

A Spatio-Temporal Data Model for Analyzing the Relationship between Property Ownership Changes, Land-Use/Land-Cover and Carbon Dynamics

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ABSTRACT

Since 1980 there has been an increasing interest, both commercially and academically, in the development of spatio-temporal data models. Such data models are designed not only to facilitate information extraction about data objects and the relationships between these objects but also to support the analysis of data in a time series from varying perspectives. We will design a spatio-temporal data model for a NASA-funded research project. This project investigates how land ownership practices and land-use/land-cover, influence changes in carbon storage dynamics in forested ecosystems in the southeastern United States. The design of such a model will determine to what extent ownership changes have affected land-use/land-cover and whether these changes have in turn influenced carbon dynamics over the past 25 years.

1. INTRODUCTION

The study of carbon dynamics in the atmosphere is significant to exploring the patterns of human and natural disturbances to ecosystems and the responses of ecosystems to these disturbances. Changes in land-cover have implications for soil quality, water runoff and sedimentation rates, earth-atmosphere interactions, the hydrological cycle, biodiversity and for the biogeochemical cycling of carbon, nitrogen and other elements at regional to global scales. Land-use and land-cover relationships form a complex and interactive system. The impact of land tenure on forest management has received widespread attention in the USA, where interest in who owns forestland and other vital ecosystems has increased significantly. This is because the type of forest ownership greatly affects how the forested land is managed and thus affects patterns and land-cover changes occurring in that forested area. (Binford et. al., 2000)

This paper describes ongoing research into how land ownership practices influence changes in land-use/land-cover and carbon storage in forested ecosystems in the southeastern United States. In determining links between changes in land ownership, land-use/land-cover and carbon storage patterns, the key questions for this project are:

- “How much carbon has been lost or gained from the SE Forests as a consequence of long-term ownership patterns?”
- “How can we model future changes in carbon storage if we know how ownership and land-use/land-cover will change?”

To answer these questions, we are studying land-cover/land-use change over the past 25 years over four randomly selected study areas in Northern Florida. Within these study areas, we will estimate how carbon storage patterns have been altered by observed changes in land-use/land-cover. We will also identify relationships between the kinds of changes occurring in land ownership over these areas (for example, state to private ownership). In investigating these relationships, we aim to ultimately determine the effects of specific land management activities on the carbon storage and sequestration rates and to establish the proposed study areas as sites for long-term monitoring of carbon storage patterns.

In addressing the questions identified above we are developing a database from existing NASA Earth Science data, ongoing measurements of components of the carbon cycle on the ground and new information gained by compiling records of land ownership and management practices. All these data will be integrated into a data model of land-use change as functions of human activities and natural climate variability. Such a data model should thus be able to handle data in both the spatial and temporal domains and requires the design and implementation of a spatio-temporal database model. The first section of the paper focuses on the issues surrounding the development of such a database model and reviews existing spatio-temporal database models and their applications. The second section of the paper introduces the spatio-temporal database model we have developed and discusses the issues involved in the successful implementation of a model.

2. MOVING FROM GEOGRAPHIC TO TEMPORAL DATA MODELS

A common characteristic of conventional GIS data models is their representation of objects at a specific point in time. However, when attempting to model phenomena in the real world that changes with time, conventional GIS data models become inadequate. This inadequacy has been considered a major shortcoming of conventional models when being applied to dynamic data (Cheng, 1999). A more desirable approach to modeling dynamic geographic data is to model the data, as closely as is possible, as it exists in reality. Such a model would be capable of representing, analyzing and predicting changes of spatial information over time rather than dealing with the data in snapshots of time.

Essentially, a temporal data model should facilitate

- An understanding of the rules that govern changes observed in the real world;
- An explanation of the state of the world at a previous time;
- Predictions of the state of the world in the future;
- A planning of a sequence of actions that will lead to a desirable future

(Cheng, 1999)

As previously mentioned, the core elements of the project involve an investigation of land-use/land-cover and land ownership changes over a study period of twenty-five years. Since we are dealing here with the same spatial objects at varying points in time, we need to ensure that no ambiguities appear in the datasets. Data for this investigation thus needs to be handled and stored such that analysis and modeling of the data can be accurately and unambiguously performed. To achieve this, we will design and implement a spatio-temporal database model that facilitates accurate analyses and modeling of the data.

