Research Contribution

Accurate Reconstruction of a 3D Object Composed of Multiple Surfaces

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In order to observe in detail the internal structure of a multi-layered object consisting of various elements, it is very important to reconstruct the original object from its cross-sectional data and display the inner along with the outer appearance of the reconstructed object.

This paper describes a technique for reconstructing a 3D object from complex contours on the cross-sections efficiently and faithfully. The proposed method succeeds even when the object's shape varies radically between successive cross-sections: cross-sections with radically different contours and/or radically different contour line segments are automatically supplemented.

The usefulness of the proposed method is demonstrated with some semitransparent and stereoscopic displays of a reconstructed mouse embryo.

1. Introduction

In order to observe the internal structure of a complex, multi-layered, three-dimensional object, the method of cutting the object into thin cross-sections, extracting the contour lines on the cross-sections, and displaying the object as reconstructed from the contours by using a semitransparent, stereoscopic display method, is commonly used, particularly in the field of medical anatomy.

In the latter field, the process consists of the following steps:

(1) The organism is sliced into thin cross-sections, rendering the inner structure visible.

(2) The contour lines of the inner structures are extracted from microphotographs and entered into a computer database.

(3) The 3D shape of the organism is reconstructed from the contour data.

(4) The resulting data is displayed by using standard computer graphics techniques.

In this paper, we will discuss the process of reconstructing the organism from contour data. A widely used method is to fill the area between contours on consecutive cross-sections with a triangular mesh. Fuchs et al. [1] proposed generating the triangular mesh with the minimum surface area. This method generates a good mesh, but fails when the shape exhibits branches or open regions. Ganapathy et al. [2] improved on the Fuchs method, but still failed to handle branches.

Christiansen et al. [3] added a technique for handling branches to the Fuchs mesh algorithm. The method is simple, and generates a good mesh, but fails if the shape changes radically between consecutive cross-sections. In addition, it does not account for multiple surfaces occurring on a single cross-section, nor for open contour lines.

Zyda et al. [4] described a method for dealing with multiple surfaces. It determines which pairs of contours should be connected, by examining the ratio of overlap of the bounding boxes of each of the candidate contours. However, the method is not suited to highly convoluted or extremely narrow contours.

Boissonnat [5] proposed a method for reconstructing an object from scattered data points in three-dimensional space. However, the method is not usable if the object has multiple surfaces and/or open regions; furthermore, it cannot use the method of reducing the calculation time by sorting the elements in order of depth of these elements from the viewpoint for display, because the elements are not generated in cross-sectional order.

We have previously described an improvement [6,7] to Christiansen's method that handles multiple contours as well as open contour lines. However, it fails for the complicated shapes that occur in some organisms. In order to compensate, the sampling density of cross-sections, as well as of points on the contour lines, must be increased, resulting in large amounts of data and a long computation time.

In this paper we describe a reconstruction method that succeeds even when the cross-section sampling density is fairly low; additional contour lines from the

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original object are automatically inserted in the inter-cross-sectional region as required. The required memory and computation time are both reduced.

2. Determination of Inter-Cross-Section Interval Based on Complexity of Contour Lines

2.1 Difficulties Inherent in Previous Methods

In Christiansen's work, the inter-cross-sectional interval is fixed, and the mesh generation always begins with the closest pair of points (called initial points) on the pair of contours (see Fig. 1). Mesh generation proceeds via the contour point closest to one of the initial points. Because the mesh elements are generated in cross-sectional order, the time required to sort elements in order of depth from the viewpoint, for display, is greatly reduced.

For shapes of the types depicted in Fig. 2, namely branching, open regions, and surfaces nearly parallel to the cross-section plane, this method fails unless the number of cross-sections is very small. It fails because contours on consecutive cross-sections are of radically different shapes; the generated triangular patches are very slender, and the reconstructed object fails to reflect the shape of the original object. These problems can be countered by increasing the sampling density of the cross-sections and the contour points, but at the expense of larger data structures and increased calculation time.

Our new method automatically inserts cross-sections in intervals that give rise to the problems mentioned above. The original cross-sections are called basic cross-sections; the new cross-sections are called additional cross-sections. The data for the additional cross-sections must be obtained from the original object.

