatiotemporal Patterns and Processes

All higher-level or derived knowledge of spatiotemporal relationships and patterns must be based on a set of elemental rules regarding the intrinsic behavior of spatiotemporal distributions. These rules constitute a generic basis for deriving spatiotemporal patterns that are characteristics of specific object types of various levels of an object hierarchy.

Intrinsic Characteristics of Temporal Distributions

Temporal distributions generally exhibit a number of characteristic tendencies that can be summarized as follows:

(1) *Temporal cohesiveness.* The cohesiveness of individual objects (e.g., a town or a tree) over time and in the absence of disturbance results in a tendency toward smooth, evolutionary transitions from one type of object to another. This *temporal inertia* may be disrupted, however, by a disturbance event that causes an abrupt change in co-existing objects of the same object type.

(2) *Temporal similarity.* Objects and locations that are influenced by a particular process tend to exhibit similar rates of change.

(3) *Temporal continuity.* The distributions of events through time that are influenced by a single process tend to exhibit an organized temporal pattern that results from a chain of cause-effect occurrences.

(4) *Hierarchical organization.* The distribution of various events through time is often generated by a number of different processes, each operating at a different temporal scale.

(5) *Incompleteness.* Our knowledge of the changing states of locations or objects is always partial. Some of these states are known, others are only partially known, and still others are unknown.

Some elaboration on the effects of these temporal characteristics on the behavior of objects in space and time and on their grounding in geographical, scientific, and philosophical literatures is useful at this point of the discussion.

Given temporal cohesiveness, change over time (particularly in the case of natural phenomena) tends to occur gradually in the absence of disturbance. Thus, objects tend to mutate gradually from one kind of identity to another. They may also come into or pass out of existence at discrete moments or gradually change their identity into another over space and time. The course of these gradual changes, what may be called an "expected" sequence through time, constitutes an object's temporal trajectory (Kelmelis 1991). For example, a meadow if left undisturbed can become a brushland and then a stand of young trees and ultimately a stand of old-growth forest. In the case of disturbance, however, gradual change is disrupted by the introduction of some new causal factor during the course of events. Logging or fire could reduce a forest stand to bare ground within a day. Similarly, a hamlet can become a village, then a town, and finally a city given the "expected" evolutional sequence for settlements. A village may suddenly cease to exist as an individual object, however, if annexed (disturbance) by a neighboring city. The possibility of disturbance and abrupt change are always present, although the frequency of disturbances may be highly variable. The difference between "abrupt" and "gradual" change is also a relative one that depends on the temporal scale used. The effects of a new zoning ordinance restricting certain types of land use may not have observable effects for several years, yet these effects would seem rapid when compared with the counterfactual rate of change (undisturbed).

An important aspect of temporal cohesiveness is the process called branching. As individual objects change, they do not necessarily remain as single objects, that is, their identities change through time. Something that is perceived as a single object at one moment can split into more than one object of the same type or of different types. Conversely, two or more objects can merge into a single object. For example, the cutting down of a tree transforms the original tree into a stump, a log, pulp, or sawdust. Similarly, a stand of trees may be split into a residential subdivision, a road right-of-way, and a park from one year to the next. Object merges represents the reverse process, as when multiple streams merge into a single large flow of water during a flood event. In these cases, objects split or merge into multiple objects over both space and time.

The characteristics of similarity and continuity are evident in the interactions of objects with one another through time. The state of an object at any given time affects not only its possible future states, but also the state of other objects at the same time or in the future. Locations similarly interact through time. Physicists and philosophers describe these space-time interactions (based on the characteristics of similarity and continuity) and the limitations upon them in terms of "light cones" (Rucker 1984; Hawking 1988). This terminology comes from the principle that nothing can travel faster than the speed of light. In a geographic sense, we may say that nothing can travel faster than the fastest jet airplane. This constraint imposes an absolute limit on the maximum possible distance in space that anyone or anything can travel in a given length of time. In the language of time geography, this is the space-time prism (Figure 4), and the path taken therein by anything or any individual is their "world line" (Hägerstrand 1970).

