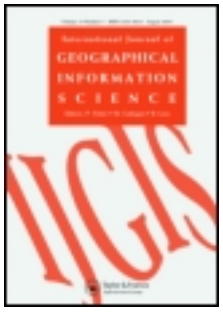
This article was downloaded by: [University of California Santa Barbara]
On: 01 April 2012, At: 15:37
Publisher: Taylor & Francis
Informa Ltd Registered in England and Wales Registered Number: 1072954 Registered office: Mortimer House, 37-41 Mortimer Street, London W1T 3JH, UK



International Journal of Geographical Information Science

Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tgis20

EDGIS: a dynamic GIS based on space time points

Edward Pultar [a], Thomas J. Cova [a], May Yuan [b] & Michael F. Goodchild [c]

[a] Department of Geography, University of Utah, Salt Lake City, UT, USA

[b] Department of Geography, University of Oklahoma, Norman, OH, USA

[c] Department of Geography, University of California, Santa Barbara, CA, USA

Available online: 10 Mar 2010

To cite this article: Edward Pultar, Thomas J. Cova, May Yuan & Michael F. Goodchild (2010): EDGIS: a dynamic GIS based on space time points, International Journal of Geographical Information Science, 24:3, 329-346

To link to this article: http://dx.doi.org/10.1080/13658810802644567

PLEASE SCROLL DOWN FOR ARTICLE

Full terms and conditions of use: http://www.tandfonline.com/page/terms-and-conditions

This article may be used for research, teaching, and private study purposes. Any substantial or systematic reproduction, redistribution, reselling, loan, sub-licensing, systematic supply, or distribution in any form to anyone is expressly forbidden.

The publisher does not give any warranty express or implied or make any representation that the contents will be complete or accurate or up to date. The accuracy of any instructions, formulae, and drug doses should be independently verified with primary sources. The publisher shall not be liable for any loss, actions, claims, proceedings, demand, or costs or damages whatsoever or howsoever caused arising directly or indirectly in connection with or arising out of the use of this material.

International Journal of Geographical Information Science
Vol. 24, No. 3, March 2010, 329–346

Taylor & Francis
Taylor & Francis Group

EDGIS: a dynamic GIS based on space time points

Edward Pultar[a,]*, Thomas J. Cova[a], May Yuan[b] and Michael F. Goodchild[c]

[a]*Department of Geography, University of Utah, Salt Lake City, UT, USA;* [b]*Department of Geography, University of Oklahoma, Norman, OH, USA;* [c]*Department of Geography, University of California, Santa Barbara, CA, USA*

(*Received 12 November 2007; final version received 16 November 2008*)

Contemporary GIS can handle static spatial data for querying and visual representation, but the temporal dimension remains a challenge. This paper addresses the need for a dynamic GIS capable of managing complex data types. The design relies on a representation of the theoretical spatiotemporal primitive known as the 'geo-atom'. This paper proposes a novel and implemented data structure called the space time point (STP) built on this theory. With the STP representation, spatiotemporal data queries can be posed to return useful results about dynamic geographic phenomena and their interaction. Two key challenges addressed in this research are (1) data structures to represent hybrid (object and field) spatiotemporal phenomena and (2) the design of a dynamic GIS interface. These challenges are addressed by the implementation of the system, referred to as 'Extended Dynamic GIS (EDGIS)', that uses the proposed STPs. The EDGIS system is described from theory to its implementation in Java™ and a series of application examples are described followed by performance metrics. The paper concludes with a discussion of areas for further research such as integration of the system with geo-sensor networks, hazards, transportation, and location-based services (LBS).

Keywords: dynamic; spatiotemporal; GIS

Downloaded by [University of California Santa Barbara] at 15:37 01 April 2012

1. Introduction

Contemporary GIS can handle static spatial data for querying and visual representation, but the temporal dimension remains a challenge. Although spatiotemporal data modeling has been researched for over 20 years (Frank *et al*. 1992, Peuquet 2000, Yuan and McIntosh 2002, Albrecht 2005, Miller 2005, O'Sullivan 2005, Reitsma and Albrecht 2005), new forms of dynamic geographic data collection are increasing the importance of this research area. These collection techniques include geo-sensor networks (Stefanidis and Nittel 2004), mobile GIS (Tsou 2004), and unmanned aerial vehicles (Bone and Bolkcom 2004). Commercial GIS products are now available to handle moving points and yet they lack many dynamic GIS capabilities associated with more complex representations such as moving polygons with changing shape and internal attribute variation. In general, despite the great need for a dynamic GIS that can handle complex spatiotemporal representation and queries, there is still no available solution that can handle the variety of spatiotemporal circumstances.

This paper addresses the need for a dynamic GIS capable of managing complex data types. The design relies on a theoretical representation of spatiotemporal data known as the

*Corresponding author. Email: Edward@EdwardPultar.com

ISSN 1365-8816 print/ISSN 1362-3087 online
© 2010 Taylor & Francis
DOI: 10.1080/13658810802644567
http://www.informaworld.com

'geo-atom' (Goodchild *et al.* 2007). For real-world implementation purposes the space time point (STP) is introduced which is based on the theory of the geo-atom. STPs are more fundamental than objects or fields and represent a key element of either. In other words, both discrete and continuous phenomena, along with their changes through time, can be represented using the STP approach. Galton (2004) refers to this class of geographic representation as a 'hybrid' approach. Once geographic phenomena are represented in this way, spatiotemporal questions can be answered about relationships between objects and fields regarding location, time, and attributes (Yuan and McIntosh 2002).

Data models and associated data structures to represent hybrid spatiotemporal phenomena are a key research challenge (Galton 2004). There are many temporal theories, methods, and models (Langran 1992, Worboys 1994, Yuan 1996, Hornsby and Egenhofer 2000, Peuquet 2002, Grenon and Smith 2004, Mennis *et al.* 2005), but more research is needed on data structures and associated operations in the context of a dynamic hybrid GIS. Designing data structures raises challenging issues in query efficiency and storage space that are rarely discussed in temporal theory and modeling (Peuquet and Duan 1995). The geographic complexity of reality demands novel spatiotemporal data models that go beyond simple concepts of space and time to capture geographic dynamics.

Another key challenge in this area is interface design. Although elegant interface designs have been proposed for static GIS analysis (Richards and Egenhofer 1995), there are few examples of proposed interfaces for interacting with a dynamic GIS. Peuquet (2001) notes that current GIS do not support a common interface for spatiotemporal databases capable of supporting both object and field views. This paper proposes a *time slider* approach for providing the user with an easy approach to stepping forward or backward through time. This interface can be used to answer questions pertaining to object-to-object, object-to-field, and field-to-field relationships. Thus, the STP approach provides a user with the power to adopt both object and field representations of geographic data phenomena and examine their relationships over time (Yuan 2001, Cova and Goodchild 2002).

The purpose of this paper is to describe the design of a hybrid dynamic GIS with a particular focus on data structures to facilitate implementation as well as an associated dynamic GIS interface. The approach is based on organizing STPs into objects and fields in both space and time to support 'hybrid' dynamic GIS queries (Galton 2004). The next section provides background on dynamic GIS research. Section 3 presents the design of a dynamic GIS based on the concept of an STP. The fourth section discusses applications and *use cases* of dynamic GIS including an implementation created in Java™. Section 5 presents performance metrics of the implementation involving computation time and space. The paper concludes with a discussion of areas for further research.