2.2 Reconstruction of Objects with Radically Changing Contours

Additional cross-sections are automatically inserted wherever the contours on consecutive cross-sections are found to be of radically different shapes; the number of cross-sections inserted depends upon the extent to which the contours on the basic cross-sections differ.

As basic cross-sections are processed, they are examined for the following conditions:

(1) Branching structure,
(2) Upper or lower extremity of an open region,
(3) Surface nearly parallel to cross-sectional plane,
(4) Regions in which the shape changes rapidly.

When any of these conditions are met, a single additional cross-section is introduced, the checks are repeated, and introduction of additional cross-sections continues recursively until none of the conditions is met or until the minimum inter-cross-sectional distance is reached.

Figure 3 shows an example of the algorithm in progress; a branch exists between the pair of basic cross-sections. Additional cross-sections, first 1 then 2, are introduced. The entire inserted contour is used for mesh generation in cases (1) through (3). For case (4), only a portion of the inserted contour is used.

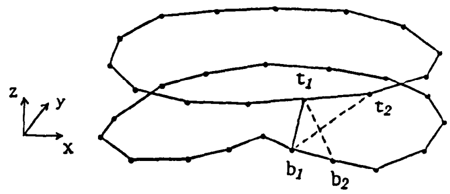
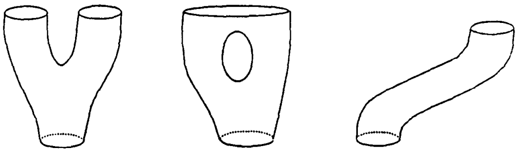


Fig. 1 Christiansen's triangulation algorithm.



(a) Branching (b) Open region (c) Element nearly parallel to cross-section plane

Fig. 2 Three types of element exhibiting radically changing contour lines.

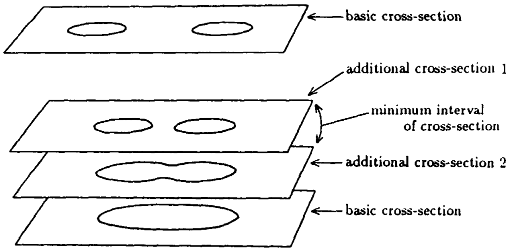


Fig. 3 Insertion of additional cross-section at branch area.

3. Reconstruction Using Entire Contour Line

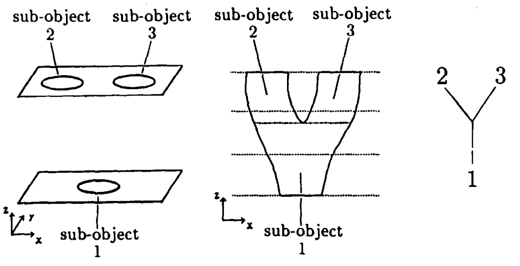
3.1 Detection of Branching Elements

Each contour line is associated, at input, with a sub-object number indicating the surface to which it belongs and uniquely identifying the branch (see Fig. 4). The counnectivity of sub-objects is separately memorized.

When a pair of contours with different sub-object numbers occurs on consecutive cross-sections, the connectivity table is checked to find whether the sub-objects are connected. If they are, a branch must exist between the cross-sections.

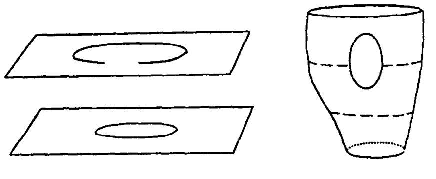
3.2 Detection of Open Regions

When one of a pair of consecutive contours is closed and the other is open, it is known that an upper or lower extremity of an open region exists between the cross-sections (see Fig. 5).



(a) Contour lines (b) Sub-object (c) Sub-object connectivity

Fig. 4 Example of sub-objects and associated connectivity.



(a) Contour lines (b) Open region

Fig. 5 Open region.

3.3 Detection of Surfaces Nearly Parallel to Cross-Section

When the object surface is nearly parallel to the cross-section plane, the distance d between the center points of contours on consecutive sections will be large (see Fig. 6). When d satisfies the condition

$$d > k_1 \min(w_{xt}, w_{xb}, w_{yt}, w_{yb}),$$

an additional cross-section is inserted midway between the cross-sectional planes. Here, w_{xt}, w_{yt}, w_{xb}, and w_{yb} refer to the widths and heights of the upper and lower contours, and k_1 is a constant parameter.

