

## A MULTI-SCALE GIS DATABASE MODEL BASED ON PETRI NET

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### ABSTRACT:

In cartographic generalization, cartographic entities would change with scale. State and event are two basic elements to describe these changes. However, current hierarchical multi-scale representation models put more emphasis on the representation of state, rather than on the event that causes the state to change. In this paper, elementary concepts such as scale reference system, scale event are firstly discussed, and then a Petri-net-based multi-scale representation model is proposed, in which place, transition, and arc of a Petri net are used for describing state, event of and relations between cartographic entities. Finally, by making some experiment benefits of this model are analyzed in great detail.

### 1. OVERVIEW OF PREVIOUS STUDIES

As applications for geographic information systems have been continuously extended and the demanding level has been increasingly on the rise, it is more and more demanded that geographic phenomena should be observed, interpreted, and described at different resolutions, and at different spatial scales (Sun, 2002). Current study shows that multi-scale representation of map features is implemented in existing basic map databases by representing, organizing, and managing their information at a single scale (Wang, 2003). This hierarchical multi-scale model can represent snapshots at a specified scale, which ignores relations between different representation instances of the same cartographic entity at different scales, thus makes it unsuitable for updating cartographic data (Sun, 2002) and spatial analyzing (Kilpelainen, 1997; Parent, 1998) and also difficult to guarantee consistency (Wu, 2002) among different representations of the same cartographic entity. Therefore, it is highly demanded that different representations of the same cartographic entity should be organically associated with each other (Kilpelainen, 1997; Parent, 1998). Current GIS and database management systems seldom provide functionality of processing multi-scale spatial data, and as a result data updating takes a great deal of time (Jones, 1996). Moreover, the process of generalizing spatial data should be saved (Hae-Kyong, 2004) for better updating multi-scale spatial data, managing its consistency, and further decreasing manual interruption (Jones, 1996) involved in data update. Thus current study should lay much importance on how to effectively create a multi-scale representation model (Stefanakis, 2003) for cartographic entities and also how to effectively deal with them. In this paper, Petri net is used to effectively describe our spatio-temporal model (Yin, 2004), and also represent scale-based spatial data model, thus clearly describing states of representation instances, scale events, and relations between them, and finally providing theoretical basis for the solving of multi-scale representation problems.

Cartographic generalization is the perfect method used in multi-scale representation. But it is difficult to be fully realized in a short period (Wang, 2003). At present, the most primary mean is using hierarchical tree/graph structure to realize maps in a series of specific scales (Wu, 2002; Stefanakis, 2003; Peter,

1995). Take Series of Maps for Nation Basal Scales for example, representation instances of the same cartographic entity under different scales are linked together with the help of some models such as Stefanakis's semi-structured data model (SSD) (Stefanakis, 2003), Wang Yanhui's extended E-R models (Wang, 2003) and so on. Their disadvantages are as follows: (1) There exists "state" of a representation instance at a "specific scale", overlooking the scale events between different representation instances; (2) Redundancy exists in Multi-scale map data in that the same representation instance is stored several times in GMS (Generalized Map Series); (3) Representation instances have no scale zones, which makes it difficult to realize continuous scalar changes in representation instances.

The scale granularity of a hierarchical model is the same to its hierarchy level, while it disagrees with generalization events of cartographical objects. In this way, it ignores details of cartographic generalization, and makes it hard to represent cartographic objects' generalization process, thus leading to discontinuous changes in the same cartographic objects at different scales. Meanwhile, as result of subjectivity in cartographic generalization, different experts may generalize the same map differently (Guo, 1998). Therefore, it is rather necessary to record, compare, and evaluate the process of generalization. As for the simulating of cartographic generalization, there are some advantages, here are: (1) helpful for recording methods and techniques used by cartographic experts; (2) helpful for comparing the process of cartographic generalization made by different cartographic experts, and also for summarizing knowledge and rules of cartographic generalization; (3) helpful for simulating changes in the same cartographic entities at different scales; (4) helpful for evaluating specific methods of cartographic generalization; (5) helpful for map updating, so that, when some geographical features at a certain scale change, map updating at other scales can be achieved by quickly finding other changed representation instances with the help of correlations between representation instances. As for our Petri-net based multi-scale representation model, it not only shows its strength in the research, evaluation, and also simulation of cartographic generalization, but also in recording cartographic generalization and its formal representation.