2. Dynamic GIS

Many approaches to representing spatiotemporal geographical phenomena have been presented including the snapshot method, event-based models, moving object databases, and object-oriented models (Peuquet 2001, Frank 2003, Albrecht 2005, Güting and Schneider 2005, O'Sullivan 2005). The snapshot method represents spatiotemporal data using a 'world state' grid file for each point in time (Peuquet 2001). The event-based spatiotemporal data model (ESTDM) is a raster-based model that stores changes through time as events (Peuquet and Duan 1995). Yuan (1996) uses a model that splits spatiotemporal data into the three separate domains: (1) semantic, (2) spatial, and (3) temporal. Moving-object databases model moving points and regions in a database and implement efficient query algorithms (Wolfson *et al.* 1998, Güting and Schneider 2005). Approaches have also been proposed that

Downloaded by [University of California Santa Barbara] at 15:37 01 April 2012

adopt the object-oriented programming paradigm from computer science (Worboys 1994, Raper and Livingstone 1995).

Representing time presents one fundamental challenge in temporal GIS. Worboys and Duckham (2005) propose several ways to represent time in a GIS. The concept of time in this world can be seen moving forward in a linear fashion for some geographical features while for others it moves in a cyclical fashion. Linear-time phenomena do not repeat at any interval (e.g., earthquake, storm, traffic accident), whereas cyclical phenomena repeat on some interval (e.g., daily, decadal, and seasonal). Worboys and Duckham (2005) also describe the distinction between transaction time and valid time, which denotes the difference between when an event happened versus when it was recorded in a database.

Once spatiotemporal data can be represented and stored efficiently there is the need to ask questions about the information. The challenge, importance, and uniqueness of querying spatiotemporal data have led to research on a typology of spatiotemporal information queries (Yuan and McIntosh 2002). Spatiotemporal queries can answer questions about attributes (what), location (where), time (when), and change (how). Yuan denotes the following classes and types of queries: one attribute query, three types of spatial queries, three types of temporal queries, and four types of spatiotemporal queries. Current GIS are able to answer attribute queries and spatial queries, but queries containing the time dimension are still a research topic. The classification of the types of queries provides a goal to work toward in spatiotemporal GIS research. Some of the most complex queries Yuan discusses combine both space and time in a question:

- Simple spatiotemporal query (Where was feature F at time T?)
- Spatiotemporal range query (How much of land L has changed from type A to type B in the last *T* years?)
- Spatiotemporal behavior query (How did the values *V* change during event E?)
- Spatiotemporal relationship query (Where and when will land L experience a flood during a hurricane?)

Many spatiotemporal queries require clear identifications of the objects of interest. Hornsby and Egenhofer (2000) describe identity-based change, which is important for distinguishing unique spatiotemporal objects in a dynamic GIS. Grenon and Smith (2004) provide a spatiotemporal ontology of entities and their relationships in reality. Spatiotemporal helixes have also been presented to illustrate the movement and change of an object over time (Stefanidis *et al.* 2003). Future research is likely to provide new spatiotemporal data models, theories, and concepts along with refinements of those previously proposed, but there is also a need to develop new GIS designs, data structures, and interfaces if dynamic GIS is to be a reality on the desktop.

3. Dynamic GIS design

3.1. Formalizing dynamic geographic representation

This section presents a new method for implementing a dynamic GIS built on a fundamental concept referred to as a geo-atom (Goodchild *et al.* 2007). They are defined by their location, attributes, and time and can be formalized as the tuple:

$$<\mathbf{x}, Z, z(\mathbf{x})> \quad (1)$$

Downloaded by [University of California Santa Barbara] at 15:37 01 April 2012

where **x** is a vector that defines a point in space-time (e.g., a four-dimensional point with $<x, y, z, t>$ values), Z is an attribute or property, and $z(\mathbf{x})$ is the specific attribute value at that point in space-time for the attribute Z.

With the geo-atom theory an object can contain an infinite amount of geo-atoms. For real-world implementation purposes this is not possible since a computer's memory is finite. Thus the STP is created and defined as the tuple:

$$<\mathbf{x}, Z, z(\mathbf{x})> \tag{2}$$

where **x** is a vector that defines a point in space-time (e.g., a four-dimensional point with $<x, y, z, t>$ values), Z is a set of attributes or properties, and $z(\mathbf{x})$ is the set of specific attribute values at that point in space-time for the associated attribute Z.

Here Z and $z(\mathbf{x})$ are sets and can contain multiple attributes for one STP. For example, an STP may represent a weather station and have multiple attributes and values such as temperature, precipitation, and elevation. The STP lends itself more to an implementable proof-of-concept prototype capable of storing, querying, and visualizing a variety of spatiotemporal information. STPs can be viewed as a building block for representing both objects and fields over time. STPs can be organized into temporal fields given one STP at each location with dynamic attributes, or alternatively, a set of STPs can be aggregated in space and time to form the basis for an object with unique identity that may or may not be contiguous in space or continuous in time. Fields may have holes in space or time, moving objects can have a dynamic boundary and internal field-like variation (Yuan 2001), objects can merge or split (Hornsby and Egenhofer 2000), along with many other concepts presented in the spatiotemporal literature, but all of this can be built on the fundamental element of an STP.

The goal of this research is to develop a dynamic GIS based on the concept of an STP. The objectives include the following:

(1) Develop a dynamic GIS based on organizing STPs into fields or objects with ascribed identity.
(2) Develop new data structures for STPs and associated algorithms to support the rapid query and retrieval of STP-based dynamic geographic representations.
(3) Design a novel and intuitive dynamic GIS interface that is easy to use.

3.2. Conceptual and logical design

Figure 1 shows an abstract view with a conceptual model of the database design and classes using the Unified Modeling Language (UML). Note that the database can contain any number of STPs, features, and themes. At the next level above STPs (Equation (2)) are *features,* that is, a lake, a county's precipitation, a vehicle, or one bird in a flock. A feature is a collection of any number of STPs along with any attributes of the feature like a name or a real extent. Features are defined by their associated STPs as well as the feature's attributes and can be formalized as the tuple:

$$<\mathbf{s}, Z, z(\mathbf{s})> \tag{3}$$

where **s** is a set (Goodchild 1992) of STPs associated with the feature, Z is a set of attributes or properties of the feature, and $z(\mathbf{s})$ is a set of specific attribute values for the feature's corresponding attribute Z, which is based on the STPs composing the feature.