4. Areas of Rapid Shape Change

Insertion of generated contours allows the reconstructed object to more faithfully reflect the shape of the original object. When only a portion of a contour line exhibits a radical change of shape between cross-sections, the required memory and computation time can be reduced by introducing inserted contours only into the problematical portion of the object.

4.1 Detecting Regions of Rapid Shape Change

In regions of rapid shape change, the sides of triangular patches generated by the algorithm in Christiansen and Sederberg [3] become very long (see Fig. 7). In our procedure, when the triangle sides satisfy the condition

$$l_{ij}^2 > k_2(h^2 + s_j^2),$$

a special process for inserting partial contours is initiated. Here, l_{ij} is the distance between b_i and t_j on the pair of cross-sections, h is the distance between the pair of cross-section planes, s_j is the distance between adjacent contour points t_{j-1} and t_j, and k_2 is a constant parameter.

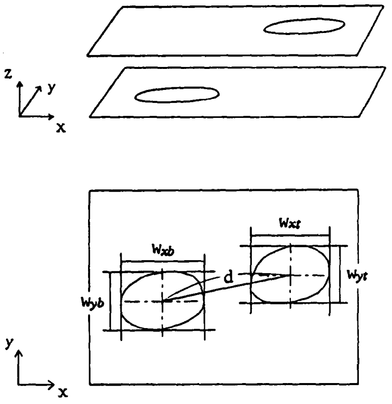


Fig. 6 Object surface nearly parallel to cross-section plane.

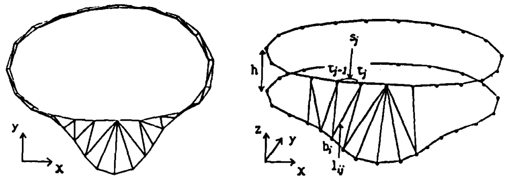


Fig. 7 Example of rapidly changing shape.

4.2 Generation of Partial Contours

Assume that rapid shape change is detected, using the above procedure, in the region including contour points b_i through b_k in the lower cross-section and points t_j through t_l in the upper cross-section ($i<k$, $j<l$) (see Fig. 8). The new partial contour will be generated on plane S, midway between the pair of basic cross-section planes. p_1 and p_2, the intersections between S and the lines b_it_j and b_kt_l, are calculated. Then, c_m and c_n, the new contour points closest to p_1 and p_2, are replaced with p_1 and p_2. The region $p_1, c_{m+1}, \cdots, c_{n-1}, p_2$, is then used as an inserted partial contour.

4.3 Generation of Triangular Mesh Using Partial Contours

Generation of mesh on partial contours mush be handled a little differently than on ordinary contours. First, as shown by the bold lines in Fig. 9 triangular patches are generated in the region including the partial contours. Next, a mesh is generated, proceeding counter-clockwise from the pair b_{k+1}, t_{l+1}, to the pair b_{i-1}, t_{j-1} (fine lines). Finally patches are generated to fill the gap on each side of the partial contour region (dotted lines). For instance, in the gap on the left side, triangulation proceeds from the pair b_{i-1}, b_i, and continues via the closest point on the boundary.

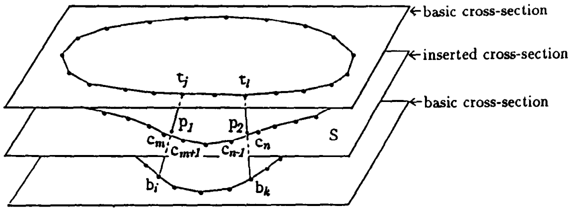


Fig. 8 Generation of a partial contour line.

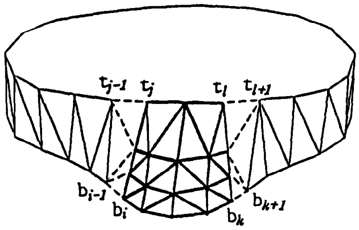


Fig. 9 Reconstruction by using partial contour lines.