**2. BASIC CONCEPTS**

**2.1 Scale**

Scale, an important property of spatial data, refers to the comparative sizes of both spatial extent and time represented by data, so that there is a big difference between information densities represented by different scales (Wang, 2001). Scales in geography can be interpreted in two aspects, the comparative size and the abstract level; while scale is described as “map scale” in cartography (Wang, 2003). Scale dimension is continuous as time dimension and can be depicted by a reference system, i.e. scale dimension, scale origin, and scale value. A line with an arrowhead is used to represent a scale, which has its origin and direction (Figure 1). In a map, scale is used to describe a scale reference system. Scale direction starts from the scale origin that sets at the scale “one to one”, with two opposite directions, one negative because of its denominator being bigger than one, and the other positive because of its denominator being smaller than one. Seen from the macro aspect, the first can be considered as the abstraction of our real world; while from the micro aspect, the second as the magnification of this real world. Scale value can describe scale variable in the form of “1 to m”; the larger the denominator, the bigger the scale value. There are basic types for scale: scale point, and scale zone. Scale point refers to the size of scale origin, such as this “1 to 10000” scale point represented as a point in our reference axis; scale zone means the scale range between two scale points, such as this [1:10000, 1:250000] scale zone represented as a line segment in our reference axis. Compound scale can be obtained by integrating these basic scale types.

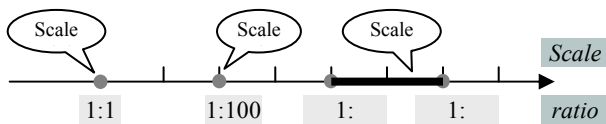


Figure1. Reference System of Scale

**2.2 Introduction to Petri Net**

Petri Net (PN) was proposed by C.A.Petri in 1962 as a mathematical model for the study on information systems and their interrelationships, including place, transition, arc and token. With its intuition, visibility and many fine mathematical properties, Petri Net has been widely applied to fields such as distributed systems, information systems, and discrete event systems and so on.

Formal languages can be used to describe Petri Net, whose static structure corresponds to a three-tuple  $N(P,T,F)$ . It can also be represented by a graph, called the Petri Net Graph. In this graph,  $F$  is the set of arcs linking  $p$  and  $t$  in two directions, among which  $p$  and  $t$  refers respectively to the element of set  $P$  and set  $T$ , with  $P$  the set of places, and  $T$  the set of transitions. Therefore, the structure graph can be regarded as directional two-tuple graph. Place usually refers to the state of this system, represented by a circle “O”; transition corresponds to the event changing the state, represented by a short vertical line “|”; arc links state and event; net structure  $(P,T;F)$  describes relations between state and event or system rules. Token is added to the

net graph to enhance Petri Net’s functionality of simulating, not only static phenomena but also dynamic one.

**3. A MULTI-SCALE SPACE REPRESENTATION MODEL BASED ON PETRI NET**

**3.1 Scale Events**

Scale changes cartographic entities by cartographic generalization. While the same cartographic entity is represented at different scales, its representation instances may change in spatial location, shape and type, which evokes events such as classification (aggregation or disaggregation), simplification (delete, structure simplification or shape simplification), exaggeration (displacement, combination, segmentation) etc. Representation instances of the same cartographic entity may change at different scales (from a large scale to a small one) in the process of generalization. Some will be deleted, or replaced by other representation instance at a different position, or form a new symbol in the integration of other symbols.

The cartographic entity, as element of a map, may have different representation instances at different scales (JONES, 1996). Take the cartographic entity man-made lake for example. It can have different representation instances at different scales, which can have different spatial geometry types (such as point, line, and area, and even no type) and different attribute types (man-made lakes, unsalted lakes, lakes and so on). In map generation, scale events happen to representation instances, thus leading to changes in their spatial geometry and attributes.  $R_i (i \in n)$  represents some representation instance (Figure 2) and  $S_i (i \in n)$  refers to some scale. Here,  $R_1$  refers to a meadow, with  $R_2$  a forest,  $R_3, R_4, R_6, R_7$  and  $R_8$  belonging to vegetation, and  $R_5$  a lake.  $R_1$  and  $R_2$  at scale  $S_1$  is changed into a new representation instance  $R_3$  at scale  $S_2$ , with their attribute type changing accordingly from meadow and forest to vegetation. Then  $R_3$  at scale  $S_2$  is simplified to  $R_4$  at scale  $S_3$ , with shape simplification occurring.  $R_5$  at scale  $S_3$  is first deleted, and then changed into  $R_7$  and  $R_8$  at scale  $S_4$ , with segmentation happening to them. Pointers can be used to describe relations between entities and generalization events.