Downloaded by [University of California Santa Barbara] at 15:37 01 April 2012

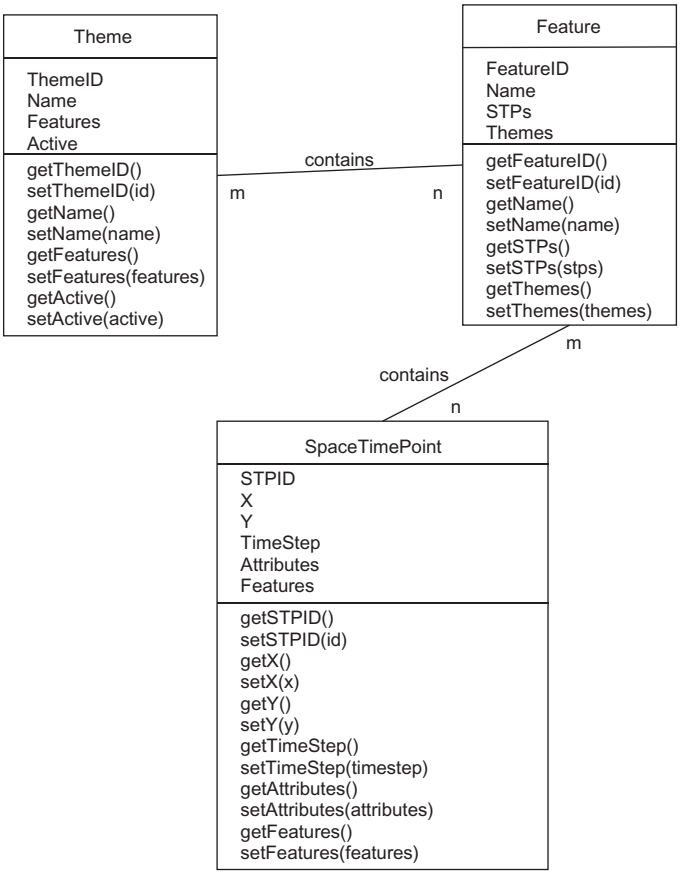


Figure 1. UML diagram of EDGIS classes.

At the highest level in this design are *themes*, which might represent any geographic phenomena including a temperature field, herd of animals, set of lakes, a state's precipitation, storm front, elevation surface, or a mob of pedestrians. A theme is a collection of any number of features as well as the theme's attributes such as a name or number of features. Themes are defined by their associated features as well as the theme's attributes and can be formalized as the tuple:

$$<\mathrm{f}, Z, z(\mathrm{f})> \tag{4}$$

where **f** is a set of features associated with the theme, Z is a set of attributes or properties of the theme, and $z(\mathbf{f})$ is a set of specific attribute values for the theme's corresponding attribute Z, which is based on the features composing the theme.

A theme may contain any number of features and each feature belongs to one or more themes, hence the many-to-many (*M:N*) relationship cardinality of themes to features. At the lowest level are STPs, which are the points in space-time that comprise a feature. Again there is a M:N relationship present, this time between features and STPs, as an STP can be related to one or more features. A theme is therefore a collection of one or more features and a feature a collection of one or more STPs.

Downloaded by [University of California Santa Barbara] at 15:37 01 April 2012

As an example in this context, a basic storm theme (as defined in Equation (4)) may contain multiple storm features (as defined in Equation (3)), each of which can have attributes. The storm features can then contain hundreds (or even thousands) of STPs that may describe a storm's changing extent and internal intensity along with its motion through space and time.

Moving one step closer toward implementation is the logical data model. Figure 2 shows the logical data model, or data structure design, and a table view of how the data are stored. The logical data model is a foundation for the physical data model implemented in a database management system (DBMS). This figure also includes sample data to demonstrate possible representations of real-world geographic phenomena. In this example there is one lake theme containing two lake features. Within these two lake features are their STPs that represent them. Here, one lake is composed of three STPs and the other lake is composed of two.

This paragraph presents an example scenario of STPs that comprise features at three distinct and successive time steps. The temporal granularity is minutes in this example and coordinates of latitude and longitude can represent the space. Initially, the storm feature is composed of seven STPs, each of which contains the feature's storm identity, location, and an attribute representing the severity of the storm at that STP. There are also two car features composed of a single STP each. Each car's STP stores the car's identity, location, and a static attribute describing its color. Using new STPs through time allows change in location, identity, and/or attribute at any time step. For example, the storm feature may gain or lose STPs through time as the storm changes shape or a real extent as the STPs increase or decrease in the attribute representing storm severity. At the same time, each car can move and change speed, but its shape and color remain static. To complete the theme, feature, and STP hierarchy in this example, the storm theme would contain one storm feature and the vehicle theme would contain two car features.

Some geographic phenomena and events can be associated with a duration of time for which they were active. Earthquakes, concerts, and storms are examples of objects that most likely will not have a permanent existence. This concept of duration in an STP implementation can be stored as an attribute of a feature. Another way of acquiring a duration value is to

Theme

ThemeID	*Name*	*Features*	*Active*
0	Uinta Lakes		True

Feature

FeatureID	*Name*	*STPs*	*Themes*
0	Mirror Lake		
1	Red Castle Lake		

Space Time Point

STPID	*X*	*Y*	*TimeStep*	*Attributes*	*Features*
0	154	153	0	101, 305, …	
1	154	154	0	101, 403, …	
2	155	155	1	102, 305, …	
3	86	86	2	103, 306, …	
4	86	87	2	103, 404, …	

Figure 2. EDGIS data structures.

Downloaded by [University of California Santa Barbara] at 15:37 01 April 2012

calculate it using STP time step data for the first and last STPs during which a feature existed. For example, an earthquake feature contains a set of STPs that comprise the earthquake throughout its time of activity. Using these STPs the earthquake duration can be determined by finding the difference between the first and last time step the earthquake was active. This provides two options for handling duration with STPs. Next, a duration attribute for a feature like a wildfire can be used for querying and analysis.

The granularity of time (or temporal zooming, Hornsby 2001) can also be explored with the STP representation. When enough data are provided, different temporal resolutions may be displayed. For example, with data recorded once a year for 100 years a default display would yield 100 time steps if no temporal zooming were used. With a temporal zoom-out, the data could be displayed in time steps of every 10 years yielding 10 total time steps. By using temporal zooming additional geographic trends may become apparent and changes can be more dramatic. Different levels of temporal zooming will result in different visualizations, where the possible levels of temporal zooming are dependent on the data available or some method of temporal interpolation between time steps (Kim and Cova 2006). This could be seconds, minutes, months, or other temporal resolutions.

Downloaded by [University of California Santa Barbara] at 15:37 01 April 2012

3.3. Querying dynamic geographic data

In the proposed representation of geographic data, information exists for each STP consisting of space, time, and attribute(s). Any one of these three types of data may be queried to return the results for the other two data types. For instance, a query of time step 1 would return all STPs that exist at time step 1 in any feature for all themes of interest. Recall that an STP's time step value can be any temporal unit such as seconds, minutes, or months. A query of time step 1 returns matching STPs with their attributes, position, and associated feature and theme. A query of an attribute such as 'conifer' in a vegetation theme will return any STP of this type as well as the associated feature and theme. This is provided along with the time step(s) and location(s) for which an STP of the conifer type existed. In addition to queries dealing with one of the three available dimensions (space, time, attribute(s)), questions may be posed by holding two of the dimensions constant and querying a third. For example: At what time steps was the location (35, 56) classified as urban? Or, what locations were classified as rural at time step 4?

Egenhofer and Franzosa (1991) note distinct topological relationships between static objects. Using STPs as a fundamental building block, queries regarding object interaction and topology through time are also possible. These object interaction queries (OIQs) can describe space–time relations between two entities. With the STP architecture OIQs can answer questions such as:

- Where and when did two object paths cross (if at all)?
- How long did two object paths coincide (if at all)?