Turning to the temporal characteristic of hierarchical organization, it is well known that certain processes operate at particular spatial and temporal scales. These processes, in turn, may be components of a higher-level process that operates over a longer time scale. For example, individual plant growth may occur over a period of weeks. Plant growth in turn may be affected by the spread of a particular disease which occurs over a period of years. The spread of plant diseases thus represents one component in the changing distribution of vegetation types that may occur over decades or even centuries (King 1991). There is also, generally speaking, a direct relationship between these spatial and temporal scales (Capra 1975; King 1991). For example, individual plant growth tends to be a microscale process since it occurs over a spatial scale of meters or fractions of a meter as well as over a temporal span of weeks. Similarly, changes in vegetation pattern tend to be mesoscale processes since these occur over a regional scale in response to changing growing conditions, management policies, and so on, as well as over a temporal span of decades (King 1991).

These temporal characteristics—cohesiveness, similarity, continuity, hierarchical organization, and incompleteness—are implicit in the temporal models of a variety of fields. Continuity, similarity, and inertia serve as mechanisms that cause the formation of patterns or rhythms in both time and space and that enables us to identify, explain, and make predictions. Within human geography, these characteristics lie at the heart of Hägerstrand's diffusion model as well as the time-geographic approach for describing spatiotemporal patterns. They are axiomatic for space-time walks and for modelling individual activity paths within a daily space-time prism (Hägerstrand 1970; Pred 1977; Carlstein 1978). Time geography, for example, uses the concepts of "path" and "project" in which any individual's life experience is conceptualized as a succession of places with locational and temporal attributes. Thus, the pattern of activities for any individual, or more generally any object, may be thought of as a continuous path (their world line) through space-time. The "path" and "project" concepts in time geography thus derive directly from the characteristic of temporal continuity.

In time geography, space and time also serve as constraints on movement, and these constraints define the hourglass shape of space-time prism models. The volumetric area of the space-time prism encloses all possible points in space that can be reached within a given temporal interval (Figure 4). If present time is located at the center of the hourglass, then in that durationless instant an object cannot move beyond its current location. Given time, however, the range of potential movement in any

RELATIONSHIP BETWEEN MOVEMENT THROUGH SPACE AND MOVEMENT IN TIME: THE SPACE-TIME PRISM

(from Rucker 1984)