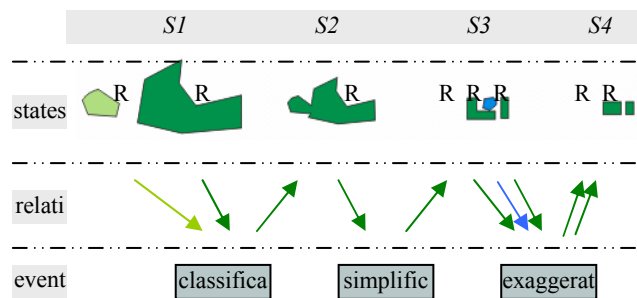


Figure2. Types of Scale Events

**3.2 Basic Principles**

A basic requirement for cartographic databases is to provide representation instances of the same cartographic entity at different scales and also to relate them with each other (JONES, 1996). Now that scale is a continuous dimension, representation instances of the same cartographic entity at different scales

should vary continuously with scale. The scale range between when a representation instance occurs and when it dies, is considered as its scale life cycle; while its spatial geometry and attributes which stay constant in this life cycle are taken as its states. In figure 3[d], the wide and horizontal line segment represents the state of a representation instance, while its length shows the life cycle of this representation instance. In figure 3[a], RI1 at scale S1 and SI1 at scale S3 have the same spatial geometry and attributes, so they should belong to the same representation instance; but as for RI4 at scale S1 and RI5 at scale S2, they belongs to different representation instances in that they are simplified in spatial geometry.

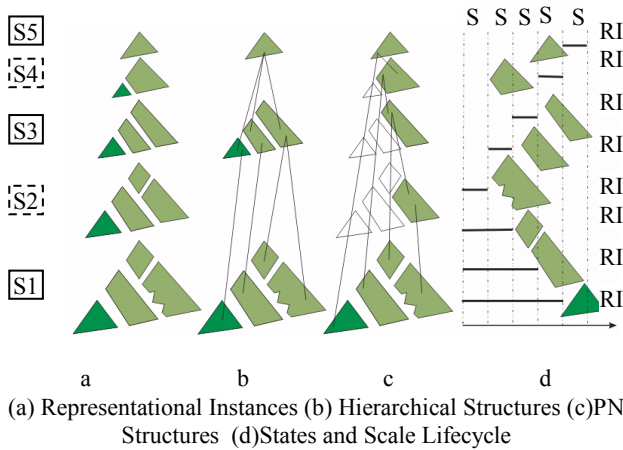


Figure 3. Models of Multi-Scale Representation

Therefore, as for a cartographic entity, its life cycle can be obtained by summing life cycles of all its representation entities together. This paper is intended to focus on representation instances, and make research on their states, scale events and correlations between these states and events. Scale events relate inevitably to states, in that it is the scale event that changes a state of a representation instance to another state. Seen from a reasoning aspect, a scale point is an event's location in the one-dimensional space; while a scale zone is the scale range represented by a straight line between these scale points. The one-dimensional topology between one-dimensional scale zones is named scale topology, which includes relations between two one-dimensional scale zones, such as the first zone meeting with the second, intersecting it, being apart from it, being contained by it and so on.

### 3.3 A multi-scale Representation Model Based on Petri net

Pet Net has place, transition, and arc as its elements, which are respectively used to describe states of a representation instance, its scale events, and relations between these states and events. In this way, not only a multi-scale map is represented, and the topology between scale zones can also be explicitly represented. In figure 4, a circle represents a state, described by a scale zone; a wide short line represents an event, described by a scale point  $S_i$  (some arbitrary scale, not specified one); a straight line shows the relation between states and events.

When it comes to the multi-scale hierarchical model, its scale variable can only choose finite (non-scalable) scales; while in our PN-based multi-scale model, the scale variable  $S_c$  can make continuous changes in the valid scale ranges, providing theoretic bases for the implementation of a scalable map.

