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Survey of Spatio-Temporal Databases

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Abstract

Spatio-temporal databases aim to support extensions to existing models of Spatial Information Systems (SIS) to include time in order to better describe our dynamic environment. Although interest into this area has increased in the past decade, a number of important issues remain to be investigated. With the advances made in temporal database research, we can expect a more unified approach towards aspatial temporal data in SIS and a wider discussion on spatio-temporal data models. This paper provides an overview of previous achievements within the field and highlights areas currently receiving or requiring further investigation.

Keywords: spatio-temporal databases, survey

1. Introduction

Spatial databases capture information of our surroundings by storing both aspatial and spatial data. The resulting systems, collectively called *Spatial Information Systems*, show great variety due to the diversity of applications in which they are used, which range from image repositories to sophisticated scientific analysis.

Current systems, however, fail to cater for many of the temporal aspects which may exist in a dynamic environment. Spatio-temporal information systems with temporal reasoning capabilities would provide benefits in areas such as environmental monitoring and impact assessment, resource management, decision support, administration, real-time navigational systems, transportation scheduling, data quality and integrity enforcement.

In recent years, a number of surveys have been published on the advances made in spatial database research [1], [34], [36], [66], [72]. Combined, they give a comprehensive overview of the field and provide a useful classification of the different areas investigated by the spatial database research community. The areas discussed include representation, spatial access methods, conceptual models, system architectures, spatial database languages, scaling and accuracy issues, query optimization and visualization. All of these are affected with the introduction of time in spatio-temporal databases. This survey is therefore structured along similar lines. The gap created by the lack of a comprehensive overview of spatio-temporality in database systems. We discuss the results of earlier research, then investigate areas which are in need of further study.

The rest of this paper is organized as follows. In Section 2, we introduce some of the concepts of spatial and temporal databases. In Section 3, we investigate spatio-temporal models proposed in the literature. In Section 4, we look at spatio-temporal database access methods. Section 5 reviews some of the already implemented systems and in Section 6, we highlight issues that can be addressed by future work. Finally, in Section 7, we present our conclusions.

2. Background

Spatial information systems can be categorized into four main groups [1]: *Geographical Information Systems* (GIS), which result from the automation of cartography and deal with digitized maps displaying geographic or thematic information, *Automated Mapping/ Facilities Management* (AM/FM) systems which automate the management and maintenance of networks such as telephone lines or power grids, *Land Information Systems* (LIS, also known as cadastral systems) which manage information such as the details of land parcel ownership, and *Image Processing* systems which process remote sensing images acquired by aircraft and satellites. Although capturing the different application areas, a particular SIS may be able to be classified in more than one of these groups.

Sinton [92] defines geographic information with the following attributes: *theme*, or the phenomena or objects being observed; *location* of the phenomenon; and the *time* of the observation. He believes that without all three of these attributes present and a record of the precision and reliability of the observation, no geographic data should be entered into an information system. Most modern SIS, however, neglect the time component. Their data contents comprise the two other components, namely spatial and aspatial (aka thematic or attribute) data. Spatial data is further divided to be either geometric information or spatial relationship descriptions. We distinguish between three types of spatial relationships: *topological*, which are concerned with concepts such as neighborhood and are invariant under topological transformations such as rotation or translation [24], [65], *metric* or *algebraic*, which are concerned with directions and distances [29], and relations based on the partial or total *order* of spatial objects, such as ‘‘north of’’ or ‘‘above’’ [49].

Current spatial information systems generally use one of two mainstream data representation structures, raster and vector. Raster (or in more general, tesseral) representation is based on the location-oriented field model where aspatial attributes, each representing a separate layer, are associated with points of a grid, which decomposes the data space into regular cells. Vector representation is based on the spatial entity-oriented object model with aspatial attributes describing entities in 2 or 3 dimensions. Points, linear features and region boundaries are stored by their coordinates, either as a single pair or triplet for points, two endpoints for line segments or a series of endpoints for boundaries. In addition, topologic information may be explicitly stored by allowing neighboring objects to share boundaries.

Temporal Database Management Systems (TDBMS) came into existence based on extensions to the relational, entity-relationship or object-oriented paradigms, due to the increased demand for functionality to handle both static and dynamic time related information in databases. Traditional database systems retain only the latest state of the modeled system (or the state at a specific point in time), presenting an up-to-date, but static view of the environment. Solutions to preserve historic data have existed for some time, archiving being the most basic. This and similar attempts, like transaction logs or using separate historical relations for certain attributes, fall short of satisfying modeling and querying requirements. Proposals for new, temporal data models are reviewed by Roddick and Patrick [82], some are collected in [97]. Basic issues concern the representation of time, the selection of appropriate temporal granularity, the level at which temporality should be introduced, support for temporal reasoning, and other database topics. For example, time may be represented by single dates, i.e., time points, or intervals, the former being implicitly applied to compute the life-span of attributes. *Valid* time, or real-world time should be stored to represent the time the change took place, with another, *transaction* or database time denoting the instance this change have been registered in the database. *User-defined* time, an attribute especially allocated by the user, is another type of time available in the database, but is not normally well supported by query operators. Handling alternative timelines, continuous, cyclic, branching and terminating time in the data model would further enhance the reasoning power of a TDBMS. Allen's temporal interval logic [4] and its extension by Freksa [32] to include semi-intervals hold parallels with spatial topological and order related relationships, and can serve as frameworks for adding temporal operators to the database. Another issue is the determination of the level at which timestamping should be introduced: the *relation* level is highly data redundant, while *tuple* and *attribute* level timestamping each have their pros and cons. Most of these concerns have been addressed; the creation of TSQL2 [95] and the laying of future guidelines [91] point to a steady progress toward establishing a TDBMS standard.

3. Models

In proposing a spatio-temporal model, it is natural to extend existing spatial data models with time, although others based on time with spatial extensions can also be considered. It is seldom that researchers propose a completely new approach (these are often based on the object-oriented paradigm, see later), because of the need to be consistent with existing solutions.

The role of temporal GIS is in the tracing of the lineage of spatial objects and their attributes. Its major functions are *inventory*, i.e., the storage of database contents, *analysis* to explain and forecast, *scheduling* to trigger responses when certain database conditions are fulfilled, *updates* to keep database contents up-to-date, *quality control* to ensure logical consistency with previous contents of the database and *display* to relay information to users, as defined in [62]. Two main approaches can be distinguished; systems that model change and systems that model time itself [6]. Koeppel and Ahlmer [52] divide the former even further: Attribute-oriented spatio-temporal databases track changes in information about spatial entities, while topology-oriented spatio-temporal databases track changes in positional information about features and their spatial relationships. They also identify five primary application groups which would benefit from the use of spatio-temporal information: planning, engineering, operations and maintenance, construction and administration. The incorporation of spatio-temporal data enhances data quality by storing lineage information and enables data integrity checks. Employing incremental update procedures and utilizing a temporal database structure would also reduce the long term costs of spatial database conversion and maintenance, known to be the most expensive elements in, for example, AM/FM system development.

3.1. Requirements for temporal SIS

Almost parallel to the initial efforts into examining temporal relational database requirements, GIS researchers recognized the advantages of storing temporally referenced data in their systems. In one of the first such papers, Armstrong [8] considers several aspects of the introduction of temporal data into spatial databases. The issues raised include the following.

- The *components* of change: the morphology (metrics), topology and attributes of a geographic object may or may not change over time, allowing for 8 different scenarios figure 1. This is also often described using the so called W-triangle (where-what-when, [85]) that represents the components of a spatio-temporal object, and observing that it can experience change in none, one, two or three different kinds of attributes at a time.

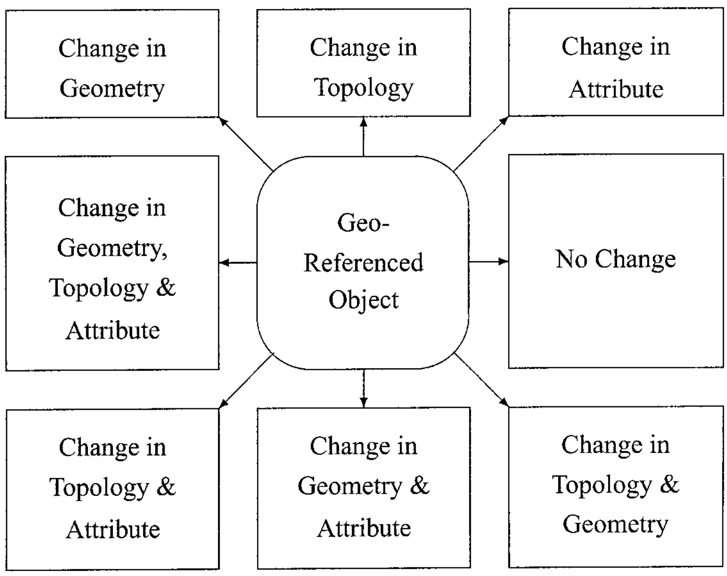

Figure 1. The eight possible spatio–temporal changes a geographic object may go through (reproduced after [85]).

- The registration of samples through *irregular* (possibly when significant changes occur) or *regular intervals*. That is, should events trigger the update of the database or can we select an appropriate interval-based approach?
- Maintaining the *duration* of the status of an object or recording *events* that imply status change.
- Storing the *lifespan* of a discrete phenomenon or *temporal differences* for a continuous one. Such structural aspects are also mentioned by Al-Taha and Barrera [6] who also discuss different continuous representations (linear, circular, ordered).
- Selecting the appropriate method of *access* to data with regards to spatial, temporal or attribute primacy. This has been reiterated by e.g., Kemp and Kowalczyk [50], who consider query response time an important issue in any functional temporal SIS.