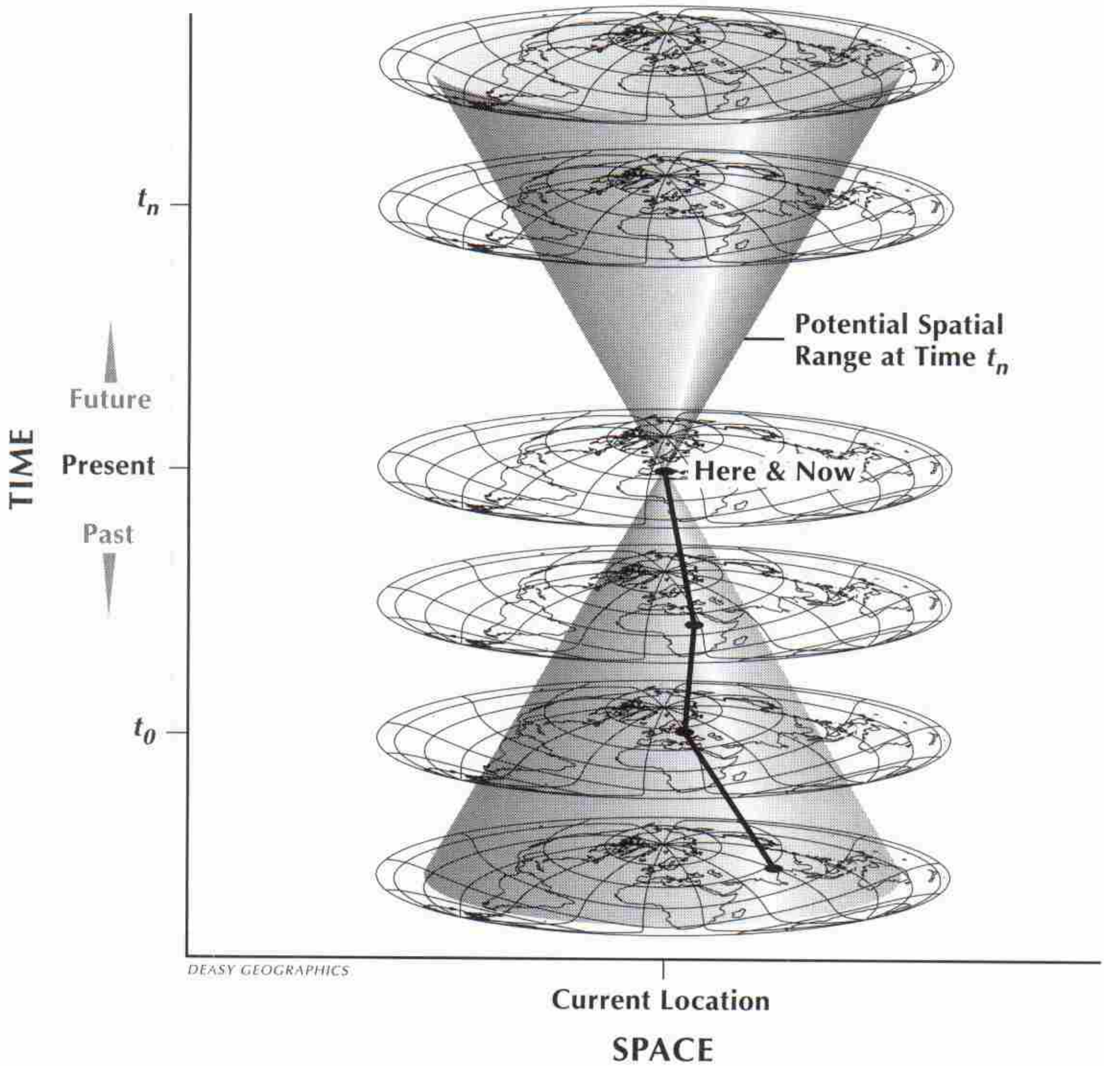

Figure 4. Relationship between movement through space and movement in time: the space-time prism. Source: modified from Rucker 1984.

direction from its central location enlarges as the object moves into the future (or the past). The concept of the space-time prism and its associated space-time interactions also assumes specific spatial and temporal scales for individual daily activity patterns. The space-time prism concept therefore does not include the characteristic of hierarchical temporal organization; in fact, by assuming a single scale for any given space-time prism model, the model explicitly ignores temporal hierarchy as a factor. This is not to say that temporal hierarchical organization is not recognized as a characteristic of spatiotemporal pattern within time geography, but rather that the simultaneous combination of all temporal (and spatial) characteristics has not yet been achieved within a single model (Parkes and Thrift 1978; Miller 1991). Incompleteness is the last of our temporal characteristics and the one that is most often excluded from spatiotemporal models (and data representations generally). Two potential reasons for this can be given: 1) current representational tools, particularly mathematics, do not lend themselves to dealing with incompleteness; and 2) science has traditionally viewed incompleteness as something to be overcome rather than to be openly acknowledged or willingly incorporated into models as a basic characteristic. New representational tools that allow simultaneous analysis of all characteristics, including incompleteness, will be discussed in the next two sections. The first of these presents an approach for describing spatiotemporal relationships and distributions as either stored higher-level knowledge or as database queries; the second section presents methodologies for deriving new spatiotemporal relationships and distributions.