Since 1980 there has been an increasing interest in the development of temporal data models where time has been incorporated into common data models such as entity-relationship models, semantic data models, knowledge-based data models, deductive data models and object-oriented data models (Cheng, 1999). In the next section we will introduce key concepts of temporal data models and review current progress in spatio-temporal models and the application of these models.

3. COMPONENTS OF SPATIO-TEMPORAL DATA

A spatial object is comprised of three components:

- The spatial component;
- The temporal component;
- The non spatio-temporal or aspatial component.

Thus to represent a spatial object in a spatio-temporal data model we need to define these three components for each spatial object. This would mean we would have to identify the “What”, “Where” and “When” for each spatial object. All three of these components need to be addressed in order to identify each object in a spatio-temporal data model.

The temporal component in a spatio-temporal data model is the most significant of the three components. When examining changes occurring in spatial data, we are essentially examining the non-temporal components of a spatial object, such as geometry, topology and attribute data. However, these attributes and geometric relationships in the data are influenced by time. Time defines what attributes currently exist for a spatial object, what geometric relationships are present and determines when changes have occurred to a spatial object. No spatial object is fixed with the passage of time and it is clear that when examining spatial objects and their attributes, time needs to be incorporated in the analysis if we are to correctly model the objects in their real world. If time is incorporated as a component of a geographical object, the possibilities of analyzing an object over time and keeping track of the objects’ history is greatly increased. In our application, the history of a land parcel and the underlying land use needs to be tracked and analyzed in order to correlate these changes with carbon storage. Thus the time of a transfer of ownership of land is as significant as the current spatial attributes of the land parcel and the time of change of any particular land-use classification.

The main challenge facing the design and implementation of a spatio-temporal database is the capture and representation of the temporal component of the data model. Changes occurring in geo-referenced objects need to be captured and sufficiently

represented in the temporal database. Initially, it is necessary to identify which are the most desirable changes to capture, as often many changes will occur in a single spatial object. The types of changes captured will vary with the type of application being designed. For example, one application might involve capturing the aspatial changes of an object such as attribute data (owner name, owner type) and another application might involve capturing the spatial changes of an object such as geometric data (area of a land parcel). In our application we are interested in capturing both aspatial and spatial changes. Attribute data, such as land ownership and changes in land use, will need to be captured as well as geometric changes in land parcels, such as consolidations and subdivisions.

Another important issue to be dealt with in the design of the spatio-temporal database is the unique identity of the object at a particular time. When a change, either spatial or aspatial occurs to an object, it becomes a new object with a new object identity in the data model (See Figure 1). It is essential to maintain a distinction between the original object and the new object in the data model if one is to track and analyze the history of an object. Each time a component of a spatial object changes, a new object is created in the data model with a new, unique object identifier. In doing this, each object will have a current identity number plus a list of previous identities.

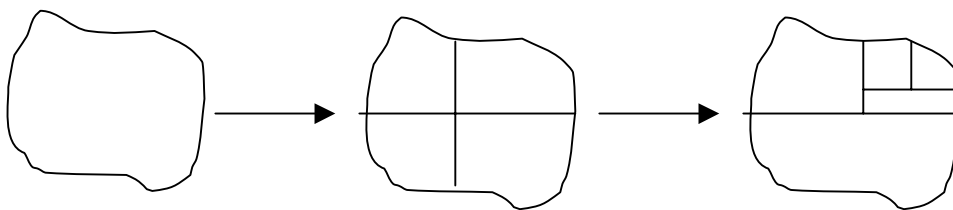


Figure 1: Changes in land parcels through time causing the creation of new objects

In this manner we are capturing the temporal component of the data model, which is comprised of irregular changes in time. In our application we are dealing with irregular changes to spatial objects through time, which are easier to represent in a data model. Representing continuous changes to spatial data through time, however, is a far more complex task.