Further papers investigate several other aspects of temporality:

- Conceptual issues: The *point vs. interval* debate. Both models should be supported in a functional temporal GIS as observed by [6] and [50].
- Object *identities* to discriminate between objects was investigated by [6], and discussed in more detail by [85]. In particular, the lifespan of an object is an important application dependant variable. The question is, when does change effect an object so much that it cannot be called the same object any more? For example, a highway tollbooth could be moved a kilometer closer to a city. From the management point of view, this represents a locational change of the same object. From a cadastral point of view, it may be more appropriate to destroy the original instance of the object in the old location and re-create it at its new one. Another critical issue is that of splitting or unifying objects. Again, selecting an appropriate solution from several suitable ones may depend on the application domain.
- *Perspectives* of time. Hazelton [41], for instance, observes two major metaphors, that of time as an arrow, representing progress, and time's cycle representing constancy and continuity. They are complemented by two other metaphors, branching and multi-dimensional time. In addition, he points to the existence of different views of time at various scales and its fractal nature. His proposal of the treatment of several perspectives of time in GIS is also supported by others, e.g., [6].
- Temporal navigation (querying) via a *user interface* [6]. The available temporal information must be appropriately supported by enhanced visualization tools, which can aid temporal analysis and decision support, currently not available in existing systems [52].
- *Valid* and *transaction* time. In temporal database research, it has long been established that both kinds of time must be internally supported by the database system. Its merits within temporal SIS are also recognized by e.g., [50], and a number of model proposals support both [108].
- *Dimensionality.* Davis and Williams [21] argue that traditional GIS with their 2 dimensional geometry and associated attribute value are no longer adequate. Although useful ''2.5'' dimensional solutions exist (perspectives, wire frame representation, stereo views, etc.), volumetric 3 dimensional GIS provide advantages in displaying

"*'real-world' renditions of GIS data*". Relegating the attribute value associated with grid locations to a fourth dimension, time can be introduced as a fifth, recognizing that geographic objects often have a past and a possible future in addition to their present. Such dynamics allow animation to become part of the spatial analysis tools for future trend forecasts. Easterfield et al. [23] note the similarities between time and space in that both have extent, but observe some important differences. Time can be "open-ended", meaning that data may be valid up to the present, while it is also a continuum in that the start of one period can implicitly define the end of the previous one. It also has a natural ordering not found in space, and usually possesses much larger extents (periods) than spatial data (size). The validity of data can be modeled either by storing a single time value denoting when the data became valid, or by a pair of values spanning its existence.

- *Evolution* at different speeds. Yeh and Vièmont [113] discuss the difficulties presented by the evolution of objects at different speeds. Normally, a geographical object is thought to continuously exist during its lifespan. On the other hand, a re-occurring event such as the daily watering of a field must be viewed discretely. Although watering may take place for several days, it is not performed continuously, but at certain times of the day and for certain periods only. Slow continuous evolution of an object may also be disrupted by sudden drastic changes, some of which may be permanent, others temporary, or even part of a cycle. To model this evolution using available information recorded at certain regular or irregular intervals, we may choose a discrete interpretation, stating that the object exists only at the recorded times. Alternatively, we may use step semantics, accepting the previously recorded state to be valid until the next recording, or use some kind of interpolation to model the unrecorded states. Similarly, extrapolation can be utilized to predict the short-term future. Another important aspect of the spatio-temporal object is the treatment of its identity. An object may evolve through a series of spatial changes: its boundary may be redrawn, or it could take part in the creation of new objects via object formation, fusion and split. This may result in the identity of the object to be changed or even lost.

3.2. Modeling

One direction in the early attempts to incorporate time into SIS was taken towards the preservation of historical information in cadastral systems. Hunter [46] provides examples for the utilization of such data. Administrative, fiscal and legal purposes are among the main reasons for preservation, but uses in social and environmental monitoring are also highlighted. Vrana [102] reiterates this by pointing to several functions of usefulness for historical data. Among these, the idea of checking for data quality and integrity, the evaluation of past performance and the ability to analyze future trends are considered important. Forest and land title management and land use planning as viable application areas are also described. In addition, three different approaches for temporal data representation are investigated in more detail (attribute timestamping, the use of transaction logs, and versioning), while noting that both spatial and attribute data as well as relationship topologies must handle the time dimension. Hunter and Williamson [47] propose timestamping parcels by their date of creation and date of cessation. They argue that in digital cadastral databases, storing full layers of graphical information for different time periods is impractical, and describe a system that keeps a graphics file of current parcels for day-to-day use while archiving historical spatial data into a separate file. Reference to this information is still kept in the files that store aspatial information via multiple versioned copies of the same parcel record.

In a more general attempt, Armstrong [8] gives three alternative proposals for the organization of spatio-temporal databases, describing them using entity- category-relationship diagrams. For grid-based databases, an attribute history is proposed for each individual cell, thus avoiding the costly storage of whole data layers for each version. For vector-based databases, depending on whether durations are recorded explicitly using from and to dates or implicitly through recording single timestamps, the method associates interval stamped attributes with locations or attributed dates with locations in many-to-many relationships, respectively.

One of the other earlier models for a spatio-temporal database is described in [77]. The model extends the relational database of an image database system (referred to as a GIS) to handle both ''valid'' (transaction) and ''effective'' (valid) time intervals. It adds new algebraic operations to the standard relational operations to manipulate the temporal dimension effectively, demonstrating a successful application of the then current temporal database research results to a spatial domain.

In a later attempt that deals with more expressive GIS representations, Rafaat et al. [78] recognize that changes effect both spatial and thematic attributes in a GIS and propose a relational method for accessing spatial and temporal topologies. In their model, a geographical entity goes through a series of historical states of various durations caused by mutations (changes), until it loses its ''essential property'' (normally a user defined object identifier), i.e., is destroyed or becomes another entity. This time, only real- world (valid) time is used in the GIS, but separate states and durations are recognized for the spatial and thematic attributes of an object. In the approach, a modified version of tuple—based timestamping is employed to independently record each spatial and thematic state of an entity. A set of relations, containing topological, attribute and a positional relation, represents the states of a single data layer. Time intervals are recorded only in designated ''master relations'', that also hold the entity identifiers as opposed to supporting ''slave relations'', which do not. For example, when talking about a map of highways, each highway would have a unique identifier. Every relation that has the highway identifier attribute is thus a master relation, timestamped with from and to dates. Other relations holding additional information, but no references to highway identifiers, e.g., data about the nodes and arcs that make up complete highway stretches, are slave relations with no time stamps. Advantages of the proposed framework over existing systems of the time are the ability to provide historical queries, the trapping of data errors through relational integrity rules, the ease of spatial queries, and the reduction of data redundancy and storage.

Another example, this time to incorporate time into raster GIS is given by Beller [13], who presents a grid-based model of a temporal GIS. He defines an ''event'' as an object with spatial and temporal extents. Examples of events are growing seasons, cloud cover, hurricanes and droughts. First, a temporal GIS is defined as a collection of Temporal Map Sets (TMS) and Neighborhoods with some operations. A TMS is a collection of timestamped GIS maps with associated attributes, e.g., $M = <\{m_1, m_2, \ldots, m_n\}, [t_1, t_n], A_i>$, where m_i are maps, t_i timestamps and A_i attributes. A cell $M(i, j, t)$ refers to the grid value of the TMS at row i and column j and time t. If t is not one of the timestamps, the value is interpolated between neighboring maps. An event then becomes a binary TMS where each cell is designated as either belonging to the event or not. In addition, methods to define, recognize (using pattern recognition techniques) and combine events are detailed. Unfortunately, this representation may be highly data redundant for maps where little or no change is registered over time.

At this stage, some researchers argued that concentrating solely on converting existing GIS to support time may not be fully satisfactory. One of the more important observations was made by Langran [61], who points to evidence as the third type of data necessary in temporal GIS. In addition to traditional maps (states) and events such as fires, flooding, harvesting, etc., evidence in the form of, for example, surveys, would provide the source of change in the database. The same representational techniques can be used for all three data types, but treating them separately would allow the description of events independently of states, remove incorrectly collected survey data and justify false decisions made based on insufficient or incorrectly registered data. Another approach was proposed by Whigham [105], who investigates the structural aspects of time. He observes that time is relative (e.g., the seasonal and academic view of a year differs), has an imposed order (events follow each other) and has different resolutions (traffic flow vs. land erosion). He therefore proposes a dual ordered hierarchical structure where time and events are represented in their own hierarchies, placed on a spatial background reference. Events such as the yearly routine of a farmer is placed in a hierarchy with locational references. An appropriate time hierarchy is then linked with the events hierarchy to establish the timeframes for the individual events. Links within the events hierarchy (or to another event hierarchy) can be used to show causal relationships between events. Along similar lines came the proposal by Hermosilla [44], who recommends a temporal GIS architecture that incorporates elements from knowledge bases and artificial intelligence. He argues that many spatio-temporal applications would benefit from, indeed require, reasoning capabilities in their operation. Global change, urban ecology and electronic navigation management are pointed to as examples where future predictions, decision support and the ability to discard unwanted data or compose complex objects are necessary system components. Simple coupling of a knowledge base, database and GIS is an available solution, but is not desirable, because problems with individual systems (e.g., long transactions) may extend to the other subsystems without realizing some of the benefits they offer (e.g., a general query language, recovery procedures). Instead, the integration of the three paradigms is proposed; using a common indexing method to store basic, complex and rule data, and a general purpose query language with standard and spatial operators. Updates are directly made to the storage module, while inferences can be effected through the use of an inference and a database engine that form the assessment module of the system. To achieve full temporal support, the incorporation of discrete and continuous, (left) bounded, linear and branching, and absolute and relative time is required. Other storage, update and assessment issues are also discussed, including the need for retro- and pro-active updates, and a temporal algebra based on Allen's interval logic [4] with time point and periodic data extensions.

In contrast, some authors believed that the solution to handling time in GIS could be given by using techniques found in related disciplines. Medeiros and Jomier [67], for example, apply the DBV mechanism to version geographical databases. The DBV mechanism, *cf.* [18], differs from traditional versioning methods, such as the physical versioning of files at different times, or the use of linked lists for the changes of individual entities of a database. Instead, it manages logical versions of the full database without replicating unchanged entities. Because of this design, alternate database versions may exist for the same time period. Applied to GIS, this enables spatio-temporal queries for the analysis of temporal data evolution, forecasting the future based on the recorded past and the comparative analysis between actual data and simulated scenarios. These queries are handled in three single steps: the collection of all database versions for the selected time period, the running of standard queries on individual versions, and performing the appropriate simulation/comparison operations required by the selected query type.