Temporal Operators in a Conceptual Representation

Many descriptions of spatiotemporal relationships have been devised, but few are satisfactory for the simple reason that these patterns are, in reality, far more complex and interrelated. Capturing this complexity requires a powerful and very flexible descriptive method. Just as a spatial distribution pattern can be random, uniform, or clustered, a temporal distribution can be chaotic, steady state, or oscillating. Moreover, the rate of temporal change can itself change, and temporal patterns therefore can exhibit convergence, divergence, or combinations of these (e.g., dampened oscillation). A series of individual events can be clustered into "episodes" and perhaps into "cycles." Perfectly cyclical distributions can represent an important form of steady-state behavior over longer temporal intervals. Thus at one temporal scale, a series of dry years in California may appear as a drought episode; at another scale, as part of the El Niño cycle. In turn, variations in the length of El Niño, its cycles, and governmental responses to its various economic and social repercussions may be interpreted as chaotic. Conversely, when viewed on a temporal scale of a century or more, the spatiotemporal pattern of the El Niño cycle can be viewed as fairly constant.

These spatiotemporal patterns may be expressed as combinations of relationships between locations, times, and/or objects within a descriptive spatiotemporal language. Relationships within such a language serve as *operators* for querying stored observational values or for storing derived relationships as higher-level knowledge in the present representational framework. These operators thereby permit: 1) ad hoc combinations of claims or facts; 2) applications of spatiotemporal reasoning in queries; and 3) in the case of temporal relationships, expressions of cause-and-effect relationships. Specific relationships and general patterns can be expressed either mathematically or in more natural-language-like if-then-else statements. The latter has an added advantage over mathematical expressions in that it does not imply exactness. Given that incompleteness of knowledge is a fundamental characteristic of temporal distributions, it follows that exactitude cannot be automatically assumed.

All temporal relationships can be derived from the basic characteristics of temporal distributions. These relationships divide into three distinct classes: 1) metrics and topology; 2) boolean operators; and 3) generalization. The first of these operate along a single, continuous, linear time line or event vector at a given temporal scale. Derived from the assumptions of temporal cohesiveness and similarity, temporal metrics and topology relate sequences of events and the distances between them.

Since time is one-dimensional, there is only one temporal metric—temporal distance. Temporal distance denotes the length of the interval between any two given locations along a time-line: the length of time (interval) for a single event (its duration), between two events, or for which some condition holds constant (a steady state). To recall a familiar distinction, metric relations regard time as objective and absolute.

Topological relationships, in contrast, define *relative* locations along a time-line. Temporal topology has been studied in a number of fields including philosophy, mathematics, linguistics and artificial intelligence (Allen 1984; Shoham 1988; Davis 1990). Given the characteristic of incompleteness (and the inexactness this implies), it is useful to be able to express relationships between events strictly in an ordering sense, where the time line itself can be viewed as elastic and events viewed as knots or singularities along the time line. These relationships are shown graphically in Figure 5 and are defined as follows:

(1) Within an ordered and continuous linear set, T, the components of interval X are defined as X[a,b] and of interval Y as Y[c,d].
(2) The topological relations are then defined as follows:

relation	condition
[a,b] < [c,d]	b < c
=	(a=c) and (b=d)
m	(b=c)
o	(c>a) and (b<d)
d	(c<a) and (b<d)
s	(a=c) and (b,d)
e	(c<a) and (b=d)

where < indicates the relation "before" and > the relation "after." Note that each of the seven basic relative interval relationships has an inverse. Thus, [a,b] < [c,d] becomes [c,d] < [a,b], or [a,b] > [c,d]. Also, since X=Y and Y=X is an identity, this makes thirteen possible temporal topological relationships in total. Consider the following topological example relating occurrences in time without regard to measurement scale:

SELECT ALL storm-events WHEN storm-event DURING ElNiño-event

TEMPORAL TOPOLOGICAL RELATIONSHIPS

RELATION	SYMBOL	X Y
X before Y	<	
X equal Y	=	
X meets Y	m	
X overlaps Y	o	
X during Y	d	
X starts Y	s	
X ends Y	e	

Figure 5. Temporal topological relationships. Source: modified from Allen 1984.