These types of queries can be helpful in modeling and simulating geographic phenomena. Geospatial lifelines research (Mark and Egenhofer 1998, Hornsby and Egenhofer 2002) focuses on individuals as points moving through space-time and can be used to determine if two individual's paths met for further investigation of disease spread. Here with the STP approach we are able to implement proof-of-concept queries that use any combination of objects and fields that are stationary or moving with static or dynamic shape and static or dynamic attributes. An example situation would be a simulation of cars in transit and a moving storm. If, when, and where a storm makes contact with traveling cars can be

determined through OIQs. This could be extended to other dynamic GIS applications including wildfires, pedestrians in urban environments, and other geographic phenomena. The GIS design would then have value in a dynamic decision-making context including spatiotemporal decision support systems (STDSS).

In addition to OIQs between objects, the STP architecture allows for object–field queries (OFQs) as well as field–field queries (FFQ). An example OFQ is a pedestrian wishing to know values of houses near which they were walking. Here both the object (pedestrian) and field (land value) have dynamic characteristics and queries for different times will return different results. An example FFQ would be between temperature and snow crystal type. Those results could be used to find correlations between temperature and crystal type (perhaps also taking into account pressure, humidity, and other values) through time.

The queries made possible by storing geographic data in this manner rely on space, time, and attribute along with the relationships between these three. For example, a user may know a time step they want to query and desire the matching location and attribute(s) returned. As a real-world example, a user could ask a theme containing weather stations what happened on 22 January 2006. The station locations and their attributes (e.g., temperature, wind, precipitation) that matched the user-specified day would then be returned. This is an example holding one of these concepts constant, while values for the other two are returned. In additional queries, two of these concepts can be held constant and the proper data pertaining to the third concept is retrieved. In the real world this could be when a user wants to know what location(s) in a land use theme were classified as urban in June of 1992. Even more challenging weather station queries can be implemented using STPs such as: When do all other stations experience similar climate patterns as station A where three short meteorological drought spells are followed by a sustained agricultural drought period?

Downloaded by [University of California Santa Barbara] at 15:37 01 April 2012

4. EDGIS implementation and use cases

4.1. Implementation

The STP framework presented in the prior section has been implemented in a raster GIS context as a Java™ program called Extended Dynamic GIS (EDGIS). Initial experimental work was done using Java™ applets and tested using web browsers. As the program advanced, the software migrated to a Java™ implementation using the Standard Widget Toolkit (SWT™) in the Eclipse™ Integrated Development Environment (IDE). Java™ was the choice for EDGIS software because of its combination of portability and speed.

Sample dynamic GIS scenarios have been created and tested using this system. The user is able to perform spatiotemporal queries on real-world data given a location in (x, y) two-dimensional coordinates, attribute, or time. If a query properly matches data in the current scenario then the appropriate results are returned. For example, if a user wishes to know the nature of objects that exist at time t, then the system returns the matching object's STPs with their coordinates and attributes as well as the feature and theme to which they belong.

Eight simple scenarios (Figure 3) were developed to demonstrate the functionality of EDGIS. Under this implementation an object may be moving or stationary, its shape can be dynamic or static, and its attributes can be static or dynamic. Using dynamic attributes allows an object to contain internal variation. This architecture allows for modeling of real-world phenomena through time. For example, a lake with changing boundary and surface variation in temperature is implemented as a static object with dynamic shape and dynamic attributes. A moving storm changing shape and severity over time is stored as a moving object with dynamic shape and dynamic attributes. Pedestrians are represented as moving objects with

1. Static Object, Static Shape, Static Attribute (Static GIS: county boundary, building)
2. Moving Object, Static Shape, Static Attribute (Automobile, pedestrian)
3. Static Object, Dynamic Shape, Static Attribute (Lake boundary changing through time)
4. Static Object, Static Shape, Dynamic Attribute (Land Use/Land Cover change)
5. Static Object, Dynamic Shape, Dynamic Attribute (Lake boundary changing along with temperature change)
6. Moving Object, Dynamic Shape, Static Attribute (Bird flock)
7. Moving Object, Static Shape, Dynamic Attribute (Ambulating pedestrian with changing goals and attributes, LBS)
8. Moving Object, Dynamic Shape, Dynamic Attribute (Moving storm that changes shape and severity over time)

Figure 3. Sample scenario possibilities for STPs in EDGIS.

Downloaded by [University of California Santa Barbara] at 15:37 01 April 2012

static shape and dynamic attributes. A pedestrian's internal variation can represent changing goals as a pedestrian meanders through a city's downtown and interacts with location-based services (LBS).

User interfaces (UIs) for temporal geographic data have been explored (Gahegan *et al.* 2002, Anselin *et al.* 2006, Rey and Janikas 2006) and continue to be improved. This research uses some of these UI principles and includes some new development due to the unique nature of the STP data. The EDGIS software implemented along with this paper proposes an interface with four windows for visualization and querying (Figure 4). The central window contains the main display of the active themes with their features and STPs at the current time step. Initially, EDGIS steps through each time step displaying all of the spatiotemporal geographic data loaded into the system. The left window is used to control which themes and STPs are visualized in the central window. The bottom window has the *time slider* and other tools for user queries: attribute querying, time step querying, time step smearing, and object

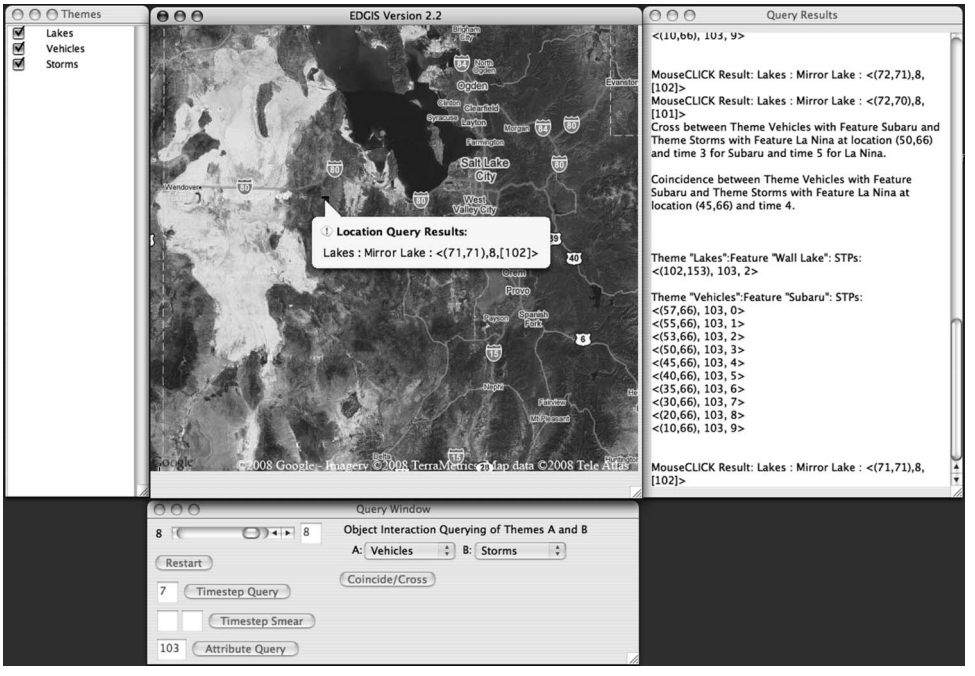


Figure 4. EDGIS interface windows.

interaction querying. The *time slider* is a tool allowing the user to click and drag the mouse to quickly move through time. Time step smearing acquires two time steps as inputs and then proceeds to display the information contained in the interval between the time steps (inclusive). The query results are returned and displayed in the rightmost window. Querying by location can be done visually by using a left mouse click. If a matching STP is found in an active theme where the mouse button was clicked, then its properties are revealed in a pop-up window.

