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Analyzing topological changes for structural shape simplification ☆

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ABSTRACT

The shapes of regions tend to be simplified with the decrease of spatial scale or resolution, which further leads to topological changes. Analyzing topological changes is an important aspect of formalizing semantic relations. An important fact is observed that shape simplification can be considered as a combination of generalizing basic primitives. Based on this fact, a shape is decomposed first into a set of simple primitives including convexities and concavities. And then the topological changes between lines and regions can be derived from the relations between lines and primitives. The approaches presented in this study can help to analyze the exact types and locations of topological changes for generalizing convexities and concavities, respectively. The approaches need not to conduct the real simplification of shapes, and they instead incorporate the idea of simplification for deriving the changes. Thus, they are independent on the algorithms of geometrical simplification. A prototype is developed and tested using the real world examples. The results show that the approaches in this study are helpful to analyze topological changes for shape simplification.

1. Introduction

Multi-scale spatial data have received much attention in recent years as their wide applications in traffic, land use/cover, etc. With the decrease of spatial scale or resolution, the details of spatial objects will be reduced, so is topological knowledge between spatial objects. Map generalization can coarsen spatial data at the detailed level, and thus change the shapes of spatial objects and topological relations. Topological changes are caused by diverse operators of map generalization, such as merge, dimension reduction, and shape simplification, etc. Different operators lead to different topological changes. For example, although roads do not intersect multiple residential regions at a detailed level, it is acceptable if the roads intersect the merged regions at a coarse level. But for shape simplification, it is not acceptable if the relations between roads and lakes change greatly over scales. From cartographic perspective, topological relations should be preserved during map generalization [14]; topologically consistent data is an important source for progressive transmission and query of multi-scale vector data, [3,5,22,23,32]. Therefore, it is fundamental to analyze the topological changes for different operators of map generalization.

Shape simplification can make complex shapes simpler and smoother by reducing redundant points or bends, while retaining important ones. The algorithms for simplifying shapes can fall into two groups: the geometrical- and structural-based. The former uses some geometrical criteria to determine which components can be removed or retained. The typical algorithms of this group include the Lang simplification algorithm [21], Douglas–Peucker method [15], Cromley's hierarchical approach [11], and Buttenfield's strip tree [7]. The structural-based methods divide first a shape into a set of primitives (such as bends,

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curves, etc.), and then analyze the measurements (such as the sizes, directions, average widths, depths of bends) on these primitives to determine the abandoned or preserved primitives. The classical approaches include hierarchical simplification based on a binary tree representation [2], and Wang's line generalization based on analysis of shape characteristics [30]. The geometrical methods are designed to inherently compress the geometric coordinates, thus cannot obtain satisfactory results. The structural methods are closer to the visual cognition of people on shapes, and the esthetic quality [2].

Topological changes over scales are the key topics in the cartographic and spatial database fields. In cartography, more attention were paid on the approaches for avoiding topological changes by introducing the inconsistent detect algorithms into the simplification [6,12,13,24,29,30,31,33]. In the field of spatial database, spatial reasoning approaches were presented to simulate the generalization process to obtain topological changes of the same pair of spatial objects at different scales for different operators of map generalization [1,4,8,16,17,20,25–28]. The existing simplifications concentrate on simplifying the shapes of regions using various geometric algorithms. Therefore, they do not formalize the topological changes caused by shape simplification, and cannot provide the information for maintaining topological consistency. The existing reasoning methods are mainly designed for analyzing topological changes caused by the following generalization operators, such as collapse operator [20], networks generalization [27], merging regions [28], etc. However, no approaches have been presented to handle topological changes for structural shape simplification. From the perspective of cartographic generalization, an effective shape description [9,10] should be explicitly used; from the perspective of topological changes, the effects of shape simplification on topological relations should be modeled; from the perspective of topological changes, the detailed information about changes should be obtained. The shape description, shape simplification, and topological changes should be closely correlated, but there still lack such a work.

As topological relations are related to the shapes of spatial objects, a shape-explicit representation is presented in this study. In the representation, the regions with complex shapes are decomposed into a set of basic primitives with simple shapes including convexities and concavities; the topological relations between a line and the primitives are also recorded. Therefore, this representation can help to model the association between the shapes and the topological relations. Based on the fact that shape simplification results from the combination of filling concavities and removing convexities [2], approaches are presented to derive the detailed information about topological changes caused by generalizing primitives. The approaches consider the effects of shape simplification on topological relations, thus they can derive directly the detailed changes for generalizing primitives. As the approaches are independent on the algorithms of geometrical simplifications and shape decompositions, they are generic and useful in different shape simplifications.

Table 1
Notations.

Notations	Meanings
R	A region
L	A line
R_s	A simplified region
R°, ∂R, and R^-	The interior, boundary, and exterior of a region R
L°, ∂L and L^-	The interior, boundary, and exterior of a line L
$T[\circ,\circ]$, $T[\circ,\partial]$, $T[\circ,-]$, etc.	The intersections between the interior of a region R and the three subsets of a line L
$T_s[\circ,\circ]$, $T_s[\circ,\partial]$, $T_s[\circ,-]$, etc.	The intersections between the interior of a simplified region R and the three subsets of a line L
$I_1, I_2, \ldots, I_n$	The concavities of a region
$V_1, V_2, \ldots, V_m$	The convexities of a region
$Count_i[\partial R,\partial]$ and $Count_i[\partial S,\partial]$	The numbers of end-points of a line L inside the two parts ∂R_i and ∂S_i
T	The topological relation between a line L and an original region R
T_s	The topological relation between a line L and the simplified region R_s of region R
T_i	The topological relation between L and a primitive of shape decomposition of region R
$T \otimes T_i$	The derivation of the simplified relation between L and R_s from shape simplification
$\oplus$	The conjunction of some conditions
$Child(V_i)$	All the primitives covered by V_i
$Parent(V_i)$	All primitives covering V_i

Topological relations are introduced in Section 2. Section 3 presents a shape-explicit representation based on the shape decomposition. The traditional and presented methods for topologically consistent simplification are discussed in Section 4. Section 5 presents the approaches to derive topological changes caused by filling concavities and removing convexities, respectively. Section 6 decomposes the shapes hierarchically and derives the changes for hierarchical shape simplification. Section 7 defines local and global topological changes, and uses case analysis to illustrate the usefulness of the approaches. Conclusions and future work are summarized in Section 8. The used symbols in this study are summarized in Table 1.

2. Topological relations between lines and regions

A line or region can divide the plane into three subsets: interior, boundary and exterior [18,19]. The nine intersections (Eq. (1)) formed by the three subsets can determine the 19 valid line-region topological relations (Fig. 1).

$$T(R,L)=\begin{bmatrix} R^\circ\cap L^\circ & R^\circ\cap\partial L & R^\circ\cap L^- \\ \partial R\cap L^\circ & \partial R\cap\partial L & \partial R\cap L^- \\ R^-\cap L^\circ & R^-\cap\partial L & R^-\cap L^- \end{bmatrix} \quad (1)$$

where R°, ∂R, and R^- refer to the interior, boundary, and exterior of the region R, respectively; L°, ∂L and L^- are the three subsets of the line L.

The 19 line-region relations (Fig. 1) are useful to derive the topological changes for shape simplification. As shown in Fig. 1, the three intersections about the exterior of a line are always non-empty, thus only the six intersections about the interior and boundary of a line are useful to