In this example, ElNiño is an interval identified between "start" and "end" locations along a time line. The derived information defining the ElNiño interval is stored in the object-based view as a temporal attribute of the ElNiño "object." More generally, temporal topological operators are able to accommodate comparisons between different rates or time-scales. Both the temporal metric (distance) and topology can be seen as deriving from the first three characteristics of temporal distributions: cohesiveness, similarity, and continuity.

The second class of temporal relationships are boolean operators (AND, OR, NOT). These combine different types of temporal distributions (thematic layers) or different values within the same type. This amounts to a temporal overlay function as in the following example:

SELECT ALL landuse-change-event WHEN ((landuse-change-event = commercial) AFTER new-road-event OR AFTER tax-change-event)

In this example, boolean operators retrieve all changes in commercial land use that occurred either after the building of a new road or after a change in the tax laws. Boolean relationships also derive from the first three temporal characteristics of cohesiveness, similarity, and continuity.

The operators for generalization, the third class of temporal relationships, associate specific events at various scales in the temporal hierarchy. Derived from the temporal characteristic of hierarchical organization, the method of generalization is dependent upon the metric (e.g., four seasons, twelve months, or 365 days equal one year) and scale (e.g., years versus days as minimum units). Temporal generalization of one set (thematic layer) of events at one temporal scale is often necessary in order to subsequently relate it to another set of events recorded at a different temporal resolution. For example, when the attributes of rainfall and economic activity are recorded at daily and monthly resolutions, respectively, it is necessary to generalize daily rainfall to monthly resolution before boolean, metric, or topologic operators can be used for comparisons with economic activity.

In addition to the three classes of temporal operators within the time-based view, temporal relations also operate on the location- and object-based views. Since these relations are already defined in the Dual framework, they are carried over directly into the Triad scheme (Figure 3). The location-based representation includes areal generalization, overlay, and spatial metrics and topology. The locationally-oriented temporal overlay uses boolean functions for comparison of changes (or similarities) at the same set of locations over a series of different times and resembles spatial overlay operators that combine a series of thematic data layers within current GIS; the only difference is that the temporal operator overlays temporal "snapshots" instead of separate thematic maps. Temporal overlay derives from the basic characteristics of temporal similarity and continuity and the resultant implied similarities of related sequences of events.

The temporal operators in the object-based representation typically focus on cause-and-effect relationships between objects of different types. Thus objects can be linked via causes/caused-by or becomes/precedes relationships. For example, the causal relationship "brushfires are CAUSED-BY lightning OR humans" can be stored as a known fact or used as a logical assertion in the form of a query for testing and verification.

From World History Models to Process Models

By incorporating derived information, a "world-history model" with its collection of observed data values (i.e., what, where, when) is transformed into a "process model" that reflects an understanding of the phenomena represented (i.e., how). That transformation depends, however, on a mechanism for deriving spatiotemporal patterns and relationships, and the mechanism for the derivation or verification of temporal rhythms, cause-and-effect, and other higher-level knowledge from observed facts called temporal reasoning. Temporal reasoning is principally concerned with two domains: 1) determining cause-and-effect; and 2) planning and problem solving. Within the context of the Triad framework, logical assertions/rules/lines-of-reasoning on the most fundamental conceptual level should be viewed as the activation of chains of relationship statements (as discussed above) via the addition of if-then-else operators and a set of evaluation rules that permit expression of complex, non-deterministic patterns and relationships. The user's issuance of a logical assertion (or the automatic "firing" of an associative rule stored as higher-level knowledge by the system) may be intended to provide a true/false, yes/no type of answer or, alternatively, model-driven data retrieval or data simulation.