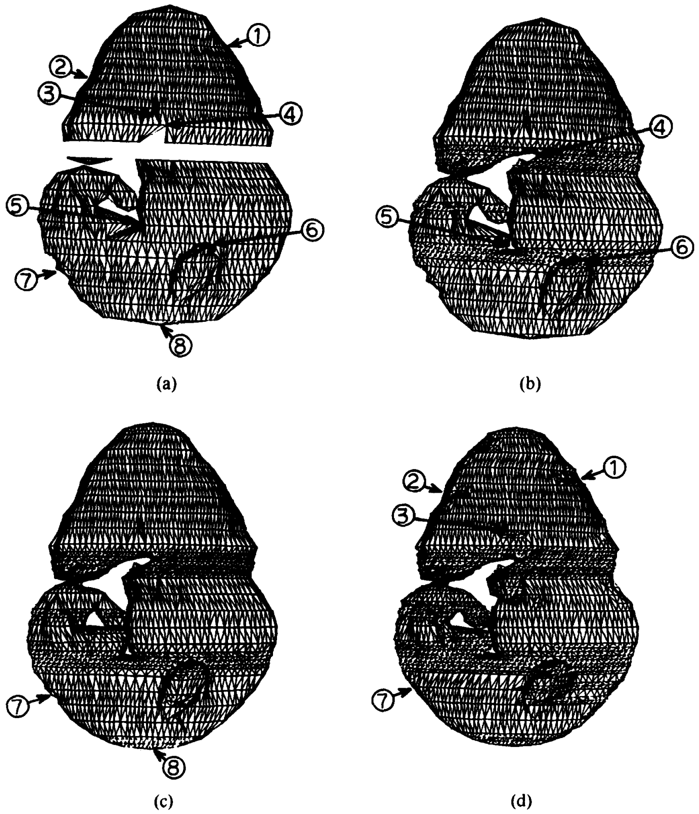
5. Examples

Our method is applied to data from a mouse embryo, used in the study of anatomy. The effect of the parameters k_1 and k_2, which determine the conditions for insertion of contours and partial contours, is demonstrated. When appropriate values are selected for k_1 and k_2, our method reconstructs a shape very similar to that of the original object.

The data is from a mouse embryo cut into 626, each 7 micrometers thick.

The main structures include the skin, neural tube, and digestive system.

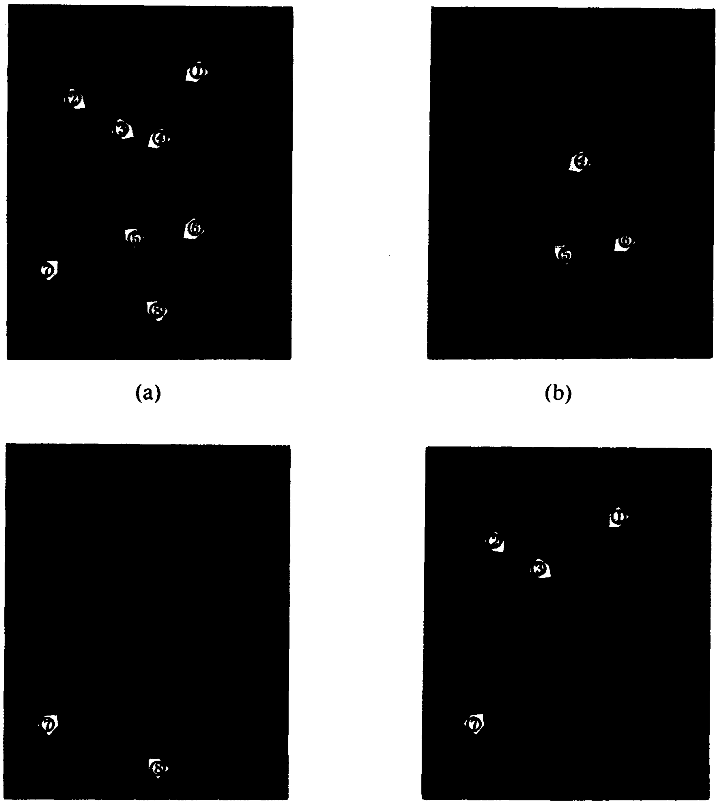
Both Figure 10 and Figure 11 demonstrate the effect of the parameters k_1 and k_2. In Fig. 10, triangular patches removed from back faces are displayed, and in Fig. 11, a semitransparent display method is employed on the object shown in Fig. 10. In Fig. 10 (a), the skin is reconstructed, using contour lines from only every 30th cross-section, by the traditional fixed inter-cross-sectional method. Triangular patches from sections 330 to 360 cannot be constructed, because of branching away into more than three parts in this region. In Fig. 11(a),