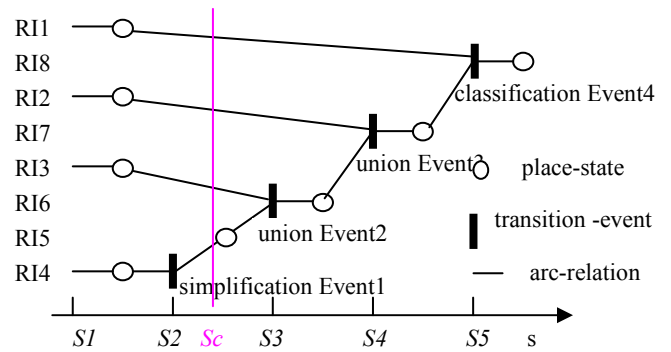


Figure 4. Multi-Representation based on Petri Net

The resolution of representation instances represented in current tree/graph-based multi-scale hierarchical representation model is only in conformance with the sampling interval. There are three scales in figure 3b, S1, S3 and S5. Snapshots at scale S1 are RI1, RI2, RI3 and RI4; while as for scale S3 there are snapshots such as RI1, RI2 and RI6, with S5 having only one snapshot. Seven edges should be recorded to save relations between representation instances. However, changes of details at scale S2 and S4 are ignored, such as the simplification event changing RI4 at scale S1 to RI5 at scale S2, and the amalgamating event changing both RI5 and RI6 at scale S3 to RI7 at scale S4, both of which show that cartographic data vary greatly with scale. RI1 and RI2 are repeatedly stored at scale S1 and scale S3, thus giving difficulty in data updating.

The PN-based multi-scale representation model records relations between basic scale events and representation instances with high resolution, with these events defining both the starting scale value and the ending scale value of a state of a representation instance. In figure 3c, as for the number of edges and the number of representation instances, PN model seems the same to the hierarchical model, but it can described twice the amount of detail as the hierarchical one, thus reducing data redundancy (unfilled polygons in the figure).

## 4. THE IMPLEMENTATION OF OUR PETRI NET BASED MULTI-SCALE MODEL

A multi-scale model based on extended E-R model is proposed by Wang Yanhui (Wang, 2003), including three fundamental elements: entity, attribute and relation. A entity may be just a entity of basic types (point, line, area), and also can be some complex one composed of these basic entities, such as a city, a building, a road and so on; attribute involves spatial attribute and non-spatial attribute; as for the relation, it can be divided into two types, spatial relation and non-spatial relation, made up of four basic semantic types (aggregation, generalization, classification, association), which can effectively reflect semantic relations between different representations involved in cartographic generalization. If Petri Net is used to represent this model, entities and relations expressed in E-R model will turn to location and transition in the PN model, while restrictions between entities and relations in E-R model will correspond to directional arcs in the PN model. However, this multi-scale model based on extended E-R model revolves around snapshots of a specified scale point, but our PN-based multi-scale model is oriented to representation instances with "scale lifetime".

This model can not only organically associates states, events and their relations with each other, but also can implement queries based on states, events and relations, and also is tailored to both multi-scale based analyses and data update applied in GIS and cartographic databases. This querying functionality can be divided according to the structure of PN as follows: 1) state-based queries, used to query states of representation instances of the same cartographic entity at different scales; 2) event-based queries, used for queries of events which change states of representation instances; 3) relation-based queries, intended to query relations between states and events of representation instances. In another aspect, this functionality can also be divided into two following types by the scale concept: (1) scale point queries. i.e. scale snapshot queries; (2) scale zone queries, queries of cartographic objects which have scale events in a certain scale zone. This PN-based multi-scale model, as a model for database organization and storage, can reduce data redundancy and therefore save more storage space compared with the hierarchical model. But because of the complexity of PN model, it takes more time than the hierarchical one when applied to query scale snapshots. Data source in our experiment is obtained from figure3, with Event1, Event2, Event3, Event4, respectively at scale 1:10,000, scale 1:50,000, scale 1:100,000, and scale 1:500,000. Tables of states, events, and directional arcs can be created with MapInfo (Figure 5).