One overall problem inherent in temporal reasoning, however, is the frame problem (Shoham and McDermott 1988; Davis 1990), which derives, in turn, from the temporal characteristic of incompleteness. The frame problem involves knowing which world states will change and which will remain *un*changed by a given event or action. For example, the migration of workers does not change their gender. However obvious and trivial this may seem in the context of everyday human reasoning, the continuity of the object (unchanged gender) is critical in formal or automated temporal reasoning because it requires explicit knowledge of the valid domain for operators. If some database elements are changed erroneously in a chain of cause-and-effect reasoning (or are predicted to change), the cumulative effects of a seemingly trivial error can be substantial.

One solution for the frame problem is explicit enumeration of the specific object/location states that are or are not affected, but such an exhaustive enumeration is impractical and incomplete information makes it almost impossible. A better solution incorporates generalized rules regarding the types of object/location states that may or may not be affected by a given type of event. In either case, the analyst must be able to separate events, locations, and objects and reference them independently.

The problem then becomes one of deriving these generalized rules and relationships. This presents a circularity since it is the various associations that define the process model that we are trying to uncover in the first place. The essential task is to extend a world-history model, consisting of observed events, objects, and locations, to a process model that also includes interpretive occurrence rules and patterns expressed as combinations of relationships.

One methodology for accomplishing this task in those cases in which little is known about the particular phenomenon or data under study is what Tukey called exploratory data analysis (Tukey 1977). Tukey's approach involves looking at the data in various ways (visually and statistically) in order to discern patterns and associations with no pre-formed hypotheses. As more extensive and detailed data are developed and become accessible through modern data capture and computing technology, exploratory data analysis will become an increasingly valuable tool for "sifting-through" observations.

Cognitive science offers another methodology that uses computers for discerning cause-and-effect relationships among complex observational data that can be verified and formalized in process models. The method is based on the way in which humans learn causal relationships in everyday life. Pazzani (1991) recently described a procedure that uses a theory of causality as background knowledge. The procedure, which he called theory-driven learning (TDL), hypothesizes causal relationships that are consistent with observed data and a general theory of causality.

Theories of causality efficiently identify cause-and-effect associations between a specific type of event and specific world state changes. As these theories of causality are gradually accumulated and refined, the attribution of causality progressively achieves greater accuracy. Causal relationships are learned inductively over a series of time-based observations by comparing before-after states. This inductive learning is based on a few elemental causal constraints that influence the acquisition of causal relationships from the observed world (Pazzani 1991):

(1) *Regularity:* An effect must regularly and repeatedly co-occur with its cause.
(2) *Temporal order:* An effect must occur after the cause.
(3) *Temporal contiguity:* An effect normally occurs very soon after the cause. The longer the temporal interval between the two, the less the likelihood of a cause-effect relationship.
(4) *Spatial contiguity:* An effect normally occurs in contact with (or very near) the cause. The greater the spatial distance between the two, the less is the likelihood of a cause-effect relationship.

Note that the causal constraints of regularity, temporal contiguity, and spatial contiguity are not absolute. The constraint of spatial contiguity applies only to processes involving spatial interaction. Many social processes do not have a direct spatial component, particularly in this current era of electronic communication. In tandem, however, these constraints on causality focus attention on the potentially relevant features and thus help to establish chains of cause-effect relationships. They also help to eliminate irrelevant features and thereby aid in ascertaining the true cause of an event. If, for example, a quarter century's worth of stored data demonstrates that the conversion of agricultural land to other uses occurs invariably where agricultural land constitutes 50 percent or more of the land within 500 meters of a new road and when conversion occurs within five years of the road's construction, the cases satisfy all four causal constraints and thus qualify as an empirically established causal link (new roads cause changes in land use near the road). Insofar as these four basic causal constraints can be incorporated into temporal GIS, such causal links could be derived by the computer.