As seen in some of the above proposals, the ability to represent time in GIS has been a major concern. From a user perspective, however, the way this is achieved may not be important. They are more interested in seeing systems that can provide answers to their queries. The realization of this requirement has led some researchers to concentrate on developing models that aim to cater for this particular need. Peuquet and Wentz [73], for example, suggest that most current spatio-temporal systems are extensions of GIS based on either the raster- or vector-representational format, with the format of the extension depending on the type of queries the application needs to be able to handle. They observe, however, that answering certain kinds of queries with these representations are excessively expensive. For questions such as ''When did a specific event occur in a given area the last time?'' or about cause and effect relationships that are temporal in nature, a new kind of representation is needed. This format, termed the *time-based representation*, captures changes in the environment along a temporal vector. Starting with an initial state (base map), events are recorded in a chain-like fashion in increasing temporal order, with each event associated with a list of all changes that occurred since the last update of the event vector. An event may represent abrupt change or can be triggered when gradual evolution is considered to be significant enough (by some pre- defined threshold) to register change. The lengths of temporal intervals between recordings hence depend on change rather than a time-clock, and are thus likely to be irregular. Changes can be stored as differences from the previous version, which avoids data redundancy, or, if they are considered to be extensive, the full map may be registered. This also has the advantage that re-creating the current map no longer requires the full traversal of the event-chain. In theory, both raster- and vector-based representations can be used for the base map and changes. In [74], however, the Event-based Spatio Temporal Data Model (ESTDM) developed on this time-based approach, is raster-based only. This is due to the fact that with a vector-based representation, maintaining the integrity of spatial topology through change is a complex problem. Ultimately, the triad combination of raster-, vector- and time-based spatio-temporal representations in the one system seems likely to cater for the diverse querying requirements of modeling dynamic geographical objects. A later study that inspires another model is conducted by Yuan [117], who states that the way humans conceptualize their surroundings is important in modeling geographic reality. Without the representation of such concepts in a GIS environment, in addition to the traditional spatial methods and temporal objects, a variety of spatio-temporal queries cannot be answered. Her three domain model addresses this problem by representing semantics, space and time separately and providing links between them to describe geographic processes and phenomena. The semantic domain holds uniquely identifiable objects that correspond to human concepts independent of their spatial and temporal location. This is in contrast to other models where, for example, a land owner is represented as an attribute of a land parcel. In the three domain model, the land owner is a semantic entity that is linked to a land parcel (spatial object), with changes to the parcel associated with dates (temporal objects), and possible other land parcels involved in the transformation. Loss of ownership is easily implemented by the linking of another semantic entity to the land parcel together with the temporal object representing the date of sale. The advantage of the model is the ability to handle movement as well as change, which is an improvement over many existing models that handle either the former or as in most cases, the latter. A set of formal definitions for these constructs can be found in [118], spanning objects in each domain, operators for their manipulation and integrity constraints. Querying from the semantic, spatial and temporal perspective hence becomes the investigation of links between the entities in each domain. A classification of change (as a general term including both ‘‘change’’ and ‘‘movement’’ as discussed above) for this purpose is given, with two groups identified in each of the three domains: semantic changes include variations in attributes over time and the static spatial distribution of a geographic phenomenon; spatial changes may be static, looking at variations of a geographic phenomenon at a snapshot, or transitional, comparing states of an event at different sites; temporal changes are either spatially fixed mutations of an event or the actual movement of it from one place to another.

3.2.1. Object-oriented approaches. In this section, we have collected some proposals based on the object-oriented paradigm. They depart from other, more traditional models in that they try to collect information (spatial, attribute, relationship and historical) into uniquely identifiable entities. Wachowicz and Healy [103], for example, create an object-oriented spatio-temporal model of real-world phenomena and events. Real-world phenomena are represented as complex versioned objects with geometric, topological and thematic properties. A new instance of an object with a different identifier is created for every version of the object establishing a hierarchical structure for the past, present and future of the object. Events, on the other hand, are manifestations of actions which invoke update procedures on one or more objects. Time is represented as an independent, linear dimension unlike other representations where the time axis is orthogonal, i.e., is modeled together with the spatial dimensions. In another attempt, Bonfatti and Monari [16] describe an integrated approach to model both geographical structures and phenomena.

They argue that cross-references between objects to express relationships are ambiguous, hence better means are needed to characterize object structure and behavior. Their proposed solution is the use of complex objects comprising of several components to express structure and relationships. In addition, *laws* describe the behavior of the components. Laws are predicates that express regularities in object states and hence determine the possible states an object can have. For example, a straight line segment which is defined as the composition of two points, a length and three coefficients for the line equation, would have laws stating that both points must line on the line determined by the equation and the length must equal the distance between the two points. Other laws may describe legal transformations between states of the object and interdependencies between its components. These interdependencies between components, however, may be different when the components are part of another object type. By defining a *virtual object* comprising these components, general conditions that exist between them can be expressed as the *invariant relation* (i.e., the conjunction of all laws) of the virtual object. Spatio-temporal processes can then be modeled easily with this framework: by attaching timestamps to objects (components) and expressing motion as laws for complex objects.

3.2.2. Reviews. Unlike in spatial database research [1], [36], there are few comprehensive discussions of the advances in spatio-temporal databases in the literature. Langran looked at the aspects of time in GIS in her book [62], but a number of new proposals emerged since. Other collections either deal with the area as part of the larger field of spatial research, e.g., [110], or address individual topics such as spatio-temporal reasoning [30]. On the other hand, individual papers often provide short reviews before introducing new ideas.

In one of these earlier reviews, Armenakis [7] looks at spatio-temporal data with respect to storage, retrieval and update efficiency. He compares three approaches which he calls ''estimation methods'' to describe time-varying spatial information. The aim of his investigation is to see if they have the ability to store/reconstruct complete geographical states, offer functionality for comparisons between states, and describe the events that lead to changes between states. In *static mode*, snapshots of full states are kept which leads to the storage of redundant information[1]. To detect changes between snapshots, relatively expensive computational algorithms must be used, although this would still not explain the *processes* leading to the change. In *differential mode*, only the initial state is fully recorded. Changes are stored in one of two possible kinds of ''delta files'', which record the differences from either the previous state or the initial one. This reduces storage requirements substantially, and makes the computation of changes between states less costly. However, to reinstate previous states or the current one, a series of delta files must be applied to the initial state which makes this operation inefficient. Alternatively, the current state can be chosen to be stored in full, keeping delta files to trace back to previous states, which is the preferable solution if the current state is more frequently accessed than historic ones. This is somewhat similar to the final, *sequential updating mode*, that also keeps the current state of the map on record. However, this approach records changes as they happen and not in a snapshot-like fashion, and uses indexes to access previous information, eliminating data redundancy. Another alternative, still following the idea of sequential updating, is to drop the use of delta files and retain unchanged components instead. In this scenario, when an object changes, its previous version is superseded but fully retained, accessible by temporal links and indexes, while a new object is created to describe the current state of the component.

Some of the more interesting papers, on the other hand, investigate system implementations. One such paper is by Kemp and Kowalczyk [50], who give an overview of temporal GIS implementations ranging from simple archiving, through versioning using time-slicing, record level timestamping and chaining to more sophisticated methods such as temporal stamping of spatial attributes. In addition, they analyze two object-oriented system implementations, POSTGRES and Zenith to evaluate their ability to satisfy spatio-temporal modeling requirements. In another investigation, Kemp and Groom [51] use an example zoological application for mammal sightings to evaluate two alternative implementations. Spatial background data and sighting information of various types (measurements, descriptions, photos, video and audio, etc.) are combined in systems based on either the geo-relational or the extended relational models. The first, geo-relational implementation uses a GIS to trace change in urban areas and record timestamped sightings. This represents a simple approach with satisfactory handling of moderate amounts of data and a good user interface, but falls short on providing adequate query support for temporal data. The second system, implemented in POSTGRES, better captures the hierarchical nature of spatial objects by allowing the definition of abstract data types and providing the primitive geometric point, line segment and polygon types. Although relation level versioning is available, temporally variant attributes are best handled by either defining variable sized arrays or using user-defined procedures. This system is found to be a better platform for temporality for the above reasons. Unfortunately, the built-in query language does not support temporal operators, so information retrieval remains awkward, but could be addressed in future versions. In another paper contemplating the utility of temporal SIS, Worboys [110] first revisits the concept of time and its implementations in temporal databases before reviewing his own object-oriented approach to spatio-temporal modeling. Then he uses four different examples to highlight the various requirements for a spatio-temporal information system: describing applications in road planning, real-time navigation, administration and land parcel management.

Not all reviewers stop at evaluating previous work. Chrisman [19], for instance, presents a critique of using time as a single axis in temporal GIS models. Drawing examples from philosophy, such as Hegel's dialectic describing competing forces and ideas or Usher's view of ''*every event has its past*'', as opposed to the continual, incremental, but linear development in the form of the ''*March of Progress*'', he arrives at the conclusion that a multi-threaded model of history seems more appropriate. He also states that it is not enough to trace geographic evolution, a record of events and processes that lead to this evolution must also be kept. Looking at potential problems from another point of view, Yuan [116] also finds that existing temporal GIS models are incapable of describing all kinds of change. She defines six different types of change in line with Sinton's proposition to fix one component, control another and measure the other of the space-time-attribute triplet [92]. Five existing models are compared with respect to their ability to model state (attribute and spatial distribution), spatial (static and transitional) and temporal (mutation and movement) changes. The first two types are easily modeled by most models (e.g., snapshot [8], Space-Time composite [59]), the third by object- oriented models [108], the fourth by event-based models (e.g., ESTDM [74], Oogeomorph [81]) with limited success, but none can successfully express temporal changes.

3.3. Data types

In order to define the building elements of a spatio-temporal database system, the atomic spatial data types (points, lines and regions) and temporal data types (events and intervals) can be combined into abstract spatio-temporal data types. Logic and algebra definitions can also be proposed to describe abstract spatial and temporal data and relationships with operations for their compositions. To cater for abrupt changes and slow evolution, there would be a need to represent time both discretely and continuously [11]. In addition, implementing branching and terminating time would allow for alternate timelines to enhance reasoning capabilities.

Most attempts thus far are examples of adjusting existing spatial data to specific application needs. Price [76] observes that a land parcel in a LIS is an entity with an associated lifespan. It is dynamically changing during its existence, is created from an existing (parent) lot and is capable of giving birth to other lots via subdivision. Therefore, he creates an abstract data type that keeps track of changes to the lot using a list of transactions (including creation), a list of the originating (parent) lots and the original and current size. A nil value in the latter indicates that the lot no longer exists. Even though simple and not addressing attribute data temporality, this model represents a departure from earlier models that used a form of versioning which required extensive use of archiving, and made historical querying difficult. In another paper, Koeppel and Ahlmer [52] propose two techniques for the integration of temporal data into AM/FM systems. *Dynamic segmentation* builds on a topological data structure and associated temporal event tables that track change. These can be combined to derive useful information regarding the status of the linear network they represent. Data redundancy is avoided by not storing explicit topological information. The other technique uses *change detection matrices* in a spreadsheet to record differences between two time periods. Each axis represents a time period. Standard matrix algebra operations are used to derive change detection matrices for multiple time periods.