In a spatio-temporal database where objects are changing over time, it is important to identify and define the criteria that cause the creation of a new spatial object. Once these criteria have been defined, this indicates which of the three components of the spatial object will carry the unique identifier. In our application, our criteria may be a transferal of ownership between land parcels, a change in parcel boundaries, a change in land-cover or a change in land-use classification. This indicates that both spatial and aspatial components of our objects need unique identifiers. The aspatial components are the attribute data of ownership information, and the classification values of pixels for land-use or land-cover, and the spatial components are the arcs and polygons that make up parcel boundaries. An example of both a spatial and an aspatial change is the subdivision of a land parcel. In this case, two new objects will have been created defining two new polygons and two new sets of attribute data. These two new polygons need a spatial identifier that both keeps them unique and ties them to their parent parcel. New aspatial identifiers will also need to be created in the attribute data attached to these polygons that keeps both the aspatial attribute component unique and also ties this attribute information to the parent information. In our spatio-temporal database we thus need unique identifiers on two components of our spatial objects.

There are certain difficulties and challenges in implementing these components of a spatio-temporal database. In the case of raster data for example, a pixel is an object but it also forms part of another larger object such as a land use classification. In the case of vector data, topological relationships such as neighboring left and right polygons need to be maintained and well defined. In dealing with these issues, we are using an object-oriented approach (See Figure 2), where concepts such as multiple inheritance and abstraction will be used in dealing with the representations of object identification and the occurrence of multiple change in spatial objects.

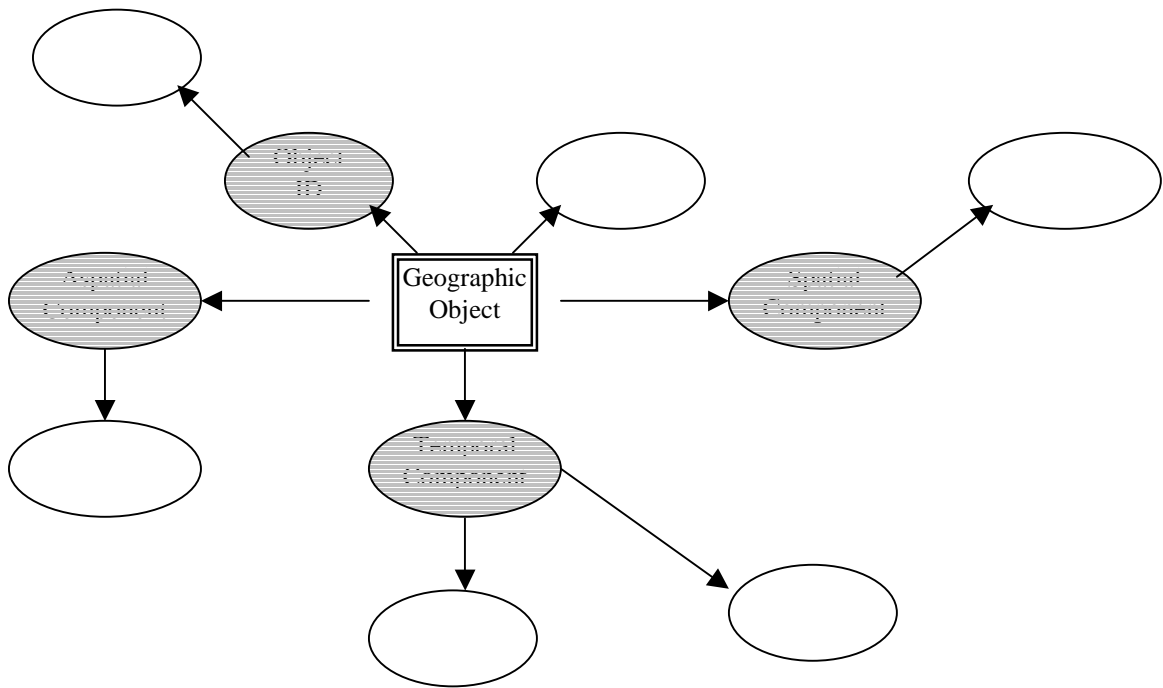


Figure 2. The structure required for defining spatial objects in a temporal data model (Roshannejad and Kainz, 1995).

3. SPATIO-TEMPORAL DATA MODELS

Before designing our spatio-temporal database, a review of existing spatio-temporal data models is necessary. Since 1980, there has been increasing academic interest in the development of data models that incorporate time. Time has since been added to many data models such as the entity-relationship model, semantic data models, knowledge-based data models, deductive data models and object-oriented data models (Yuan, 2000). Most research and development in temporal data models however has been based on the relational data model where a change of an entity is represented as a new version of an entity (Bagg and Ryan, 2000). Four basic spatio-temporal data models have been proposed in the literature at the conceptual level. These models are based on the relational data model and incorporate time as an additional dimension to the existing spatial dimensions.