4.2. Use cases

Examples of real-world applications requiring a dynamic GIS were provided in the prior section. This section further expands on some use cases that come under various categories of Figure 3. By utilizing geo-sensor networks, real-time data about phenomena such as tornados, wildfires, and other moving objects with dynamic shapes and attributes can be collected. Along with land type change, one use case contains urban density and urban growth along with transportation networks. Historically, an urban planner may want to know in a certain area whether a transportation network or urbanization came first. This scenario would involve Category 4 from Figure 3 (static object, static shape, and dynamic attribute) for land use/land cover, Category 5 for transportation networks, and Category 8 for urbanization. Only a few use cases are discussed here but the future may lead to many more.

There has been recent research for using evacuation trigger buffers to keep communities safe during wildfires in the Wildland Urban Interface (WUI) (Dennison *et al.* 2007). These trigger buffers are a polygon with perimeter based on specific fire spread characteristics. By combining these concepts, EDGIS can be used to represent a scenario that includes wildfire movement and attribute changes as it approaches a community's trigger buffer. Once a fire (i.e., dynamic field-object) meets the evacuation trigger buffer (i.e., dynamic object) an evacuation is triggered whereby cars (i.e., moving objects) leave the town on roads (i.e., static objects with dynamic attributes). This example is a demonstration of the variability possible by representing geographic phenomena in this manner. The buffers are polygons that will stay relatively static given there are no extreme changes in fire conditions like wind and fuel while the fire contains internal variation of attributes such as flame height and temperature.

On a different geographical scale from the previous wildfire setting is a scenario involving pedestrians in an urban environment making use of LBS (Category 7 in Figure 3). A pedestrian in a downtown environment may be searching for a place to mail a package, an establishment for food, or another service. Through GPS and LBS an ambulating pedestrian can quickly receive a list of suitable destinations based on their preferences. A person can have different attributes like age, sex, money, and movement abilities. On the basis of their attributes a dynamic GIS paired with LBS can give paths, distances, and other geographic information about a service. The results all depend on what the pedestrian user deems something of utility.

Figures 5–7 show sample use cases implemented in EDGIS. Figure 5 is an annotated screenshot using a 'time step smear' of three separate time steps. As noted earlier, another useful dynamic GIS scenario contains a storm and a traveling car. In this example, there is a storm theme and a car theme. The storm features can change direction, size, and attributes. A car feature may change its speed attribute as it is driven along roads. Here the car is traveling west on Interstate 80 (I-80) and a storm is moving south toward I-80. Through successive time steps one can see the storm coincides with the car at the third and final time step. This is also shown in EDGIS using an OIQ, which returns a result stating the location and time when

Downloaded by [University of California Santa Barbara] at 15:37 01 April 2012

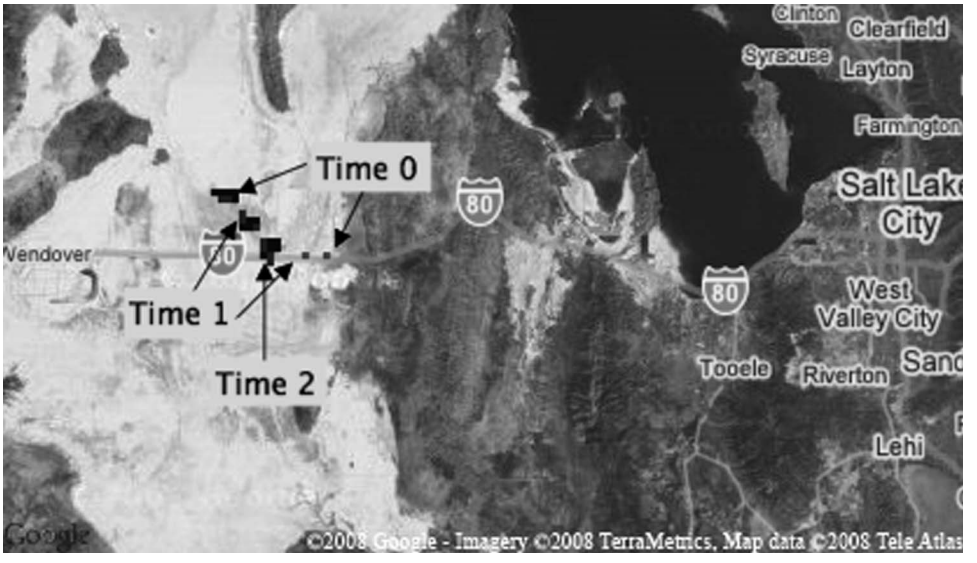


Figure 5. Annotated EDGIS screenshot with storm and vehicle themes through three successive time steps. This example shows phenomena changing shape, attribute, and location through time. Here many STPs compose a storm feature and that feature is a member of a storm theme. The storm feature is represented by the red and blue STPs (showing storm intensity and precipitation levels). The vehicle feature is shown as green STPs (may change based on speed).

the car and storm coincided. These data can be gathered via a weather forecasting source and by asking a user for specific car travel times and speeds. The dynamic GIS using OIQs can then help a traveling family or road-tripping crew avoid driving through a potentially hazardous storm. Also avoided would be traveling too soon after a storm has passed thereby not encountering dangerous road conditions.

Figure 6 demonstrates an example WUIVAC scenario. White STPs represent the evacuation trigger buffer, the light to dark gray demonstrate internal variation of the fire due to attributes such as flame height and temperature, and the darkest black STPs represent example vehicles evacuating once the fire crosses the buffer. Figure 7 is an example scenario with pedestrians in an urban environment. Initially, the family decides to eat at one of the many restaurants nearby and on their mobile device they receive a list of all Asian restaurants in the area. As they continue walking toward the restaurants they further refine their search criteria looking for only Chinese restaurants within 500 m and with meals less than €10. Restaurants matching current selection criteria are black STPs, white STPs represent the family searching for dinner, and gray STPs for all other pedestrians.

5. EDGIS performance metrics

The cross-platform EDGIS software was written using Eclipse™ IDE Version 3.2.2 with SWT™ and Java™ 2 Runtime Environment, Standard Edition build 1.5.0_07. The software was tested for performance metrics of both speed and size. Tests were done on a MacBook Pro 2 GHz Intel Core Duo with 1 GB of 667 MHz RAM. The operating system used was Mac OS X version 10.4.10.

The tests were done on STP data sets of 1–1,000,000 in powers of 10. Scripts were written in Python™ Version 2.3.5 to create the STP data input to the EDGIS STP reader.