A more general approach is taken by Worboys [108], who defines a spatio—temporal object as a unified object with both spatial and bitemporal extents. An elemental spatial object (a point, line segment or triangular area), also called a simplex, is combined with a bitemporal element, *cf.* [94], to form an ordered pair. A finite set of such ST-simplexes satisfying certain properties is then further defined to form an ST-complex on which a query algebra is developed. An ST-complex traces changes in discrete steps, therefore is unable to represent continuous evolution, but is well suited for processes where mutations occur in sudden jumps. Also based on the object-oriented paradigm, Rojas-Vega and Kemp [83] describe a structure for distributed, multi-media spatial applications. The

Structure and Interface Definition Language (SIDL) is developed for this purpose. To achieve full encapsulation necessitated by the distributed nature of the spatial database, the basic object type has a structural and an interface part. In the structural part, an object identifier, conventional attributes, an object component grammar and conceptual relationships are defined, while the interface contains methods operating on the object. The object component grammar contains the list of other objects that form part of the object, including compositional semantics, such as sequence relationships and compositional relationships that determine if a component is mandatory or optional, shareable or non-shareable, or dependent or independent of the existence of the object. Conceptual relationships are constraints setting or prohibiting relationships between objects. With these parts, complex object structures can be built to fully model real-life entities and their interactions. Time is introduced by separate objects that can be attached to time-varying components, with the use of separate objects for different models of time, e.g., intervals or points.

Attempting to solve the problem of object evolution at different speeds, Yeh [114] and Yeh and de Cambray [115] provide a model for highly variable spatio-temporal data using behavioral functions. A behavioral function forms a spatio-temporal object triplet together with a timestamp and spatial data to describe versions during data evolution. At each time point when a version is recorded, the associated function shows how the data is evolving. Data evolution is hence described by a sequence of values $\{(v, t, c)\}$, where v is a value, t is a timestamp and c is a behavioral function. This extra information allows the modeling of complex evolution as opposed to simple versioning or versioning with a global function (such as linear interpolation), making the data less redundant and resolving data deficiency between states. Another advantage is that existing geometrical algorithms (such as plane sweeps) can be utilized in the evaluation of temporal queries.

3.4. Relationships

In addition to locational, temporal and attribute data, relationships between spatio-temporal objects express valuable information about the interactions of the real-life entities they represent. Relationships may be derived from examining the contents of the database, or can be explicitly stored, depending on the data model and application demands. Topological, algebraic and order related spatial relationships are further complemented by temporal relationships, which are either topology-like (e.g., meets, during), or order-like (e.g., before, after).

A simple spatial reasoning model is given by Guesgen [35], who defines four basic one-dimensional spatial relationships based on Allen's temporal logic [4]. The relations (left of, attached to, overlapping, and inside) can express spatial relationships between multi-dimensional objects by introducing orthogonal axes and describing the relations along the individual axes as a tuple. A transitivity table is provided to derive relations in a collection of objects. However, since some of the combinations of relationships give unspecified results, ambiguity can be a problem. Although not specifically mentioned in the paper, time may be introduced as a fourth dimension using the same relationships in a temporal meaning to provide a model for spatio-temporal relationship topology.

Building on the already existing framework for topological spatial relationships, Hazelton et al. [42] list possible topological relationships between objects of various dimensions in up to 4-D space. This work extends the efforts of [24] figure 2 by examining 0 to 4 dimensional objects and their interactions in their ''natural'' and higher dimensions, with the fourth dimension representing time. In this 4-D GIS, two types of objects are recognized, space-like and time-like, depending on their temporal persistence. For example, a 3-D space-like object is a (physically) 3-D object that exists only for a time instant, while a 3-D time-like object is in fact a 2-D spatial object with its history/future representing the third dimension. While providing a greater insight into the possible interactions of objects of different dimensions, the natural ordering time possesses (e.g., before, after) remains uninvestigated. Egenhofer and Al-Taha [25], on the other hand, examine topological relationships of 2-D objects in 2-D space when undergoing gradual changes. They provide a mathematical formalization for scaling, translation and rotation of the objects by defining the ''topology distance'' between the 8 possible relationships (*cf.* [65], figure 2), and observing its properties (value, range, symmetry and triangle inequality). Using these distances, they create the Closest-Topological-Relationship-Graph (CTRG, figure 3), which connects relationships with minimal topology distances. The CTRG is then employed to demonstrate the effects of the different kinds of transformations by traversing its nodes following the gradual steps occurring during those changes. For example, when one of two identical objects that are initially disjoint moves towards and then across the other, the disjoint relationship gradually becomes, meets, overlaps, equals, then overlaps, meets and becomes disjoint again. These experiments culminate in a revision of the CTRG, which differs from the original by having arcs between the equal relationship and the overlay, inside and contain relationships. The

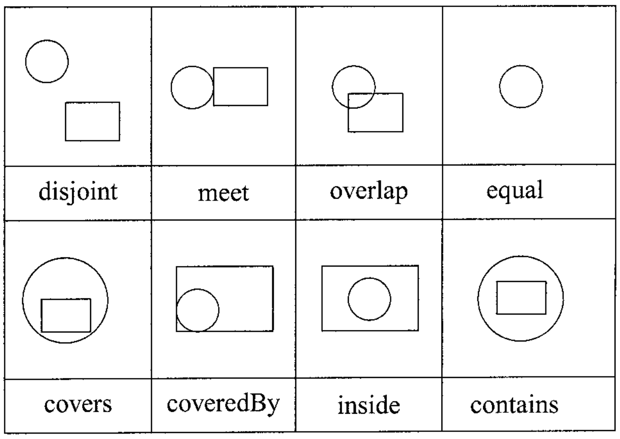

Figure 2. Topological relationships between two 2-D objects A and B in 2-D space with object A denoted by a circle and object B by a rectangle (except in the 'equal' case where both objects are a circle of the same size).

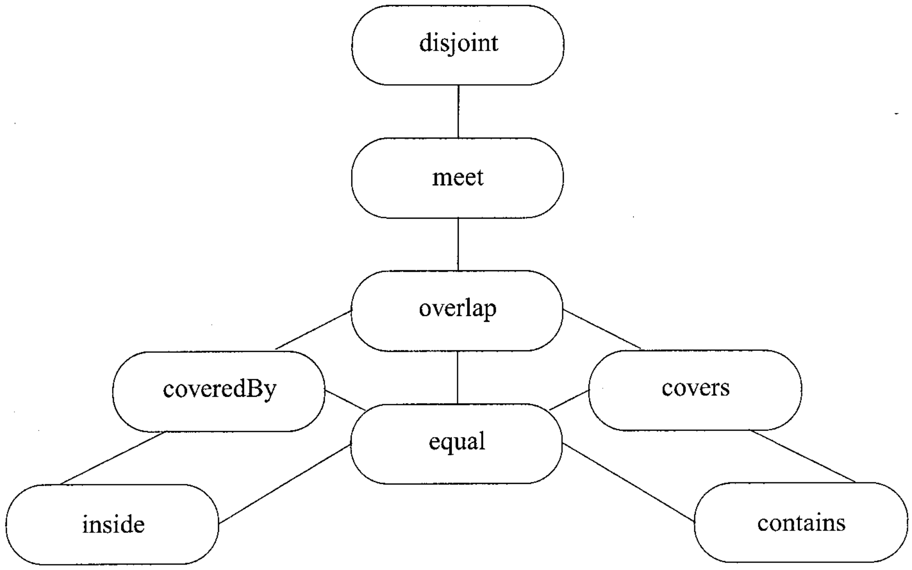

Figure 3. The revised Closest–Topological-Relationship-Graph (reproduced from [25]).

usefulness of this computational model is twofold: having two or more relationships between two objects taken at different times, we can infer the kind of deformation that occurred. Secondly, when an object is deformed, we can predict the change in its topological relationships. It is worthwhile noting that the model caters for those ''snapshot-like'' application types where change is slow and continuous, and explicit registration of these changes is either omitted or is impossible; instead, they are recorded at regular intervals in a selected temporal resolution (e.g., hurricane or soil contamination information). Where change is sudden and is explicitly recorded, topological information is readily available or computable for all states and need not be inferred. However, even in the latter case, the CTRG can be utilized for its predictive properties.

Approaching the problem of describing relationship operators from another perspective, Frank [31] relaxes the use of explicit, calendar-like timestamping considered necessary in temporal GIS and investigates the relative ordering of events. Assuming events to be point-like and that all events are recorded (''closed world assumption''), he defines the operator ''before or equal'' from which he derives others to provide both generic, totally ordered (with a single time line), and partially ordered time models. These are then seamlessly extended with an equality operator, with an imposed tolerance to cater for possible discrepancies in the registration of events due to measurement error. When used in a spatio-temporal GIS that de-couples spatial and event information, these time models add flexibility of reasoning for events where only their ordering is known, e.g., in archaeology and geology.

In an attempt to add uncertainty handling to relationships, Dutta [22] uses fuzzy logic to bind spatial and temporal reasoning into an integrated framework of approximate topological reasoning. Acknowledging that spatial and temporal information is often imprecise and uncertain, fuzzy logic enables the construction of a reasoning model with topological entities and constraints as its building blocks in a point based representation. Topological entities refer to both events and objects, while topological constraints express constraints on the location of entities along some topological axis. They are grouped into four categories that express representational precision: crisp and precise, crisp but imprecise, fuzzy, and complex fuzzy. The framework also includes the definition of relationships between entities and (temporal) intervals, and the description of axioms and properties, such as support, topological equivalence, complement, intersection and union of entities.

4. Access

Accessing information stored in a data collection of any kind can be classified into operators dealing with the acquisition (capture, transfer, validation, editing), storage, and processing (restructuring, generalization, transformation) of the data [66]. In order to extract the information contained therein, specifically designed languages facilitate the easy querying of database contents. The effectiveness of these querying mechanisms, in turn, depends on the speed and efficiency of the indexing methods available within the database. The contents of the collection as well as the results of queries can then be presented to the user using several visualization techniques.

