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Visualizing and representing the evolution of topological features

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Abstract

Simplicial complexes are discrete representations of topological spaces that are practical for computational studies. The first three Betti-numbers (indicating the number of components, tunnels and voids), as well as the topological persistence of each such feature, is well-defined and can be efficiently computed for simplicial complexes embedded in 2D and 3D [1, 2].

We introduce a novel representation of the evolution of topological features in simplicial complexes using so-called tunnel-trees in 2D and void-trees in 3D. This new representation makes it possible to analyze topological evolution by applying tools for analysis of binary trees. Furthermore it supplies a new method for visualizing topological evolution.

Introduction

A simplicial complex, \( K \), is a set of simplices where any face of a simplex in \( K \) is also in \( K \) and the intersection of two simplices in \( K \) is either empty or a face of both simplices. Delfinado and Edelsbrunner [1] define a filter to be a sequence of simplices, \( \sigma^1, \sigma^2, \ldots, \sigma^n \), where \( K_i = \{ \sigma^1, \sigma^2, \ldots, \sigma^i \} \) is a simplicial complex for any choice of \( i \) (see left part of Figure 1). The filter represents the evolution of a simplicial complex and will be the focus of the methods described here. The topological features of a complex can be described using the Betti-numbers, \( \beta_d \), which indicate the rank of the \( d \)th homology group. The first three Betti-numbers \( (\beta_0, \beta_1, \beta_2) \) can be interpreted more intuitively as the number of components, holes, and voids respectively.

A \( O(na(n)) \)-time algorithm exists to calculate the evolution of \( \beta_d \) as a simplicial complex is grown using a filter [1]. This method identifies each \( k \)-simplex, \( \sigma^i \), as either positive if it creates a new \( k \)-cycle and thereby increases \( \beta_k \), or negative if it changes a \( k \)-cycle into a \( k \)-boundary and thereby decreases \( \beta_k-1 \). For each positive \( k \)-simplex, \( \sigma^i \), the negative \((k + 1)\)-simplex, \( \sigma^j \), that is responsible for turning the \( k \)-cycle, created by \( \sigma^i \), into a \( k \)-boundary can be efficiently identified [2]. The difference between the indices of such two simplices is defined to be the persistence of the \( k \)-cycle represented by \( \sigma^i \).

Tunnel- and void-trees

One interesting observation about tunnels in simplicial complexes embedded in 2D is that, often, when a positive \( 1 \)-simplex (edge) is added to the complex, it splits one tunnel in two. If the empty space around the complex is considered a bounding tunnel, then every positive edge will split an existing tunnel in two. Similarly, if the entire space around a simplicial complex embedded in 3D is considered a bounding complex, then a positive \( 2 \)-simplex (triangle) always splits an existing void in two.

Based on this observation we define a tunnel-tree (or \( \beta_1 \)-tree) of a 2D filter to be a binary tree where each node represents a distinct tunnel (see right part of Figure 1). The root is the bounding tunnel, and the leaves are triangular tunnels that will not be split further. With each node \( n \) we associate the positive edge that represents the tunnel, \( \epsilon(n) \), and with each leaf, we associate the negative triangle that fills this tunnel, \( \tau(n) \).

The tunnel-tree is ordered such that for any node \( n \), the triangle of the rightmost leaf, \( \tau(\text{Tree-Max}(n)) \), is the triangle that ‘destroys’ \( \epsilon(n) \) and hence determines its persistence. A void-tree (or \( \beta_2 \)-tree) of a 3D filter is defined in a similar fashion, only with positive triangles as nodes and negative tetrahedra as leaves.

A \( \beta_k \)-tree is constructed by running through the filter backwards as shown in Algorithm 1. Leaves are created when a negative \((k + 1)\)-simplex is encountered and the roots of leaves are connected when positive \( k \)-simplices are encountered.

Algorithm 1 Build a \( \beta_k \)-tree given a filter

1: Create a ‘bounding node’, \( n_b \)
2: for \( i = n \) to 1 do
3: if \( \sigma^i \) is a negative \((k + 1)\)-simplex then
4: Create a new node, \( n \), and set \( \tau(n) \leftarrow \sigma^i \)
5: else if \( \sigma^i \) is a positive \( k \)-simplex then
6: \( (n_0, n_1) \leftarrow \text{Nodes of the two } (k + 1)\text{-simplices adjacent to } \sigma^i \)
7: \( (n_0, n_1) \leftarrow (\text{Root}(n_0), \text{Root}(n_1)) \)
8: Swap \( n_0 \) and \( n_1 \) if \( \tau(\text{Tree-Max}(n_0)) \) is younger than \( \tau(\text{Tree-Max}(n_1)) \)
9: Create a new node \( n \) with \( n.left \leftarrow n_0 \), \( n.right \leftarrow n_1 \), and \( \epsilon(n.left) \leftarrow \sigma^i \)
10: end if
11: end for
12: return Root(\( n_b \))

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In line 4, the \((k+1)\)-simplex can be associated with its node using a hash-map. This ensures that locating the nodes of adjacent \((k+1)\)-simplices in line 6 can be performed in constant time. In line 6, if one of the \((k+1)\)-simplices adjacent to \(\sigma_i\) is not defined then the bounding node \(n_b\) is used instead. If \(\sigma_i\) has no adjacent \((k+1)\)-simplices then a new node is created for \(n_0\), and \(n_1\) is set to \(n_b\). Line 8 guarantees that the youngest simplex in a subtree can always be found by going to the far right in the tree using Tree-Max.

A \(\beta_k\)-tree may be arbitrarily unbalanced, so a straightforward implementation will run in \(O(n^2)\) time worst case. The Tree-Max-method can be improved to \(O(1)\) time by maintaining the maximum of each sub-tree as they are constructed. A data structure similar to disjoint-sets can be used to make the Root method run in \(O(\alpha(n))\)-time, so the entire method runs in \(O(n\alpha(n))\) worst case time.

**Applications**

One attractive property of \(\beta_k\)-trees is that they give an alternative representation of the topological evolution of a filter. This can be used in several ways.

First, the fact that simplices in the subtree of a particular node will tend to be spatially close to each other gives rise to a new definition of **local persistence**. A particular edge, representing a tunnel, might be deemed particularly persistent if its subtree contains more than a certain number of nodes. Such a definition of persistence will not be affected by the addition of simplices outside the tunnel.

Using a Delaunay complex and the radius of the smallest empty circumcircle to generate an \(\alpha\)-filter [3], the arrangement of a particular sub-tree also gives an indication of the shape of the corresponding feature. For instance, a node with an unbalanced sub-tree indicates a tunnel that is narrowing, whereas a balanced node indicates a constant width.

For some applications, a tree might be a better visualization of the topological evolution than e.g. \(k\)-triangles [2]. The above mentioned properties of locality can be computationally analyzed, but they can also be derived simply by inspecting \(\beta_k\)-trees. The length of edges in the tree can furthermore be scaled to reflect the difference in birth time of the \(\epsilon(n)\) simplices.

Another interesting property of \(\beta_k\)-trees is that all \((k+1)\)-simplices within a particular tunnel/void are easily identified by locating the node in the tree with the desired \(\epsilon(n)\) and then collecting all leaves in the subtree using any tree-traversal method. In this manner the area of tunnels/volume of voids, for instance, is easily calculated.

Finally, any analysis method that works on trees is now applicable to topological evolutions. For instance the topology of two point-sets can be compared by finding the tree-edit-distance between the tunnel-trees (or void-trees) of their respective \(\alpha\)-filters.

**References**