The *Space-Time Cube* is a three-dimensional cube representing one time dimension and two space dimensions. Accessing information in the cube requires referencing points, tracing vectors, slicing cross sections and extracting smaller cubes out of the larger cube. As the cube increases its data volume, however, each of these operations becomes more and more complex. More intuitive representations of time than

the Space-Time cube are those spatio-temporal models that have incorporated time through time-stamping of components (Cheng, 1999), (Yuan, 2000).

The Snapshot Model applies time-stamps to layers, the Space-Time Composites time-stamps attributes and the Spatiotemporal Object Model time-stamps spatial objects.

The Snapshot Model shows the states of geographic distributions and different times without indicating whether any changes have taken place in the time lag between the representations of any two geographic states. Each snapshot of a geographic state describes what exists in time at that point in time but does not record any changes that may have occurred from one snapshot state to the next. Since no changes are recorded however, large amounts of duplicated data are present in the model which results in data redundancy and can lead to data inconsistencies in the model (Cheng, 1999), (Yuan, 2000).

The Space-Time Composites (ST-composites) describes the change of a spatial object through a period of time and can be derived from temporal overlays of time-stamped layers from the Snapshot Model. The model represents the world as a set of spatially homogeneous and temporally uniform objects in a 2-D space. Attribute changes are recorded at discrete points and thus the model fails to capture continuous motion or movement. Since each change causes an object to break from its parent object and to become its own distinct object, updating a ST-Composites database requires the reconstruction of STC units which results in the updating of both spatial objects and attribute tables (Cheng, 1999), (Yuan, 2000).

The Spatiotemporal Object Model was developed using an object-oriented approach. The model represents the world as a set of discrete objects consisting of spatiotemporal atoms that can be referenced as spatiotemporal objects or non-spatiotemporal objects. A spatiotemporal object can record changes in both space and time, while no change occurs within each of its spatiotemporal atoms. In this way, the ST Object Model is able to record changes in the attributes of a ST-object in both the spatial and the temporal dimensions, together or separately, by projecting a ST-atom to the spatial and/or temporal space. Gradual or continuous changes cannot be represented in the model since the ST-atoms are discrete (Bagg and Ryan, 2000).

The four basic models described above have been adapted to facilitate various kinds of analysis and case studies through the years (Cheng, 1999). Location-based and feature-based representations are not well suited for the analysis of overall temporal relationships of events and patterns of changes through time such as the analysis of raster data.

The ESTDM (Event-based Spatio-Temporal Data Model) is an example of a model developed to facilitate the analysis of raster-based data. The ESTDM model groups time-stamped layers to show temporal observations of a single event in a temporal sequence. Changes in relation to previous states are stored rather than a snapshot of an instance. A header file contains thematic information, a pointer to a base map and pointers to the first and last event lists. The base map is an initial snapshot of a single theme of interest in a geographic area and the event list is a series of events consisting of the spatiotemporal dynamics and of the thematic domain in a geographic area. Each event in this list is time-stamped and associated with a list of event components to indicate where changes have occurred to a predefined location such as a raster cell at a particular point in time. The most significant feature of the ESTDM model is its capabilities to support both spatial and temporal manipulations on data. However, since the ESTDM is based on raster data, modeling a vector-based system using this model will be difficult since changes stored by the model are based on grid cells, not spatial topology. Our application requires the storage of both raster and vector temporal data. Concepts presented in the ESTDM model will be useful in the design and implementation of our spatio-temporal database (Cheng, 1999), (Yuan, 2000), (Bagg and Ryan, 2000).

There have been various other notable adaptations of the four basic models described above. Object-oriented concepts are used in the 4-D geomorphic information system Oogeomorph, which models and represents the dynamics of geomorphologic system such as a coastal system (Cheng, 1999). The Three Domain Model was proposed to manage wildfire information in a GIS environment (Bagg and Ryan, 2000). The model defines semantical, temporal and spatial objects in three separate domains where time is modeled as an independent concept instead of being treated as an attribute of location.