4.1. Querying

Generally, one expects that languages provided for the users of a system for querying purposes are easily applicable. Most available textual languages therefore borrow words from our vocabulary to resemble natural language, which represent powerful operators that facilitate analysis. Simple sorting and grouping instructions are complemented with tools for aggregation, conditional selection, filtering and generalization. Direct interactive techniques to manipulate database contents are often offered to replace or complement textual query languages. Formal definitions in the form of algebras and calculi place query languages on mathematical ground. Issues such as genericity, completeness, soundness, extensibility and the availability of set operators form part of these formalisms, and hence must be part of proposals for spatio-temporal query languages as well.

4.1.1. Languages. Query languages for both spatial and temporal databases can be used as candidates for the creation of a spatio-temporal language. Because of the extra semantic complexity added by both the temporal and spatial dimensions, it is desirable to have features in a spatio- temporal query language that go beyond those provided by currently available mainstream relational languages. Previous efforts in temporal query languages include HQL [86], which is an extension of the relational query language DEAL. DEAL has nested queries, conditional statements, loops, and function definitions that allow recursivity, which makes it more powerful than traditional query languages, such as SQL or Quel. Both metric (longer, shorter, equal) and relationship (before, after, meets, etc.) operators are defined to handle temporal elements. This similarity to spatial relationship operators as well as its expressive power makes this language a possible candidate for extension to handle spatio-temporal queries. At this stage, there are no specific spatio- temporal query language proposals in the literature. Some other examples for languages that can be potentially converted include some temporal query language extensions, such as Ariav's TOSQL and Snodgrass' TQuel [97], with the latest research culminating in TSQL2 [95]. Spatial query languages of interest include Berman's Geo-Quel, Joseph's PicQuery and Ooi's GeoQL, see [38] or [34] for references and further examples.

The main issue in the construction of a spatio-temporal query language is its expressive power. We must determine the kind of queries we expect the language to provide answers for. Examples for what STIS users are likely to ask about include object/database states at different times, location of objects and phenomena, their full history, the occurrence of events and so on. We have discussed some of these in more detail in the Modeling section. Langran [63], for example, compiles a ''wish-list'' for the addition of analytical capabilities to temporal GIS. In her cubic spatio-temporal representation, space and/or time are allowed to dominate the other dimension(s), thus recognizing space- dominant, time-dominant and spatio-temporal activities. Queries may be of any type. For example, the retrieval of a spatial snapshot at a given time is space-dominant, the retrieval of the history of a spatial object is time-dominant, while the retrieval of features within a given time-span is spatio-temporal. Likewise, generalization operations may be of any of the three types. The purpose of generalization operators is to describe properties that persist over time, rather than those that are present at a given moment. This makes it possible to observe cyclical and other enduring features that may not be present at the time of investigation. Other important spatial operators affected by the time dimension are adjacency or proximity computations (in space and time), triggering mechanisms that initiate system actions, inter- and extrapolation, and projection. The sixth and final desired capability class is the ability to correct discrepancies between information provided by multiple data sources. This reconciliation process could take the form of an interactive procedure, or be semi-automated employing tolerance values and weights to derive an estimate, *q.v.* [64].

4.1.2. Operators. In the spatial domain, Langran [63] distinguishes between several types of spatial operators: *aspatial*, e.g., logical relationships, arithmetics, *spatial metrics*, e.g., position, orientation, extent, surface, area, volume, shape and perimeter, and *spatial topology*, e.g., disjunction, neighborhood, intersection, inclusion, and equality. Worboys [107] also notes *set-oriented* operators, e.g., union, cardinality, difference and membership.

In a spatio-temporal system that is based on an existing spatial one, therefore, temporal operators must be considered as a new type of operators. Temporal topology is analogous to spatial topology, and some of the spatial metric operators can be directly translated into representing temporal extent (duration), with the passing of time represented by 1-D orientation operations. Along these lines comes Worboys' proposal, who represents time as a single, linearly ordered, uni-directional dimension orthogonal to the spatial dimensions [107]. He proposes two projection operators, ϕ_S and ϕ_T to project his spatio-temporal primitive, the ST-atom onto the sets of spatial objects or time intervals, respectively. In this way, purely spatial and temporal relationships between objects can be investigated, and ''*any spatio-temporal relationships between ST-atoms can always be decomposed into the Cartesian product of separate spatial and temporal relationships*''. Further details of these new operators are given by Peuquet and Wentz [73], who classify temporal operators into three groups in their discussion of the time-based data model: linear metrics and topology, Boolean operators and generalization. The time-based data model represents events along a vector that operates as a time-line. Thus, the only metric operator required is the temporal distance, which is either an event duration or describes a period where certain conditions remain unchanged. Temporal topological relations are represented by the 13 operators identified by Allen [4] in his temporal logic. Boolean operators combine simple temporal expressions into more complex ones, using intersection, union and negation. Generalization is used to express events at other resolutions and scales than the ones they were recorded at, often to temporally align phenomena to facilitate comparison between them.

Temporal correlation operation comprises a hypothesis, the STIN operation part involves selecting the spatio-temporal data sets for analysis. The STIN itself involves 3-D reconstruction and 3-D intersection. First, a suitable representation technique is 2-D raster then 3-D voxel data sets returns the common volume contained in the data sets. Correlation generated from the STIN is tested for reliability employing standard.

4.1.3. Formalisms. In order to mathematically describe the behavior of the spatio-temporal querying process, first order predicate calculus, modal temporal logic, dynamic logic and non-monotonic logic are proposed as candidates for query processing formalisms in temporal GIS [11]. Temporal database research has also produced several alternative extensions to existing algebras and calculi to represent temporal semantics. Gabbay and McBrien [33], for example, add two modal operators, *until* and *since*, to first-order classical logic, from which they then derive several others. In their Temporal Relational Algebra (TRA), they include the definitions for a since- and until- product to add to the five classical operators of relational algebra (select, project, the Cartesian product, set difference and union), for historical database environments. Based on TRA, they design the Temporal-SQL language extending the functionality of standard SQL. Their example demonstrates how temporal extensions to the relational model dominate research interest, but also hints at the opportunity to add temporal operators to other formalisms that already handle space.

Some of the existing proposals include one by Coenen et al. [20], who define a temporal calculus for raster based GIS. Their Event Space Calculus is based on time as another spatial dimension, expressed by the same tesseral representation as raster spatial data. The calculus is non-monotonic in the sense that it allows amendments and additions, but inhibits the delete operation to conform to the concept of non- destructive assignment found in classical logic. Both instantaneous events and temporal interval entities are represented, but due to the minimum size tesserals must have at any granularity, the representation is not dense, i.e., it may not be possible to arbitrarily add new events between existing ones. Another disadvantage is that only a given time window can be expressed: the representation is bounded by a start and end tesseral address. However, a great deal of versatility is achieved by allowing events to be either referenced or free[2]. Intervals are defined by their start and end events, and by allowing these to be either free or referenced, five different kinds of intervals can be constructed, with variable (unknown) or constant (known) duration: free variable, start referenced variable, end referenced variable, free constant and referenced constant intervals. Using simple arithmetics on tesseral addresses and utilizing Allen's temporal logic [4], 34 different relationships can be constructed between events and intervals, representing powerful temporal reasoning capabilities, *cf.* [32]. Based on his own object-oriented concept of ST-complexes, Worboys [108] also defines the elements of a query algebra. A range of spatio-temporal operators are presented, including equality, subset and boundary operators, spatial and temporal selections and joins, and spatio-temporal β-product, union, intersection and difference operators, extending and redefining components of the classic relational algebra.

4.2. Indexing

As in all databases, fast access to raw data in spatio-temporal databases depends on the structural organization of the stored information and the availability of suitable indexing methods. A well designed data structure can facilitate straightforward techniques to rapidly extract the desired information from a collection of data, while complex indexing methods can be used to quickly locate single or multiple objects in the database. Many of these, however, tend to favor certain types of application-dependent queries. Hence, we can expect the same bias in newly proposed spatio-temporal techniques, most of which so far have been based on extensions of existing spatial indexing methods. Such well known techniques include quadtrees [89], R-Trees [37], and others, see [36] for an overview. Most of these indexing techniques follow the conventional wisdom of producing well-structured, balanced trees with low depth to achieve maximum traversing speed, although some hash-based approaches also proliferate.

By nature, a spatio-temporal database contains historical data that may play a lesser role in its day-to-day operation, although they still remain an important source for strategic decision making. The indexing techniques employed thus should be built to provide faster access to operational data as opposed to archival information. This access is also influenced by factors such as the update frequency or the storage medium. Operational data typically has a need for a read/write (or append) capability on fast access devices. Archival information is typically larger, read-only and can often afford to be on slower devices such as CD-ROM. Appropriate strategies must also exist for the migration of no longer current operational data onto such devices as time passes.

4.2.1. Indexing methods. As the simplest approach, multi-dimensional spatial indexing techniques can be utilized as a crude form of spatio-temporal indexing, with time treated as an extra dimension. Additionally, several techniques from the temporal database literature can be directly used for indexing aspatial temporal data in temporal Spatial Information Systems. Some of these techniques are described by Salzberg and Tsoutras [88], who provide a comparison of proposed temporal indexing methods. Since the cost of I/O operations, or the number of disk page accesses far outweigh other considerations in the retrieval and update of data, in their view it is essential to select well-paginated index techniques with low space requirements, and achieve optimal data clustering on the storage media for the selected query criteria. Addressing these problems, Salzberg [87] describes some spatial and temporal indexing methods, the holey brick tree (hB-tree) and Time- Split B-tree (TSB-tree), but makes no attempt to propose a structure incorporating both time and space.

Another simple form of spatio-temporal indexing, as evaluated by Langran [58], could be partitioning. She argues that most temporal GIS applications will feature either spatial or temporal ''dimensional dominance'', i.e., one or the other will be more prominent in the day-to-day use of the application. Therefore, she proposes space- and time-dominant partitioning approaches. The first creates partitions according to present data requirements, then creating temporal layers of these cells. The other accumulates temporal data first, then organizes them into spatial cells. This is somewhat refuted by Easterfield et al. [23], who argue that there is little need for temporally indexing spatio-temporal data. Because of the relatively long periods that data are valid, the effective reduction in the volume of data by indexing for temporal query execution would not be enough to warrant its use. However, temporal joins could be produced easily if records were timestamped with temporal intervals. This would require additional features in the DBMS: an automatic facility to adjust end times of records when their successors are inserted, and implementing temporal semantics internally so that queries can be made with simple single time specifications without the explicit need to specify starting and ending times. Hazelton et al. [42] also confirm the difficulty of indexing spatio-temporal data by highlighting problems with data access, database size and disk storage schema. Since functional 4-D (spatio-temporal) GIS are non-existent, it may be premature to talk about querying without the experience of knowing exactly what types of queries and optimization would be required.