The combination of vast amounts of complex observational data with TDL has two complementary virtues. The combination has the capacity for, on the one hand, formulating explanations and predictions on the basis of relatively few selected factors, and, on the other hand, introducing additional factors into play, thereby utilizing more detailed information when exceptional conditions arise. In the Spatiotemporal Triad version of TDL, the system stores known or presumed causal relationships with the objects as causes/caused-by links. These links can be added directly by the analyst or derived empirically (and automatically) by examination of the stored observational data. Causal constraints and rules on the interactions of objects, locations, and times (i.e., theories of causality) are built into the learning mechanism (represented by the upward arrow in Figure 3). Thus, the system continuously refines theories of causality through iterative examination of new observational data, and it permits the derivation and storage of constraints on other relationships such as temporal clustering or rhythms.

"Process models" also require a logic for expressing questions and assertions about spatiotemporal phenomena (using relationships as operators) that are testable against subjective knowledge and objective observational data stored in the system. Such a logic is essential for querying the database in an explanatory, predictive, or planning analysis mode (by the TDL mechanism) and for storing known patterns and cause-effect relationships within the database. One form of logic capable of utilizing incomplete or potentially erroneous information is known as non-monotonic logic (Shoham 1990). Unlike standard monotonic logic in which the set of all provable statements increases monotonically as new axioms are added (that is, the entire line of reasoning is invalidated if any axiom is proved false), non-monotonic logic is able to cope with the very real possibility of unforeseen disturbance. In everyday life, most of us seem to reason non-monotonically. Consider the following example:

> In order to attend a conference in a nearby city, Dr. Jones arranges to rent a car knowing that it is only a 3 1/2 hour drive to the conference hotel. On the morning before her planned trip, she learns that snow is forecast for the entire area, so she decides to cast her fate with the airlines and fly, instead.

In this example, Dr. Jones uses non-monotonic logic. The default rule of a reasonably short, and presumably pleasant, drive becomes invalid when she acquires contradictory evidence for the specific situation at a later time. Although the initial conclusion is retracted, the entire line of spatiotemporal reasoning remains valid.

The problem with currently existing formalisms for expressing non-monotonic logic is that they can only look backward in time. They can explain current or past states, but they cannot express plans or predictions of *future* states from known rules or axioms. This is particularly true when the combination of spatiotemporal relationships involved are complex. Although researchers in artificial intelligence are actively working on the problem of developing a formal temporal logic that can be expressed via a spatiotemporal language for posing queries to a database, or expressing assertions, plans, and predictions (Davis 1990; Worboys 1990), much remains to be done. Nevertheless, current non-monotonic logic formalisms provide provisional means for analysis in exploratory and explanatory modes within the Triad framework.

Summary and Conclusions

This paper has proposed an integrated approach for representing spatiotemporal data in geographic information systems. With the advent of geographic information systems and spatial decision support systems, the availability of a rapidly growing store of observational data, and the expanding data handling capabilities of modern computers, the time has come when the ideas of time geography and of spatiotemporal process models developed in various fields can be empirically tested and refined within an integrated environment. The potential of spatiotemporal data representations and temporal geographic information systems is significant indeed. With them, temporal state parameters can be modified in a process model (e.g., for forest evolution, atmospheric circulation, or land-use change) which can then generate one or more simulated realities, compare these simulated "world states" with the observed reality as represented in the stored observational database, and test and refine the process model under study.