(a) (b)

(c) (d)

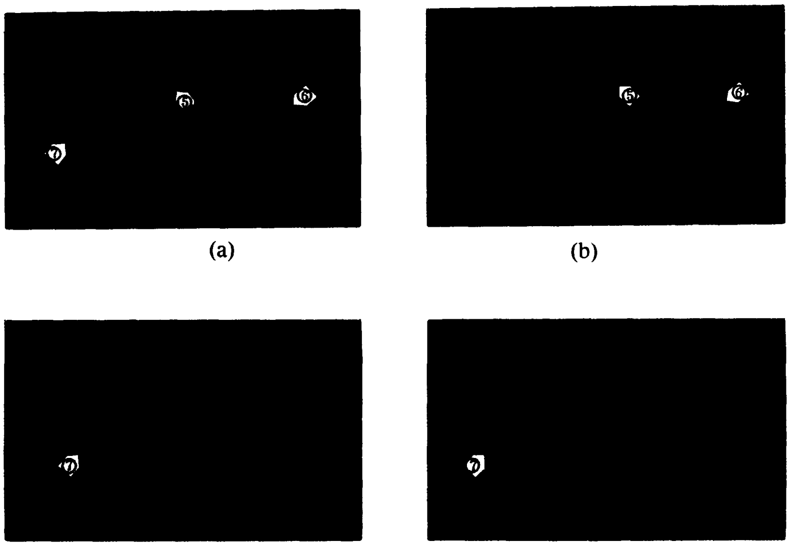
Fig. 10 Effect of parameters k_1 and k_2. (triangular patches)



(a) (b)

(c) (d)

Fig. 11 Effect of parameters k_1 and k_2. (semitransparent display)



(a) (b)

(c) (d)

Fig. 12 Enlargement of part of the foreleg.

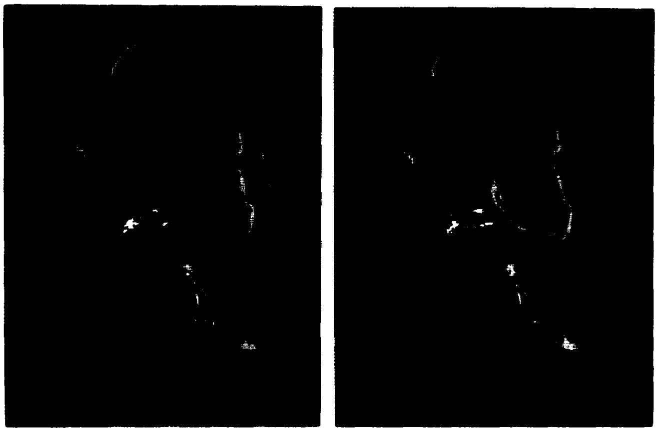


Fig. 13 Semitransparent stereoscopic display of mouse embryo.

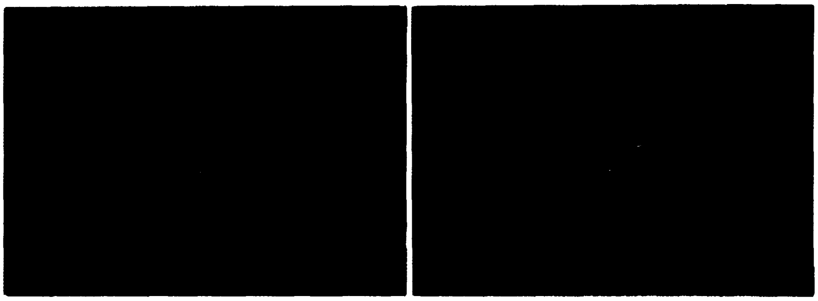


Fig. 14 Display of skin and digestive system only.