In one of the more concrete attempts, Xu et al. [111] investigate R-Trees for spatio-temporal indexing. An R-Tree, *cf.* [37], is a spatial indexing technique that stores information about spatial objects by referencing their Minimum Bounding Rectangle (MBR). Each node of a tree of order M has at least $M/2$ and at most M entries of the form (R, P), where R is a rectangle that covers all the rectangles of the descendants of the node, and P is a pointer that either points to a descendant in a non-leaf node or to a spatial object in leaf nodes. Improvement on the R- Tree indexing methods can be made to handle spatio-temporal information in image sequences. The simplest method would be to create an R-Tree for each image and link them in temporal order. However, a space saving technique, called the MR-Tree, can be used if the R-Trees indexing consequent images are allowed to reference parts of the R-Tree structure of the original (or previous) image, by sharing sub-trees which index spatial information that remain unchanged between snapshots. This is a viable technique because in some applications images do not go through drastic changes, making parts of existing indexes ''reusable''. An alternative approach is to use a single, modified R-Tree structure, the RT-Tree, that stores temporal interval information in each node with start and end dates denoting image recording times, in addition to the bounding rectangle and pointer data. Initially, a regular R-Tree is constructed for the first image, then as new images become available, information is inserted into this tree. For unchanged data, this involves a simple update of the time interval information. For objects that changed location, shape or size, new nodes are created based on time interval and covering rectangle information. Both approaches represent efficient indexing structures that are well suited to access spatio- temporal information stored using the snapshot model.

Providing another opportunity for spatio-temporal indexing, Kolovson and Stonebraker [53] create Segment Indexes to reference both interval and point data in a single index, the SR-Tree. Aspects of the Segment Tree, *cf.* [15], are merged with R-Tree features in an attempt to improve the performance and efficiency of spatial indexing. Three different tactics are employed in the process: allowing the storage of index records (pointers to data records) in non-leaf nodes of the tree, the variation of node size to maintain high fanout, and the pre-construction of an index based on expected data distribution. The index records of higher level nodes are intervals that span the lower level nodes. To avoid problems that may arise due to the sensitivity of the index to insertion order, such as a high degree of overlapping or regions with too high or too small aspect ratios, a Skeleton SR-Tree may be constructed that pre-partitions the entire domain according to some expected data distribution figure. Kolovson [54] continues this work by outlining two modified spatial indexing techniques that can be applied to spatio-temporal data as well. Multi-dimensional segment indexes handle historical data represented by time intervals, with time treated as a separate dimension (see above). Lopsided indexes, the other alternative, are designed to index append-only (suited to certain spatio-temporal data models) databases with highly non-uniform query requirements, for example, with emphasis on querying the most recently added data. The idea is to use conventional indexing methods for different layers of information (snapshots), referred to as ''epochs'', then tie these together with simple time ordered links between the roots of the indexes of the different layers, to maintain fast access to the data layers, with the most recent layer having the immediate path in the index link.

4.2.2. Data structures. Basoglu and Morrison [12] devised one of the earliest spatio-temporal data structures for historical U.S. county boundary data. The four-level hierarchical structure organizes information by states, counties, dates and coordinates. The state has been chosen to be on the top level to better facilitate querying requirements. This file contains pointers into the counties file to locate the first county for each state. In the county record, further pointers are stored to historical boundary information in the dates file, the next county in the state and a possible additional record of the same county, both in the counties file. The dates file on the third level holds interval stamped line segment information referenced from the counties file, while line coordinates are stored in the lowest level, the coordinates file. This level is implemented as two separate files, one holding a pointer to the first coordinate pair of the line segment (or point is some cases), the second having the list of coordinates making up the segment. On this structure, after a strict interactive specification process, queries to display and plot historic maps can be generated.

After specific solutions such as the one above, a number of more general proposals emerged for storing spatio-temporal data. Langran and Chrisman [59] evaluate three of these alternative structural organizations for temporal geographic information. The simplest approach, taking snapshots of the data, is found to be inadequate due to its inability to represent events that lead to the changes in data observed as the different states of the geographic entities in different snapshots, the redundant information storage and the lack of support to enforce integrity. These shortcomings are addressed by another technique, where only changes from the previous version are registered in a newly created ''overlay''. In this case, the current state of the map is derived from superimposing all existing overlays on the original base map. Hence, a single overlay acts as an ''event'', recording the ''mutation'' of the previous state into the current one. The final alternative, named the ''space-time composite'' (STC) is a variant the above technique without the notion of overlay. In this representation, the base map is fragmented over time into smaller and smaller units with their own temporal attribute sets (history). When an area of the map changes, it is split into two objects, one that has changed, and another that remained the same. The necessary spatial information is stored for both for identification. Consequently, each object is treated separately, i.e., they may be further split or retain their identity in later versions. Yuan [116] comments on a negative aspect of this model: during fragmentation ''*geometrical and topological relationships among STC units change and the whole database, both spatial objects and attribute tables, needs to be re-organized*''.

Other researchers approached the storage problem using the object-oriented paradigm. Ramachandran et al. [80], for example, describe a generic object-oriented data structure for spatio-temporal information. This is basically the implementation of the temporal change object (TCObject) data model, in which real world entities are treated as objects that encapsulate the change component by embedding past, present and future states within the objects. Past and future states (TCState objects) are temporally ordered chains, each with its own lifespan and corresponding spatial and aspatial attributes, while the present is represented by a single state object. In addition, operations for creation, change and display are implemented locally for each object type. Unfortunately, the system cannot be integrated with most existing GIS, mainly due to their proprietary nature. It is therefore structured as a tool box that is interactively used for creating, entering details of, and generally manipulating new object classes. Because of this genericity, the model can be extended to a wide variety of application domains, such as medical and legal information systems, marketing and sales applications and CAD. Another object-oriented implementation for bi-temporal spatial objects is given in [109]. Through the example of an imaginary bypass development, two possible implementations are discussed, the coupling of time and space at the spatial primitives (in this case, point, string, node, chain and polygon) level or at point level only; with propagation of the temporal element upwards for other spatial elements. In the first instance, a temporal chain would be the combination of a chain and a bi-temporal period (set of time intervals), in the other it would be subclassed from the basic bi-temporal point class. Both approaches have been implemented, the first using the Smallworld GIS, while the second in Megalog/Eclipse.

A different, novel approach is presented by Teraoka et al. [98], who describe a data structure for spatio-temporal data based on multi-dimensional persistent search trees. Initially, three conventional spatial data structures are investigated to manage spatio-temporal data with respect to storage requirements, search efficiency and dynamic data handling. The structures examined include a multiple tree approach that stores every version as a distinct tree, a single tree approach, and multi-dimensional approach that stores N-dimensional data as $N + 1$-D to include time. As a result, an extension to the existing Persistent Search Tree, *q.v.* [90], is defined that combines the desirable properties of the other possible methods. These include fast spatial and spatio-temporal searches, the ability to handle dynamic temporal data, and avoiding the storage of redundant spatial information.

Finally, Peuquet and Duan [74] outline an event-chain data structure in their Event-based Spatio Temporal Data Model (ESTDM). ESTDM uses a chain of events, the event vector, to model changes in raster-based thematic maps. Each chain represents the evolution of a single thematic layer of a given geographic area over time. The header of the chain contains identification information for the thematic domain and geographic area, a pointer to the initial stage of the full map, the starting date, as well as two pointers to the first and last elements of the event list. Each event has an associated date, pointers to the next and previous (if any) elements of the list, as well as a list of pointers to event ''components'', i.e., areas of the map where change has occurred. Each component has a single thematic value associated with (x, y) coordinate pairs, whose attribute change to the value. A form of compression is used to avoid storage of unnecessary data points, taking advantage of the fact that change normally effects contiguous areas. A number of (x, y_1, y_2) triplets describe strips of the changed grid in the following fashion: if, for example, the same new value appears in points $(0, 0)$, $(0, 1)$, ..., $(0, 5)$, the triplet $(0, 0, 5)$ is saved in the component. This new data structure helps to speed up answering a range of temporal queries, and has favorable storage requirements as opposed to full storage of map layers (snapshots). Future extensions of the data model should target the representation of changes in a vector-based fashion. This, however, constitutes additional challenges due to preservation concerns of topological relationships.

4.3. Visualization

In order to present the contents of the data collection or the results of queries, most modern database systems provide the user with visualization tools. Some of the standard tools for spatial database systems include browsers, plotters and map displays. Most of these, however, are poorly adapted to display dynamic and/or temporal information. Therefore, alternative graphical presentational techniques must be investigated to successfully communicate geographical processes.

To establish guidelines for spatio-temporal visualization, we must first determine our expectations and goals. To this extent, Kraak and MacEachren [57] review aspects of visualizing dynamic processes. Augmenting an existing definition, they define a temporal map as ''*a representation or abstraction of changes in geographic reality: a tool (that is* *visual, digital or tactile) for presenting geographical information whose locational and/or attribute components change over time*''. In addition, they detail six dynamic visual variables for use in dynamic maps to complement existing static ones: display date, the time at which some display change is initiated; duration, the time between two separate states; frequency, the number of identifiable states per unit time; order, the sequence of frames; rate of change, the difference in magnitude of change per unit time for each of a sequence of frames; and synchronization, the temporal correspondence of two or more time series. They also present several earlier classification attempts for temporal maps. Muehrcke [70], for example, divides them into four categories: maps showing qualitative, quantitative and composite change, and space-time ratios. Monmonier [69] uses dance maps, chess maps and change maps to visualize time series data. Koussoulakou and Kraak [56] distinguish between three distinct methods for displaying processes: *static maps*, with the temporal component transcribed graphically by means of variables, *series of static maps* of progressive time slices, and *animated maps* where change is observed through real movement on the map itself. When testing to evaluate the usefulness of the different methods, there was a significant statistical difference in response time in favor of animated maps. However, the correctness of the results were not influenced. This leads to the conclusion that the utility of animated maps in spatio-temporal visualization is a viable option, while observing that it may not be the best choice in situations where conventional techniques provide a more straight-forward solution. Underlining this observation, Asproth et al. [10] also note the need to present dynamic information, such as traffic flow on a static street map. In their case, it is important to do this in a way where variations can be easily perceived by the human eye. They therefore distinguish between real time and presentation time, the latter being a function of the observation interval and the picture rate, thus enabling the user to follow a course of events by either slowing down or accelerating the display of individual frames. Various methods for doing so are proposed. Missing observations can disrupt the fluidity of the presentation, therefore, if possible, they should be estimated using one of several available techniques. The concept of a stream, *q.v.* [9], is chosen to model the atomic element of dynamic information, with properties such as quantity, rate, acceleration/retardation, and start- and endpoints. Streams then can be combined into hierarchies such as chains or networks. For management purposes, several base and temporal functions are also outlined. In another paper, Herbert and Kidner [43] present two methods for visualizing spatial data taken at different times. Spatial information is obtained about a geographical site by mapping the contours of two-dimensional sections of the site at various heights (depths). A three-dimensional graphical site image can then be reconstructed using existing methods for correspondence, tiling/branching and surface fitting. A sub-problem of this reconstruction is finding the best set of triangulated facets to define the surface connecting contours, known as the tiling problem. Two approaches for this are discussed, the contour-level method and the section-level method, which are then employed to deduce new contour sets. This is done by interpolating two existing models, taken at different times but of sections of the same heights (depths). By examining reconstructed and deduced images over a period of time and observing the rate of change to the site, effects to the site can be predicted helping to plan for future management.