In summary, the research and development of temporal data models in the computer sciences has significantly influenced the trends of temporal modeling in GIS. Most of these models, however, treat time as snapshots of states (Snapshot Model) or as differences between states (ST-Composites, ST-Objects). These models do not adequately model interactions between natural phenomena such as merge and split and processes causing changes in geometric and thematic aspects of an object at the same time. In order to sufficiently model land ownership (thematic) histories, parcel (geometric) histories and land-use/land-cover change (natural phenomena), we propose to develop a spatio-temporal model using and adapting the concepts presented in the models described above. We will build the model using the EER Model (Extended-Entity Relationship), which will translate into a relational database system resulting in a spatio-temporal model based upon an object-relational database system (Elmasri and Navathe, 2000). The object-oriented properties of the EER model will allow the development and formalization of our objects with the relational database facilitating the storage and retrieval of our information.

4. DESIGN AND IMPLEMENTATION OF THE MODEL.

As argued previously, the dynamic characteristics of spatial objects can be represented by their states and processes (See Figure 3). Thus the most important spatio-temporal constructs to be incorporated in the design of the model are 'state' and 'process'. As presented in section 2, there are three possible types of processes that could occur to a spatial object. The first type is a purely spatial change affecting only the geometric aspects of the object. The second type is a purely thematic change where only the thematic aspects or attributes of the object are affected. The third type of process is a combination of the spatial and thematic changes affecting both the geometric and thematic aspects of the object at the same time. An example of the third type of process in our ownership database would be the selling and subdivision of a property by its owner. The parcel will undergo geometric changes in that it will be split and the attributes attached to the parcel will change in that the previous owner will cease to exist in the database and two new owners will come into existence.

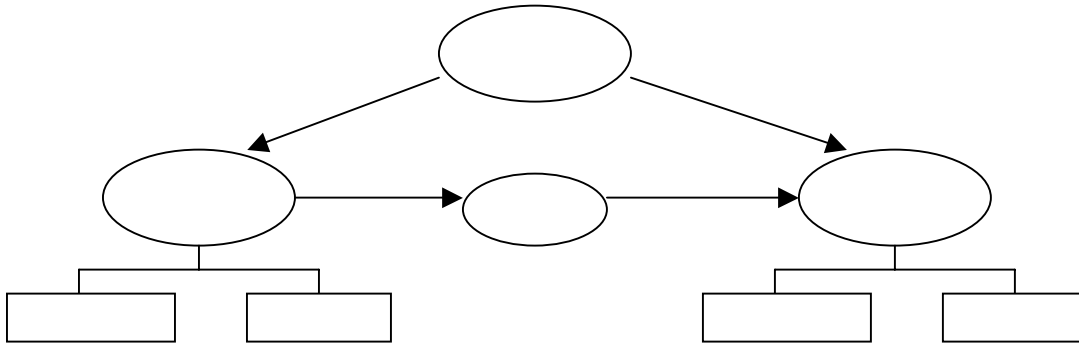


Figure 3. The transition of an object from one state to another through a process.
 (Diagram adapted from Cheng, 1999)

Object: Represents an owner of a parcel of land such as a commercial owner, a government owner or a private owner. The state of the object is the existence of the object at a specific time;

State: Represents the state of an object at a specific time. The *state* also includes what the current geometric and thematic properties of the object are at that time.

Theme: Represents the thematic aspects of an object, which would be the attributes attached to a parcel of land;

Process: Represents the process causing the change in the spatial and thematic aspects of the object;

Time: Represents the time at which a particular state of an object exists

The five terms presented above describe the spatio-temporal constructs that should be defined in a spatio-temporal database model to represent spatial objects and their dynamics. These five objects and the relationships between these five objects can be represented in the EER (Extended-Entity Relationship) Model as illustrated in Figure 4.