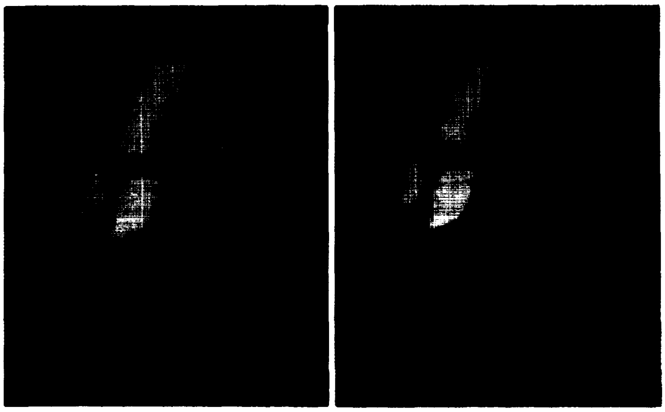


Fig. 15 Opaque display of neural tube.

Table 1 Comparison of the number of triangular patches and the CPU time.

	number of triangular patches	CPU time [min.]		
		reconstruction	display	total
traditional method	31,859	1.0	20.1	21.2
proposed method	17,413	1.1	13.1	14.2

(computer: 2.8 MWIPS)

in order to connect the missing region, two cross-sections are inserted by an interactive command. In Fig. 11(b), k_1 is set to 1.0, inserted contours, but no partial contours, are automatically introduced, and the branching areas (④, ⑤, and ⑥) are more faithfully reconstructed. In Fig. 11(c), k_2 is set to 2.5, partial contours are introduced, and the quality of reconstruction in areas ⑦ and ⑧ is improved. Fig. 11(d) shows the case of $k_1=1.0$ and $k_2=0.5$; the quality of reconstruction is quite high, especially in areas ①, ②, ③, and ⑦. A portion of the foreleg is shown on a larger scale in Fig. 12. The values of k_1 and k_2 are the same as in Fig. 11.

In order to compare the proposed method and the fixed inter-cross-sectional method [7], the number of triangular patches and the CPU time for creating the stereo pair of two elements, the skin (shown in Fig. 11) and the inner surface of the neural tube (the green element in Fig. 13), are shown in Table 1. In the fixed inter-cross-sectional method, every seventh cross-section was used for reconstruction, while in the proposed method, every 30th basic cross-section was used and the minimum cross-sectional interval was set to seven, because in this case it is enough to use contours on every seventh cross-section. The results show that the proposed method is superior in terms of both memory and computation time. Even in the proposed method, reconstruction takes only 7.7 percent of the total time, and the rest is spent sorting triangular patches in order of their depth from the viewpoint and rendering. The sorting time increases in proportion to $O(N^2)$, because fast sorting algorithms such as the quick sort or heap sort cannot be employed, since the priority cannot be determined by using the relationship between two triangular patches [8], while the rendering time increases in proportion to $O(N)$, where N is the number of triangular patches. Therefore, the more complicated the data, the more useful the proposed method.

Figure 13 is a stereoscopic, semitransparent rendering of the reconstructed mouse embryo, with $k_1=1.0$ and $k_2=0.5$. The inner structure and outer appearance can be simultaneously observed, and stereoscopic display provides information about the relative locations in space of each structural element.

In Fig. 13, the number of triangular patches for reconstructing the mouse embryo is 31,864, and creation of the stereo pair took 24.8 minutes of CPU time on a 2.8 Whetstone MIPS machine.

The skin and digestive systems only are displayed in Fig. 14. Part of the mouth is visible as an open region. It is emphasized by lowering it transparency coefficient and selecting an appropriate viewing angle.

In Fig. 15, the transparency of the neural tube is set to zero and the position of the light source is set directly in front of the tube. In this way, the surface of the neural tube can be very clearly distinguished.

6. Conclusions

A method has been described for faithfully reconstructing a complex object from multi-layered cross-sectional data. The method consists of automatically introducing cross-sections between those designated by the user, according to the difference in shape of contours on adjacent cross-sections. As a result, the original object can be faithfully reconstructed, even when branching elements, open regions, surfaces nearly parallel to the cross-sections, and regions of rapid shape change are present.

The method has been applied to a mourse embryo, and the effect of the reconstruction parameters examined. When appropriate values are selected for the parameters, the original object can be accurately reconstructed. The resonstructed object is displayed by using semi-transparency and stereo effects. In this way, the outer appearance and inner structure can be easily and simultaneously observed.

Acknowledgments

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