Some of the other efforts concentrate on giving users the ability to communicate with the display in a language form. Holmberg [45], for example, extends the Classical Map Language (CML) with dynamic variables to handle dynamic features in a map. The standard visual variables in CML, size, value, color, texture, grain, shape and orientation, which may be associated with complex map symbols made up from the basic point, line and area symbols, are complemented with dynamic properties for movement, oscillation, pulsation and rotation to form the Dynamic Map Language (DML). Provided with these new properties, dynamic symbols can vary in speed, frequency, amplitude, the number of levels, and rotation and display frequency. A further discussion on dynamic variables is proposed as part of an international standardizing effort, as a possible step towards multimedia GIS. Trepied [99] also discusses language feasibility and states that to end users of GIS, non-textual languages may prove to be the most useful for querying purposes. The alternatives, natural languages and artificial languages (e.g., SQL) are considered either too difficult to research or poorly adapted to the user. Among the different kinds of non-textual languages (form based, graphical, visual and hypermap), visual languages are investigated and some limitations are outlined. To provide a solution to some of the limitations, he proposes the use of dynamic icons. They are able to represent spatio-temporal point, line and region type objects and can change shape, size and color, move, disappear or be combined with other icons to fully depict the temporal processes in the environment. Each icon consists of a sign (stylized drawing), some text describing the spatio-temporal object it represents and its temporal location, a frame with boundary lines and interior, a color to make object type identification easier, and a screen location which assists in the determination of topological relationships between objects. The result is more intuitive database schema/query expression/result visualization, uniform handling of spatial and non-spatial objects, and the visualization of the dynamic aspects of geographical processes.

Approaching the problem from a more application-oriented point of view, Slocum et al. [93] commit to the development of a prototype visualization system. According to them, three different approaches are currently available to users to visualize, highlight and compare time series (dynamic) data: utilizing separate software packages for individual tasks, developing a library of tools with a development kit, or using a single specific exploration package designed for these purposes. Unfortunately, none of these approaches provide a satisfactory solution. The first approach is very time consuming, the second requires (often advanced) programming skills, while in the third category there is still no system capable of satisfying all user requirements. Their proposed software will fill this gap. Its additional features are the support for different data and map types, and the availability of animation and ''*small multiples*'' (the display of individual frames of animation simultaneously on screen). In addition, comparison of two maps at the same time, graphical, statistical and tabular displays of data are permitted, as well as ''pure'' data queries as opposed to only visual ones. In order to achieve the best results, the system, the graphical user interface, and the set of tools incorporated is to be tested according to the 'participatory design', which means that potential users provide feedback throughout the development process.

5. Systems

Fully developed Spatio-Temporal Information Systems (STIS) are becoming a reality with the development of new spatio-temporal data models and the availability of raw computing power and cheap storage media. Existing systems already demonstrate features that surpass those provided by most traditional spatial information systems; examples for this are the ability to integrate multiple data formats, extended analytical capabilities and enhanced visualization of queries and database contents. Most of these systems are temporal extensions of existing GIS, although some projects center on specifically designed scientific databases. At the other end of the scale, we find tool sets aimed at providing generic tools for quickly producing specific spatio-temporal applications.

5.1. GIS extensions

Temporal extensions of existing GIS generally aim to provide functionality to handle time from a specific perspective. Thus, most of these extensions are designed to solve a given application specific problem. Indiana Dunes National Lakeshore, for example, uses historical water quality data in their GRASS (Geographic Resources Analysis Support System) GIS to analyze spatial and temporal water quality parameters, such as chloride concentrations in lakeshore groundwater [100]. Data dating back to 1931 is converted to formats for use in ATLAS*GRAPHICS, a desktop mapping program, that is capable of quickly displaying simple queries on water quality details. A further conversion to GRASS provides more analytical power via its built-in hypothesis testing tools. In another example, Yates and Crissman [112] describe the SIIASA spatio- temporal database containing historical local administrative boundaries of East, Southeast and South Asian countries. The database uses Langran's space-time composite model [61] for temporal spatial data, while a versioning method exists for temporal aspatial data. Several existing GIS software products, including ARC/INFO, MGE and MapInfo can serve as the base for the SIIASA database. Also building on results found in the research literature, Joerin and Claramunt [48] detail the theories behind their prototype system for assessing the agricultural impact of floods. Damage caused to crops depends on the duration of submersion in water and the state of plant growth at the time of flood. This crop sensitivity follows a re-occurring cycle: it evolves during the four periods of a crop season, winter, agricultural activities, harvesting and sowing. Crops may vary from season to season (they follow rotations to preserve soil quality), but the basic structure of a season remains the same, although the durations and starting dates of its periods may change in each cycle. Whigham's ''*hierarchy of events*'' is elected to model this cycle, *q.v.* [105], with Rolland et al.'s [84] dynamic conceptual approach employed to describe the appropriate update operations to take when events occur. Three events are modeled this way: the rotation of crops, the regular update of crop sensitivity and the action to be taken after flood occurs. In their implementation, an attribute-versioned parcel table is updated by the first type of events using a separate table that stores crop rotation rules, while crop sensitivity is table-versioned, retaining only the latest information after update is initiated at regular intervals.

Some of the other systems go beyond of just adding temporal functionality to their features. Halls et al. [39], for instance, have developed a system for urban growth analysis from multiple data sources. The goal is to forecast future growth patterns with respect to specific requirements as well as to determine the point at which land saturation has taken place. Land use/land cover, multispectral imagery, census block count and building permit information have been integrated using ARC/INFO to analyze spatio- temporal data and provide predictions in multiple output formats. Also using data from several sources, Turkstra [101] describes a system developed to study spatio-temporal land value behavior. The subject of the study is a medium-sized Colombian town, where land values are recognized to be influenced by such factors as location, access to major roads, neighborhood status, availability of infrastructure and legal aspects. Therefore, the system uses a structure that integrates data from different sources, including land use, value, cadastral records and census data recorded over a period of time.

Non-application specific solutions also exist. The TEMPEST temporal GIS prototype is described in [73]. It uses a time-based approach to create a tool for the analysis of spatio-temporal dynamics. It incorporates all necessary temporal operators for topological relationships, combination and generalization, while leaving the spatial capabilities to be handled by a shell that interfaces another, conventional GIS. Hence, time-based representation is directly supported within the system, while raster- and vector- based spatial data originates from and is saved to an external GIS. Access is provided via a graphical user interface which offers flexibility, easy modification of the prototype and visual layout of the system components. Another example, OOgeomorph is an object-oriented implementation of a multi-dimensional GIS [81]. Its approach follows a ''layered'' philosophy in that it is a system that is separate from, but is built on an existing GIS storing the actual data. A new class structure, ''geomorph_system'' stores the geomorphological representation, while another, ''geomorph_info'' enables the matching of the stored data with the representation. Time, however, is implemented as valid time only, thus making the system four dimensional in total.

5.2. *Scientific databases*

Another particular application group where spatio-temporal information plays an important part is scientific databases. Vast amounts of data are available for researchers in fields such as environmental studies, and thus there is a need to efficiently store, access and analyze this information. One of the most studied problems currently is global change, and several systems have been built specifically to investigate this issue. Beller et al. [14] describe one such prototype system, which is an object-oriented tool set interfacing a conventional GIS (Genamap) that stores raw satellite-derived vegetation index data with temperature and precipitation information for a selected study area. The additional capabilities the system provides include temporal database management built on the Temporal Map Set (TMS) concept [13]; temporal interpolation methods to provide continuity within a TMS even though only a limited number of time slices may be available; the ability to transform existing TMSs into new ones; the use of animation to visualize temporal data; the ''event'' concept to enable investigation of causal relationships between objects; and the provision of export/import routines to interface external statistical and modeling packages to further investigate the processed data sets. Hachem et al. [38] detail GAEA, which is another object-oriented scientific database management system for global change research. Project data for global warming, the greenhouse effect, acid rain, the ozone hole and tropical deforestation necessitate the ability to integrate data of multiple formats. In addition, to facilitate the need for complex scientific analysis and to cater for future needs, the system includes sophisticated analytical tools integrated within the database manager, and an operator set that is interactively extensible by the user. Spatial and temporal analysis capabilities, visual queries, distributivity due to database size and the locational spread of data sources, and the ability to track the processing steps and source of raw data are also features of GAEA. Data objects possess three dimensions: spatial, temporal and type, the latter defining the operators available for the particular object. The components of the database comprise the Graphical User Interface that handles user interaction, the Spatio-temporal Object Database (STODB) that stores the data objects, the Query/Analysis Processor that responds to queries, the set of Current Objects of Interest, which contains the workspace with data that may or may not eventually be inserted into the STODB, the Entry Processor that converts input data into the native format of the system, Entry Operators that describe the transformations taken during the conversion process, the Operator Object Base (OOB) containing available operators for scientific analysis, and the Operators Editor to create new or update existing operators in the OOB. Some of these operators are programmed for merging, conversion, editing, and selecting data, others are used for prediction (extrapolation in time), quantitative statistical analysis, comparisons, displays, and the calibration and checking for consistency and sensitivity of the data.