Events	description	arc_of_states_changed	arc_of_states_created	scale_of_event
Event1		Arc(Event1,RI4)	Arc(Event1,RI5)	10,000
Event2		Arc(Event2,RI3)	Arc(Event2,RI6)	50,000
Event3		Arc(Event3,RI2)	Arc(Event3,RI7)	100,000
Event4		Arc(Event4,RI1)	Arc(Event4,RI8)	500,000

States	geometry	start_Event	end_Event
RI1	NULL	Event4	
RI2	NULL	Event3	
RI3	NULL	Event2	
RI4	NULL	Event1	
RI5	Event1	Event2	
RI6	Event2	Event3	
RI7	Event3	Event4	
RI8	Event4	Event5	

arcs	states	next_arc
Arc(Event1,RI4)	RI4	NULL
Arc(Event1,RI5)	RI5	NULL
Arc(Event2,RI3)	RI3	Arc(Event2,RI6)
Arc(Event2,RI6)	RI6	NULL
Arc(Event3,RI2)	RI2	Arc(Event3,RI7)
Arc(Event3,RI7)	RI7	NULL
Arc(Event4,RI1)	RI1	Arc(Event4,RI8)
Arc(Event4,RI8)	RI8	NULL

Figure 5. The Tables of the Petri Net-based Multi-Scale Model in MapInfo

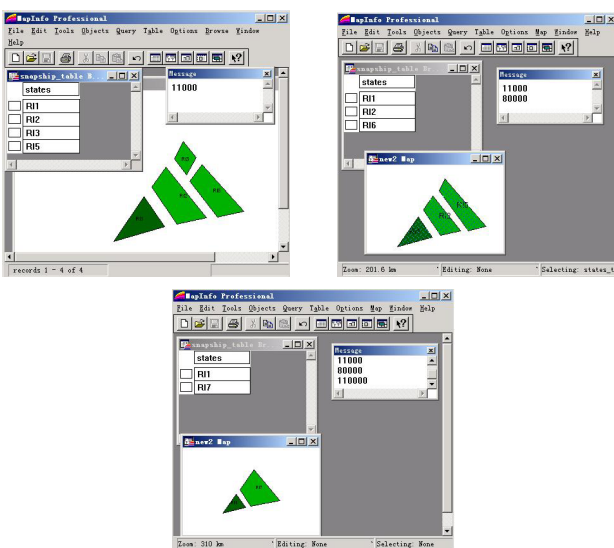


Figure6. The Snapshot Querying Operation on any Scale

Scale snapshot queries are made to exemplify how this PN-based multi-scale model can implement scalable scales. Here we can input three “random” scales (1: 11000, 1:80000 and 1:110000) to query three snapshots (See figure 6). But these queries can’t be implemented in the hierarchical multi-scale model, which only supports queries of snapshots at a specified scale.

Queries of states of specified representation instances can track changes and events evoked when these representation instances vary with scale, and further provide convenience to update in cartography. When update of representation instances of large-scale cartographic data is made, multi-scale update can be achieved by first using a pointer to search for according representation instances of a series of small-scale cartographic data and then making updates according to the scale events, which further guarantees consistency of multi-scale spatial data. Meanwhile, those unchanged representation instances can stay constant at a series of scales, which avoids repeated map generalization and greatly reduces the amount of labour work done by cartographers.

Spatial objects have six-dimensions, such as x, y, z (in the geometrical space), attribute, time, and scale. Time and scale can respectively change geographical objects in quantity or in quality, with their spatial geometry and attributes changed, thus producing geographical objects of different time and scale versions. In current GIS, time sequence maps mainly adopt the snapshot sequence model, while the scale sequence model uses the single sequence scale model. Scale can change attributes of a spatial object, through classification, and also can change its properties of spatial geometry by simplification, amalgamation, segmentation, displacement, deletion, exaggeration, and some complex operation. When time doesn’t vary, a cartographic object only changes with scale, forming the scale sequence model. This still holds for the scale. A cartographic object can only change with time, if scale doesn’t vary, forming time sequence model. Time possesses basic properties such as states, events, and relations just as scale does, so our Petri Net model can also be used to represent these properties of time, with place, transition, and directional arc respectively corresponding to its state, event and relation (Yin, 2004).

5. CONCLUSIONS

In current multi-scale representation, how to build and manage relations between original features in GIS and their derived representation instances becomes a really hard problem]. By combining benefits of both multi-scale representation and the Petri Net model, a Petri-net based multi-scale representation is put forward in this paper, which can explicitly express the same geographical feature’s representation instances, and scale events, and relations between them as well. It is experimented that queries of scalable scale snapshots can be effectively implemented in our proposed model, giving benefits to the updating of multi-scale maps.

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