Downloaded by [University of California Santa Barbara] at 15:37 01 April 2012

Figure 6. A wildfire scenario near an urban area through three consecutive time steps in EDGIS.

Downloaded by [University of California Santa Barbara] at 15:37 01 April 2012

Downloaded by [University of California Santa Barbara] at 15:37 01 April 2012

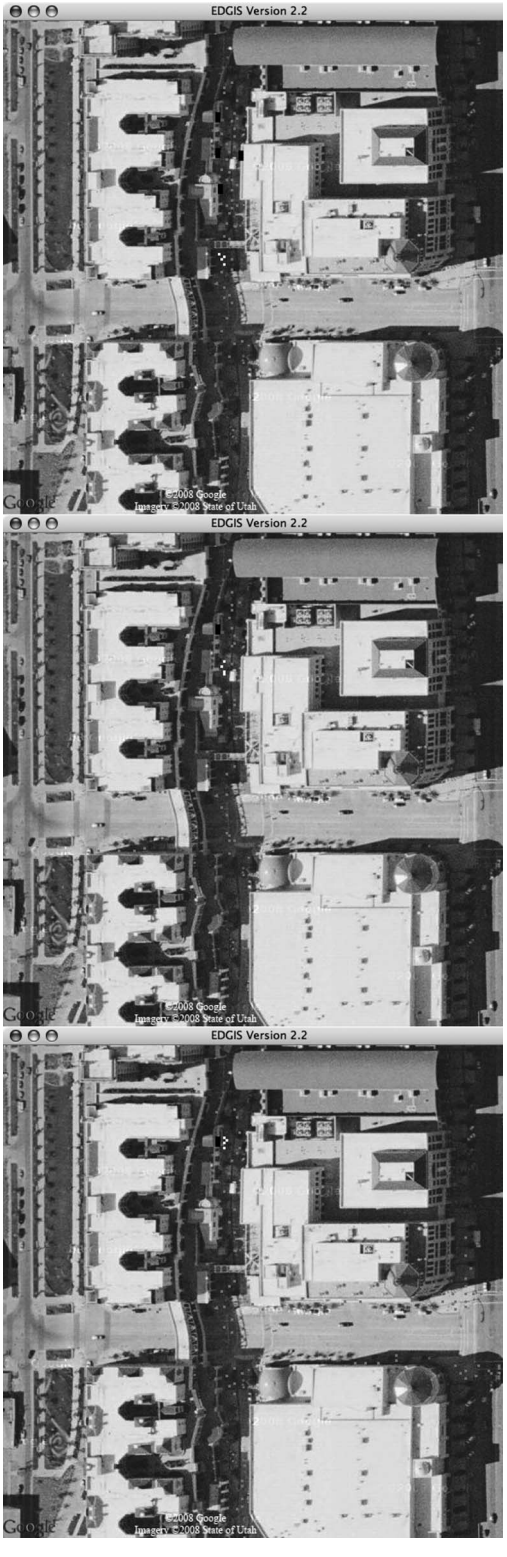


Figure 7. Pedestrians within an urban environment through three successive time steps in EDGIS.

Once the appropriate number of STPs were loaded into the system tests on five functionalities of EDGIS were completed:

- Attribute query
- Location query
- Time step query
- Display draw time
- Object interaction query

Each test was run 10 times and the average values are used in the figures presented here (Figure 8). Here are visualizations of the increase in computation time as the number of data points grows. The attribute and time step queries remain relatively quick through the increases in STPs. The location query is a little slower as its results are currently returned

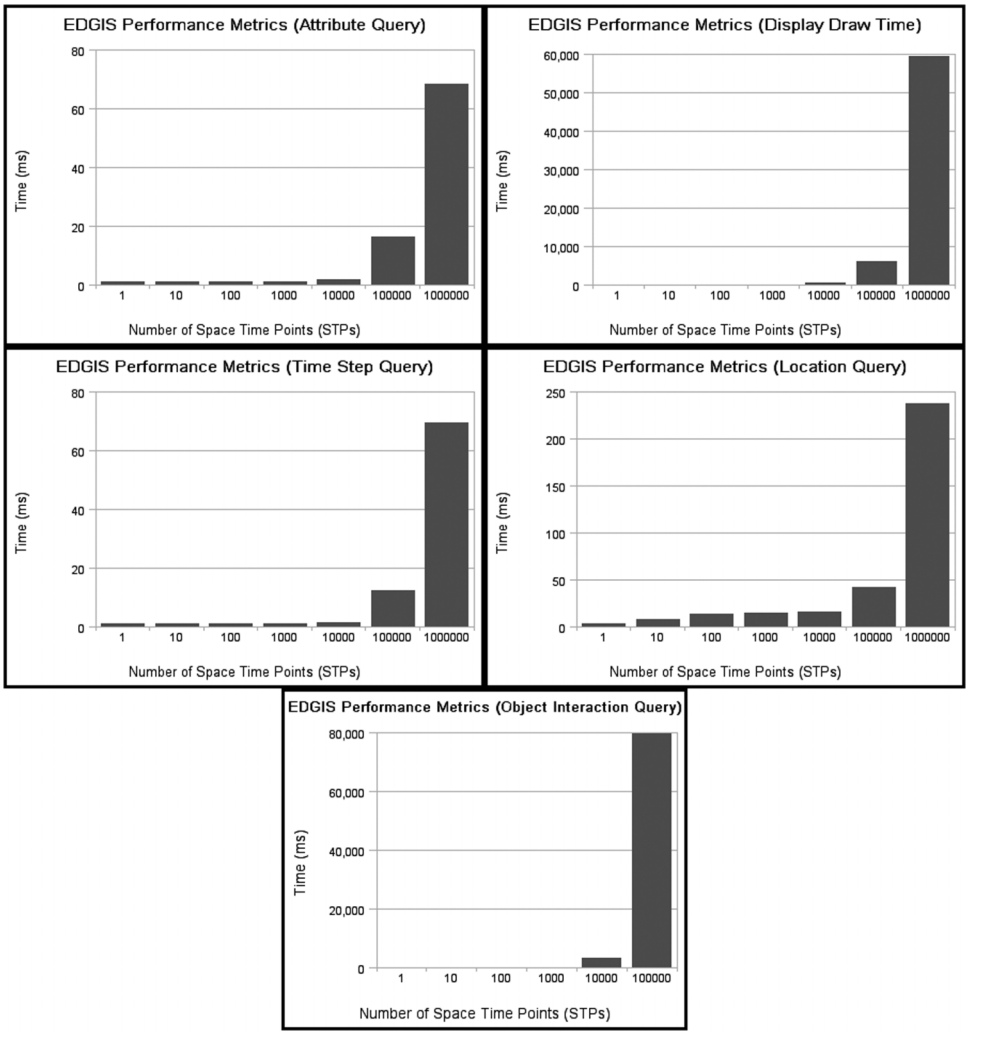


Figure 8. EDGIS performance metrics.

Downloaded by [University of California Santa Barbara] at 15:37 01 April 2012

in a balloon pop-up window, which takes more time than the raw text output currently used for attribute and time step queries.