Developed for other scientific reasons, Muntz et al. [71] report on the progress of the QUEST (QUEries over Space and Time) project. QUEST is a prototype system built to serve as a testbed for ''*validating various techniques and demonstrating the feasibility and benefits of building information systems for atmospheric and earth science databases*''. In particular, cyclone detection and tracking is of interest. System components include a graphical user interface, a database manager, a visualization manager implemented in IDL for plotting, animating and analyzing data, and a query manager. After cyclone information is extracted from a generated synthetic data set, it is placed in the information collection (a POSTGRES database) in a flat relational format. LDL++ [119], a deductive database system is chosen to manage complex spatio-temporal queries because of its extensibility, rapid prototyping and advanced query processing capabilities. It provides additional reasoning power to that found in POSTGRES, which is used as a ''pre-processor'' to LDL++ queries. LDL++ is also preferred over traditional temporal query languages, because the latter normally require data to be stored in their own native format as opposed to the flat relational table used in POSTGRES. In addition, LDL++ offers a new dimension: querying using a rule based approach. The Event Pattern Language (EPL) has been developed on it, which utilizes event tables derived from the original cyclone relation allowing nested, recursive queries to further enhance analytical power.

5.3. Tool sets

Producing applications that address individual needs can be approached from a higher level, utilizing ready-built tool sets that allow the rapid creation of particular systems. As an example, Story and Worboys [96] describe a design support environment prototype for building spatio-temporal database applications, implemented by temporally extending the CASE tool of the commercially available Smallworld GIS. Temporality is introduced through the definition of several new classes (temporal, event modeling, parallel state and auxiliary), and is integrated at several levels. Thus, the developer is provided with the ability to define the temporal domain of an application, select from a variety of temporal classes, associate these classes to application classes at any level and test out the model hence defined. Brown et al. [17], on the other hand, describe a visualization extension tool set for the Geographic Resources Analysis Support System (GRASS) to enable analysis and simulation of spatio-temporal processes. GRASS is an open, extensible system placed in the public domain, possessing full GIS capabilities, but limited in its display abilities. Multi-dimensional dynamic cartography (MDC) is an approach that recognizes that GIS must be integrated with tools to visualize dynamic 3-D data and processes, using animation and data exploration techniques at the ''operational'' level. This means, that unlike simple data sharing and exchange between database and visualization tool, data consistency is provided by coordinate-system transformations, cross validations and the tailoring of visualization tools to spatial data characteristics. The implementation of the MDC environment requires the addition of new data types and algorithms to GRASS. To demonstrate these new capabilities, Mitasova et al. [68] give two examples of spatio-temporal analysis. The first example examines spatial and temporal distributions of soil erosion in a development area by generating a series of raster maps for soil loss scenarios in the course of a year. Spatial distribution maps prove useful in identifying regions least susceptible to erosion, while temporal analysis shows time-frames for intensive use not to coincide with periods of high rainfall. The second example uses time series data obtained on nitrogen concentrations in water levels. With time treated as the fourth axis, multi-variate spline interpolation is used to visualize the dynamics of nitrogen level distributions over time using animation.

6. Issues

In previous sections, we looked at modeling and database aspects of spatio-temporal information. In addition to these considerations, several other issues need to be addressed in order to ensure full functionality and user support within spatio-temporal systems. Among these, we consider the question of system implementation, the smooth transition from traditional SIS to Spatio-Temporal Information Systems, ensuring data quality and finding alternative means of exploring the resulting large data sets some of important issues.

Database issues. Spatial databases inherently contain large amounts of information about the environment. Temporal information in STIS, even with no data redundancy, further increases the database size. Storage costs of this data, even on inexpensive media, may become unmanageable to users. A solution to this problem could be the design of new, innovative data structures with minimal storage requirements. Distributed systems could also enable cost-sharing within or inter-organizations, as well as accommodating user data needs by storing information at locations where it is used the most. Another of the problems presented by database size is the increased difficulty of rapid data retrieval. Fast access to information through improved indexing methods is essential in making a spatio-temporal information system operational. We have seen examples of modified spatial indexing techniques for this purpose, further are expected in the future. Another important aspect of spatio-temporal information is the need for strong analytical capabilities. This requires advanced querying, visualization and analytical reasoning abilities integrated within the Database Management System, optimized for the native data types of the system. These can be quite diverse, as STIS generally need to be able to integrate multiple-format data. In the absence of a ''universal'' spatio-temporal model, it is unclear at this stage how all this will be achieved. Indeed, it is unlikely that an all encompassing model will cater for all individual requirements. Thus we could either settle for integrating models to co-exist in one system, or optimizing each system for their application specific needs.

Architectural types. Three different architectures for spatial information systems are described in [36]. The first, *dual* architecture handles spatial and aspatial data in two separate subsystems, being often of proprietary nature, with an integration layer handling communication between the subsystems. The second, *layered* architecture is implemented on top of an existing DBMS, with spatial operators added as another layer to operate on the spatial data types. *Integrated* architectures provide extensible relational or object-oriented database management capabilities on which spatial data types are defined. Querying is hence directly supported by the DBMS. This latter architecture supports extensions for the time dimension as well, thus it could be preferred for STIS. The former two architectures can still be used: by either developing a triad architecture with a temporal subsystem or layering spatial data types on a Temporal DBMS. We must also consider difficulties arising from database size. Developing architectures suited for parallel, distributed, or some other form of non-linear machine organization can help solving this problem.

Legacy systems. If and when a spatio-temporal information system comes into existence to replace an old, possibly outdated SIS, problems may arise due to the incompatibility of data formats. The contents of the old system are clearly essential as a data source. The question that arises then, is how to format/migrate the old to the new system, if that is at all possible. If it is not, then how to ''bridge'' the gap between the two systems presented by the lack of initial data in the new system. A possible solution to this problem is to build new STIS on existing SIS, i.e., making available spatial information systems temporal. We have seen examples for this approach earlier in the Systems section. This can, however, constitute a step backwards, by limiting the design of the new system. Some form of co-existence may be the other solution, with the old system supplying data to the new until it can be phased out and the new can replace it. Another alternative may be utilization of a data warehouse that also offers the benefit of enabling several of these legacy systems to be incorporated in a data-supply role. Investigating this possibility is, however, outside the scope of this paper, as one of the requirements of a data warehouse is the ''cleanness'' of the data, which might be a problem (see the Data Quality section below).

Data mining. Interactive, user defined querying of large information bases are often very specific, displaying derived data or looking for the existence of expected patterns. Some may be semi-automated, e.g., with the use of deductive databases, by triggering actions when certain conditions are fulfilled. An example for this could be the recognition of cyclone formation in a sequence of images. Large databases, however, often contain unexpected information that is not necessarily explicitly recorded or is searched for by user queries. The extraction of such implicit data or rules about data belong to the field of knowledge discovery and data mining. For an introduction to this field, see [40], [79], or refer to the monographs [28], [75]. Its utility has been investigated in spatial databases [55], but remains unexamined for spatio-temporal information. Adding the temporal element, two kinds of new rules can be discovered from STIS: spatio-temporal *evolution rules* that describe processes or state changes of objects over time, and spatio-temporal *meta- rules* [2] or rules about rules, which describe changes between two rule-sets generated for static snapshot states of the database. In addition, the application of ''standard'' data mining techniques, such as generalization, classification and association can provide additional insights into data, and is an interesting research area [3].

Data quality. Geographic information captured in digital form contains uncertainty in several ways. They stem from data measurement errors during recording, the discrete representation of numbers in computers, or simply from difficulties in the identification of geographic objects/phenomena at the time of measurement. Imprecision manifests itself in geometrical as well as topological data, as the latter is normally derived from geometric information [106]. Clearly, the temporal dimension further complicates matters. However, existing methods to resolve imprecision problems, such as visualization, simulation and statistical (probabilistic) procedures could be employed in the same fashion as in the treatment of spatial imprecision, since explicit timestamps in the database are similar to stored geometric data, while implicit temporal data (e.g., before, during) resemble topological relationships.

Data quality depends on a variety of factors: the data gathering mechanism (sensors), the derivation method in the case of inter- and extrapolation, and the variability of the data itself [104]. Visualization may provide an insight into spatio-temporal data quality. For example, Ward and Zheng [104] use five variables for the three spatial dimensions, time and quality on a display screen. Incomplete or contradictory information in registered data also poses a problem. The latter may be alleviated by applying integrity constraints on the contents of the database. Such constraints, e.g., in the form of rules, may be either specified by domain experts or can be automatically generated by data mining algorithms on previously recorded data.

7. Conclusion

Spatio-Temporal Information Systems improve on existing spatial information systems by handling temporal information. Past, present and future states of the modeled environment in one system make the incorporation of new features possible to surpass current SIS capabilities. In particular, enhanced analytical power, process visualization and data integration are worth mentioning. Multiple source information allows the investigation of causal relationships between different factors affecting our surroundings. The presence of temporal data is important in this process, because with a potential time gap between cause and effect, both may not be present in a non-temporal database at the same time. Temporal extrapolation, or future trends analysis based on historic data, also benefits many application areas. Additionally, previously unknown regularities in the data could be discovered using data mining techniques to complement the reasoning power of our STIS.

It is clear, however, that many issues remain to be resolved before these systems become commercially viable. Most existing prototype systems are extensions of existing spatial systems, with only a few built from the ground up. Even these systems are for mainly specific purposes (such as global change research), although they do incorporate some of the basic additional features a STIS must possess. It is unclear if a generic spatio-temporal information system will be commonly used, but the idea of an extensible system tailorable to different needs could provide a common frame of reference in working towards a multi-purpose platform. Before this happens, numerous database issues, including the incorporation of different models, legacy data, indexing, data storage, querying, etc. need to be investigated. The initiative has already been taken by the academia and some corporations and research organizations. The National Center for Geographic Information and Analysis (NCGIA), for example, sponsors research on temporal GIS [26], [27]. Several other organizations have also enrolled and provide financial incentives to researchers of the field. Large database providers have also realized the potential and now include abstract spatial data types in packages such as Oracle and Informix. Perhaps a tighter coordination between the spatial, spatio-temporal and temporal database communities could provide that extra element of effort that is needed to work towards a standard and the underlying mathematical formalisms.

Notes

1. Data redundancy in the snapshot model may not always be a problem. With the cyclone example in QUEST in the Systems section, we see that this is not the case, because a cyclone is a continuously evolving phenomenon and the recording granularity used is large enough to always register significant change.
2. A free event is an event that does not have an associated fixed tesseral address, as opposed to a referenced one.

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