Of course, simulation modelling is nothing new. What is new is process modelling within the Spatiotemporal Triad framework. It has three main advantages. First, process models are expressed as systems of rules and constraints that represent alternative and non-deterministic states. Thus complex, non-deterministic process models can be more explicitly and robustly represented than with purely mathematical methods. Second, the Triad framework accommodates analyses of complex spatiotemporal distributions with simultaneous events at various locations and many participants. In this way, distributions are more effectively understood with respect to the structural causal elements of the underlying processes and to the connections between processes (which may be at the same or different spatiotemporal scales). Third, the Triad framework provides a powerful tool for uncovering potential spatiotemporal patterns and associations and for understanding them through modelling. As already mentioned, the functioning of the Triad framework corresponds in a very general sense to the way in which humans view the world and the way we learn about it by gradually identifying meaningful patterns and recurrences of elements in spacetime. My intent has been to offer a broader perspec- tive, one that incorporates concepts from perceptual psychology, artificial intelligence, and "traditional" spatial data representation techniques, and thereby providing a conceptual basis for developing computer database representations that are at once flexible, efficient, and conformal with the way in which humans learn concepts, store information, and cope with unknown factors and unexpected changes. The union of three representational views—object-, location- and time-based—and the incorporation of both objective and subjective perspectives on time and space permits us to ask better questions and to answer them more effectively. The addition of a separate, time-based view offers new tools to the analyst who may, for example, reorder the sequence of events according to the value of a specific variable and identify temporal associations that could not be discerned by simple visualization of a temporally-ordered series of "snapshot" images.

The Triad framework constitutes a general formalization within which specific operational data models can be designed and customized according to the specific data and the range of applications. If the benefits of this expanded framework are to be fully realized for GIS, however, many issues and problems remain to be solved. Full implementation of the Triad approach in a functional GIS will require research that 1) provides suitable extensions to non-monotonic logic or similar formalisms; 2) refines spatiotemporal logic and query languages; and 3) fully integrates widely known and used tools such as object-oriented programming techniques and Extended Relational Database Systems (ERDBMS). A provisional illustration of the way in which the time-based view can be designed and implemented as a functional, observational data model while working in concert with locational and object-based views is given in Peuquet and Duan (1994). As the present paper has hopefully shown, a comprehensive spatiotemporal model will entail interdisciplinary research that integrates geographic concepts on time and change with the concepts and tools of perceptual psychology, artificial intelligence, database management systems, and related fields.

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Notes

1. The term *representation* here means an arrangement or organization of data defined within an explicit set of primitive elements, attributes (properties), and relationships. Such an arrangement serves to preserve the information inherent in the data for subsequent use in problem-solving or analytical evaluation. A representation can be purely conceptual, but any representation must be expressed in formalized mathematical or programming-language terms for computer implementation. A formalized representation intended for computer implementation is known as a *data model.*
2. Please note that the use of the term *object* in the current discussion is distinct from, and carries none of the special connotations associated with, the use of that term in the National Digital Cartographic Data Transfer Standard.
3. A *quadtree* in the usual sense is a nested grid structure constructed conceptually in the following manner: A (customarily square) geographic area is subdivided into four equal squares. Each of the resultant squares is further subdivided into four equal squares. This process is repeated until the

final subdivision results in minimum-sized squares (pixels) of the desired resolution.

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Peuquet, Donna J. 1994. It's About Time: A Conceptual Framework for the Representation of Temporal Dynamics in Geographic Information Systems. *Annals of the Association of American Geographers* 84(3):441–461. *Abstract.*

The study of spatiotemporal dynamics is certainly not new, nor is it unique to the field of geography. Nevertheless, addressing complex human and environmental issues such as global warming and human impacts on the environment requires empirical examination from a much broader and integrated perspective than can be accomplished with current techniques.

Although Geographic Information Systems (GIS) are intended to provide an integrated and flexible tool for analyzing large volumes of data, they are historically geared toward the representation and analysis of situations frozen in time. Efforts to enhance the temporal capabilities of GIS have served to reveal many problems at a fundamental conceptual level. In order to address this problem, this paper presents a new Triad representational approach that unifies temporal- as well as locational- and object-related aspects and that incorporates concepts from perceptual psychology, artificial intelligence, and other fields. The goal of this research is a drawing-together of a range of concepts and ideas not only to improve our representational and analytical capabilities, but also to provide more common ground among the various fields noted above.

The discrete yet interrelated time-, location-, and object-based views incorporated within the Triad framework allow for questions to be asked and answered relative to each of those aspects. Fundamental types of temporal relationships are also defined as part of the temporal view. **Key Words:** geographic information systems, spatiotemporal analysis, spatiotemporal representations, time geography.