The time to draw the display gets longer as the STPs increase and is a specific area where future dynamic GISs can improve. Drawing of up to 10,000 STPs took less than a second but research into faster drawing routines could prove useful here. Using more hardware acceleration such as OpenGL for display could speed these times up as well as using general-purpose computing on graphics processing units (GPGPU) or GPU programming.

These OIQs present an implemented ability to query between dynamic geographic phenomena such as storms and cars that are able to change their attributes and shape through time. The OIQ tests were done by putting half the number of test STPs (e.g., 50,000 for the 100,000 test) at the same time step into two separate themes. The OIQ then found all of the results of coincidence (e.g., 50,000) for each of the STPs. The computation times may be long but this complex dynamic GIS query is doable with the STP approach. For instance, the query was less than a few seconds with up to 10,000 STPs coinciding, while the time for the 1,000,000 STPs test was minutes. This is the most computationally intensive query implemented in the current EDGIS software and perhaps the future will yield more attempts at more efficient dynamic GIS queries.

Algorithms were also used for determining the size in bytes of the EDGIS data structures, which contained Integers, Booleans, Strings, and ArrayLists. In the Java™ programming language Integers use 16 bytes, Booleans 16 bytes, and Strings 40 bytes. The ArrayList class is used for storing sets of attribute values, attribute descriptions, STPs, and features. This Java™ data type is dynamic and variable in size so estimated sizes are reported here. Algorithms for base tests returned a size of 112 bytes for STPs containing between 1 and 10 attributes. Beyond this the STP size generally increases by 4 bytes with each additional attribute. The size of a feature was determined based on how many STPs with 10 attributes it contained. A feature with one to 10 STPs containing 10 attributes each used 104 bytes. Generally as a feature grows in number of STPs it contains the storage size increases by 4 bytes as a new pointer is created to each additional STP. The theme class grows similarly to the feature class and was tested by loading it with features of 100 STPs containing 10 attributes each. Themes containing between one and 10 features of this variety allocate 104 bytes and generally increase by 4 bytes for each new feature included in the theme. With today's ever-increasing hard drive space, computation and draw time can be a more important issue than storage. The number of themes, features, and STPs utilized will vary widely based on the different use cases and scales user desires. STP implementations needing larger data sets (e.g., greater than 1 million STPs) may make good use of tools such as relational database management systems (RDMBS) in combination with structured query language (SQL).

Downloaded by [University of California Santa Barbara] at 15:37 01 April 2012

6. Discussion

Section 4 described a dynamic GIS implementation that can be used to store, visualize, and query spatiotemporal geographic data. Phenomena represented in this system may change shape, attribute, and location at any point in time. The STP provides a new look at dynamic GIS and has the strength of being used as the basis for a hybrid implementation, but lacks the ability for vector-based representation of objects or fields over time, a much more difficult challenge.

For example, dynamic GIS applications were mentioned earlier in this paper and others are possible with more to be discovered in the future. STPs provide a theoretical basis that can be applied to many different situations where hybrid geographic representations and

queries are desirable. More advanced queries may be implemented such as Yuan and McIntosh's (2002), 'Where and when will land L experience a flood during a hurricane?' by making use of STPs and associated algorithms. As EDGIS research continues, more querying capabilities will be implemented. Visualizations with different color representations can better represent certain geographic phenomena so use of more color gradients will increase appearance and usability characteristics (Brewer 1994).

Tools for dynamic geographic data entry into STP, feature, and theme form can also be further developed to aid users in creating data. Conversion techniques can also be used to create STPs from other data types such as shape files, GML (Geography Markup Language), and feature classes. Future research can also build upon the research presented here by adding additional temporal concepts such as cyclic time and purely temporal objects such as daytime and nighttime. In addition, an STP-based dynamic GIS may provide utility for storing and analyzing the rapidly increasing amount of geospatial data available on the Web as a form of volunteered geographic information or VGI (Pultar *et al.* 2008). Work can also be done for handling vector representations as well as multi-aspect/scale phenomena.

The new steps completed with this research include the representation of geographic features through the eight scenarios shown in Figure 3. The methodology used in this work allows for these combinations of moving versus stationary, dynamic versus static shape, and dynamic versus static attributes. This is a key contribution to represent real-world spatiotemporal information with internal variation. Some phenomena able to be represented by this approach were mentioned previously but many more are out there to be discovered.

Another novel concept implemented here is the capability for OIQs. These OIQs afford queries between spatiotemporal information contained in separate themes such as airplanes and storms, predators and prey, as well as other any combinations necessary. While these queries can become less intensive in the outlook, these steps bring us to a new doorstep while showing some new work that lies in the future.

7. Conclusion

A dynamic GIS is a useful tool for storing, querying, and visualizing real-world data describing geographic phenomena. Further research is still needed of dynamic geographic data representations along with questions and problems that surface. Further topological relationships between objects in space-time are another interesting topic. Dynamic objects just as static objects may have properties like covers, inside, or contains. A greater awareness of the need to implement a fully functional dynamic GIS will produce more applications as society gains more access to dynamic geographical data.

In this paper some real-world use cases of a dynamic GIS were suggested, but there are more out there and many more waiting to be discovered. This is a growing field that will cover a great breadth and depth of disciplines. For example, anthropologists can use a dynamic GIS to do visualization and research of the origin and spread of languages and dialects. Biologists can use human elements such as mitochondria to trace family lineages. Engineers doing wind energy assessment utilize anemometers to collect meteorological data at one location one day then transport the anemometer to another location the next day. These are some hypothetical examples to show some of the potential diversity and usefulness of a dynamic GIS. Between the various applications one can see a difference in the size of geographic interest as well as the diverse time step granularities necessary for effectiveness.

Typical static GIS handles scenarios of stationary objects with static shape and attributes that contain no internal variation. This paper described a means for handling more dynamic GIS scenarios such as those containing moving objects with dynamic shape and internal

Downloaded by [University of California Santa Barbara] at 15:37 01 April 2012

variation through use of dynamic attributes. EDGIS does not solve every dynamic GIS representation problem (e.g., vector), but it provides an implemented, easily extendible software solution capable of representing and visualizing dynamic geographic phenomena using STPs, features, and themes. This representation allows EDGIS to query spatiotemporal data by location, time, and attribute using the proposed dynamic GIS interface.

Acknowledgements

This research is partially funded by the US National Science Foundation through Collaborative Awards BCS-0416208, BCS-0416300, and BCS-0417131. Thanks to Harvey Miller, Phil Dennison, Lorenzo F. Gonzalez, and Martin Raubal for their comments and guidance. This work was done as part of an M.S. degree in Geography at the Department of Geography, University of Utah. An earlier version of this paper was presented at the 2007 Annual Meeting of the Association of American Geographers (AAG) in San Francisco, CA, U.S.A., where it was awarded first prize in the GIS Specialty Group Student Paper Competition.

Downloaded by [University of California Santa Barbara] at 15:37 01 April 2012

References

Albrecht, J., 2007. Dynamic GIS. In J.P. Wilson and A.S. Fotheringham, eds., *Handbook of Geographic Information Science*, Oxford: Blackwell, 436–446.

Anselin, L., Syabri, I., and Kho, Y., 2006. GeoDa: an introduction to spatial data analysis. *Geographical Analysis*, 38, 5–22.