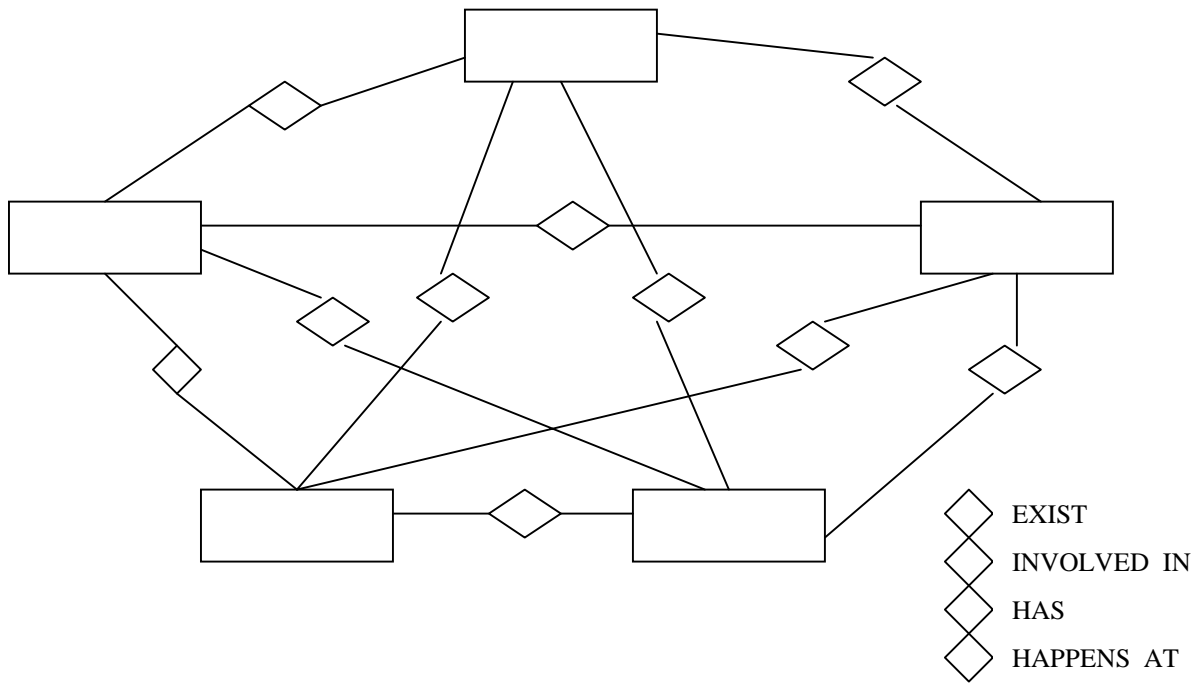


Figure 4: Generalized EER-Model of a Spatio-Temporal Database. (Cheng, 1999).

This EER Model was named the Star Model by Dr. Tao Cheng who designed such a database model to support time-oriented, object-oriented, location-oriented and process-oriented query and analyses. We will base the design of our database model upon the concepts and theories presented by Dr. Cheng in the Star Model. In the Star Model, the states and temporal dynamics of objects are revealed through processes affecting the objects and thus this model can be seen as a process-oriented model where all entities/objects are connected through processes. Changes over space relative to time are explicitly represented in this model and interactions between objects are represented as processes. Since the Star Model stores changes occurring to objects relative to time as processes, temporal queries and analytical tasks for comparing various sequences of change are greatly facilitated through the design of this model.

5. SUMMARY AND DISCUSSION

To determine much carbon has been lost or gained from the SE Forests as a consequence of long-term ownership patterns and management practices, temporal analyses need to be performed upon cadastral data and classified satellite imagery. These data needs to be stored such that temporal query and analyses can be easily facilitated. Conventional geographic models become insufficient when attempting to model and represent dynamic data. We propose the design of a spatio-temporal data model, based

upon the Star Model where changes occurring to spatial objects over time are stored and represented as processes occurring at different snapshots in time. Through such a model, we are able to:

- Perform time-oriented queries such as querying the existence of objects (commercial owners) and processes;
- Perform object-oriented queries such as tracking the development and histories of objects;
- Perform process-oriented queries such as querying the number and occurrence of commercial ownership changes;
- Perform location-oriented queries such as determining which cadastral parcels have been subdivided or consolidated

If we are to model future changes in carbon storage, the queries and analyses as described above will provide information on trends in ownership and land management over the past twenty-five years in our study area. With sufficient carbon-related data collected over the same time period, we should be able to draw correlations between the datasets and thus determine how carbon storage in the atmosphere has responded to these trends in ownership and land-use. If we are able to predict and model the changes in these trends through the information gained from the data model, we should successfully be able to predict and model future changes of carbon storage.

6. REFERENCES

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