Bone, E. and Bolkcom, C., 2004. *Unmanned aerial vehicles: background and issues*. Hauppauge, NY: Novinka Books.

Brewer, C.A., 1994. Color use guidelines for mapping and visualization. *In*: A.M. MacEachren and D.R.F. Taylor, eds. *Visualization in modern cartography*. Tarrytown, NY: Elsevier Science, 123–147.

Cova, T.J. and Goodchild, M.F., 2002. Extending geographical representation to include fields of spatial objects. *International Journal of Geographic Information Science*, 16, 509–532.

Dennison, P.E, Cova, T.J., and Moritz, M.A., 2007. WUIVAC: a wildland urban interface evacuation model applied in strategic wildfire scenarios. *Natural Hazards*, 41, 181–199.

Egenhofer, M.J. and Franzosa, R.D., 1991. Point-set topological spatial relations. *International Journal of Geographic Information Systems*, 5, 161–174.

Frank, A.U., 2003. Ontology for spatio-temporal databases. *In*: G. Goos, J. Hartmanis, and J. Leeuwen, eds. *Spatiotemporal databases: the chorochronos approach* (Lecture Notes in Computer Science 2520). Berlin: Springer, 9–77.

Frank, A.U., Campari, I., and Formentini, U., 1992. *Theories and methods of spatio-temporal reasoning in geographic space* (Lecture Notes in Computer Science No. 639). Berlin: Springer.

Gahegan, M., *et al*., 2002. Introducing GeoVISTA studio: an integrated suite of visualization and computational methods for exploration and knowledge construction in geography. *Computers, Environment and Urban Systems*, 26, 267–292.

Galton, A., 2004. Fields and objects in space, time, and space-time. *Spatial Cognition and Computation*, 4, 39–68.

Goodchild, M.F., 1992. Geographic data modeling. *Computer and Geosciences*, 18, 401–408.

Goodchild, M.F., Yuan, M., and Cova, T.J., 2007. Towards a general theory of geographic representation in GIS. *International Journal of Geographic Information Science*, 21, 239–260.

Grenon, P. and Smith, B., 2004. SNAP and SPAN: towards dynamic spatial ontology. *Spatial Cognition and Computation*, 4, 69–104.

Güting, R.H. and Schneider, M., 2005. *Moving object databases*. San Francisco, CA: Morgan Kaufman.

Hornsby, K., 2001. Temporal zooming. *Transactions in GIS*, 5, 255–272.

Hornsby, K. and Egenhofer, M.J., 2000. Identity-based change: a foundation for spatio-temporal knowledge representation. *International Journal of Geographical Information Science*, 14, 207–224.

Hornsby, K. and Egenhofer, M.J., 2002. Modeling moving objects over multiple granularities. *Annals of Mathematics and Artificial Intelligence*, 36, 177–194.

Kim, T.H. and Cova, T.J., 2006. Tweening grammars: deformation rules for representing change between discrete geographic entities. *Computers, Environment and Urban Systems*, 31, 317–336.
Langran, G., 1992. *Time in geographic information systems*. Bristol, PA: Taylor & Francis.
Mark, D.M. and Egenhofer, M.J., 1998. Geospatial lifelines. *In*: O. Guenther, T. Sellis, and B. Theodoulidis, eds. *Integrating spatial and temporal databases*. Dagstuhl Seminars: Report No. 228.
Mennis, J., Viger, R., and Tomlin, C.D., 2005. Cubic map algebra functions for spatio-temporal analysis. *Cartography and Geographic Information Science*, 32, 17–32.
Miller, H.J., 2005. What about people in geographic information science? *In*: P. Fisher and D. Unwinm, eds. *Re-presenting geographic information systems*. England: John Wiley & Sons, 215–242.
O'Sullivan, D., 2005. Geographical information science: time changes everything. *Progress in Human Geography*, 29, 749–756.
Peuquet, D.J., 2001. Making space for time: issues in space-time data representation. *Geoinformatica*, 5, 11–32.
Peuquet, D.J., 2002. *Representations of space and time*. New York, NY: Guilford Press.
Peuquet, D.J. and Duan, N., 1995. An event-based spatiotemporal data model (ESTDM) for temporal analysis of geographical data. *International Journal of Geographical Information Systems*, 9, 7–24.
Pultar, E., Raubal, M., and Goodchild, M., 2008. GEDMWA: geospatial exploratory data mining web agent. *In*: *Proceedings of the 16th ACM SIGSPATIAL international conference on advances in geographic information systems (ACM GIS 2008)*. Irvine, CA, 5–7 November 2008 (Association for Computing Machinery (ACM) GIS), W. Aref, M. Mokbel, H. Samet, M. Schneidor, C. Shahabi and O. Wolfson (Eds)., 499–502.
Raper, J. and Livingstone, D., 1995. Development of a geomorphological spatial model using object-oriented design. *International Journal of Geographical Information Systems*, 9, 359–383.
Reitsma, F. and Albrecht, J., 2005. Implementing a new data model for simulation processes. *International Journal of Geographical Information Systems*, 18, 1073–1090.
Rey, S.J. and Janikas, M.V., 2006. STARS: space-time analysis of regional systems. *Geographical Analysis*, 38, 67–86.
Richards, J. and Egenhofer, M., 1995. A comparison of two direct-manipulation GIS user interfaces for map overlay. *Geographical Systems*, 2, 267–290.
Stefanidis, A., *et al*., 2003. Modeling and comparing change using spatiotemporal Helixes. *In*: *Proceedings of the 11th ACM international symposium on advances in geographic information systems*: New Orleans, LA, 7–8 November 2003 (Association for Computing Machinery (ACM) GIS), E. Hoel and P. Riganx, Eds, 86–93.
Stefanidis, A. and Nittel, S., 2004. *GeoSensor networks*. Boca Raton, FL: CRC Press.
Tsou, M., 2004. Integrated mobile GIS and wireless Internet map servers for environmental monitoring and management. *Cartography and Geographic Information Science*, 31, 153–165.
Wolfson, O., *et al*., 1998. Moving objects databases: issues and solutions. *In*: *Proceedings of the 10th international conference on scientific and statistical database management*. Capri, Italy, 1–3 July 1998 (IEEE Computer Society), M. Rafanelli and M. Jarke, eds. 111–122.
Worboys, M., 1994. A unified model for spatial and temporal information. *Computer Journal*, 37, 26–34.
Worboys, M.F. and Duckham, M., 2005. *GIS: a computing perspective*. Boca Raton, FL: CRC Press.
Yuan, M., 1996. Modeling semantic, temporal, and spatial information in geographic information systems. *In*: M. Craglia and H. Couclelis, eds. *Geographic information research: bridging the Atlantic*. London: Taylor & Francis, 334–347.
Yuan, M., 2001. Representing complex geographic phenomena in GIS. *Cartography and Geographic Information Science*, 28, 83–96.
Yuan, M. and Mcintosh, J., 2002. A typology of spatiotemporal information queries. *In*: K. Shaw, R. Ladner, and M. Abdelguerfi, eds. *Mining spatiotemporal information systems*. Dordrecht: Kluwer Academic Publishers, 63–82.

Downloaded by [University of California Santa Barbara] at 15:37 01 April 2012