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Advanced Digital Terrain Analysis Using Roughness-Dissectivity Parameters in GIS

I-Kuai Hung
Arthur Temple College of Forestry and Agriculture, Stephen F. Austin State University, hungi@sfasu.edu

ADVANCED DIGITAL TERRAIN ANALYSIS USING ROUGNESS-DISSECTIVITY PARAMETERS IN GIS

Peter P. Siska and I-Kuai Hung

ABSTRACT

The local variation of terrain properties causes profound changes in the biosphere, microclimate, hydrologic cycle, and in the distribution of human activities on this planet. With the dawn of computerized technology, the terrain is represented in a digital form and new methods are needed to effectively describe, evaluate and quantify terrain properties. The purpose of this project is to develop new methods and procedures for terrain analyses within a GIS environment. The focus is to develop tools for capturing the local terrain variability. The selected parameters such as the hypsometric integral (modified Martonne's index), roughness index, and basic statistical measures (mean, range and variance) are combined with newly developed dissectivity parameters, drainage lengths and landuse characteristics in one unified package and programmed in GIS using the ARC Macro Language (AML). The digital terrain data from this analysis can then be correlated with other spatial information to determine the influence of terrain properties on the ecosystem or other variables of interest including the human systems.

INTRODUCTION

The terrain characteristics have an enormous impact on the natural environment and socio-economic activities. The vast scientific and technical literature accumulated over the years has examined every possible aspect of terrain influence on natural and human processes on this planet. Recently, Wilson and Gallant (2000) collected a significant amount of work regarding terrain analysis methods and their applications to soils, hydrology and vegetation. Pike (2000) underlined the significance of digital terrain modeling and computerized technology in practical applications, and numerous publications have emphasized the role of terrain in hydrologic modeling, sediment transport, soil erosion estimation, drainage basin morphology, vegetation, and ecology (Krcho 1991, Parson and Abrahams 1993, Rodriguez-Iturbe and Rinaldo 1997).

The terrain analysis and modeling requires the implementation of existing metrics as well as the development of new tools, indices and parameters that would appropriately describe the terrain and its properties. In addition, both the existing measures and the new metrics should be incorporated into GIS to enhance the work of spatial analysts in natural resource management research. Therefore the objective of this project is to develop a new tool (program and methods) for terrain analysis that would provide new metrics for analyzing the terrain roughness and dissectivity directly in a GIS environment. Traditionally, the most widely used metric in terrain analysis is slope and aspect. Many authors regard slope as the most important surface form on our planet (Evans 1972). The convenient concept of slope is that of a straight line connecting two points on the earth's surface. From this point of view, slope is a basic approximation of the surface gradient, and its accuracy depends primarily on two factors: a) the distance between two points and b) local variability of a terrain. If the distance is too large and the surface highly diverse, then much of the local variability is ignored. Burrough and McDonnell (1998) defined slope as a plane tangent to the surface and Skidmore (1989) noted that gradient is a property of slope and is defined as the maximum rate of change in altitude. In quantitative terms in GIS, slopes and aspects can be readily derived from digital elevation models; GIS actually approximates the gradient of a straight line that connects the nearest neighboring points (hillslope) as opposed to a gradient evaluated at the point and computed using advanced mathematical models such as finite difference methods (Skidmore 1989, Meyer *et al*. 2001). A number of parameters attempt to measure the terrain curvature using higher derivatives of altitude and parameters of regional convexity (Evans 1972, Schmidt et al 2003).

However, the terrain can also be studied at different levels of complexity. A set of slopes composes terrain entities at various levels of complexity such as surface grain and texture (Mark 1975). The terrain also appears at different levels of roughness and dissectivity. The term dissectivity is derived from the Latin "dissectum" and "dissecare" meaning to cut or cutting apart. Analogously, the terrain dissectivity originated through the work of geologic processes and fluvial erosion that cut apart the earth's surface into a variety of geomorphic entities whose principal components are slopes and gradients. The rapidness of vertical changes per unit of the horizontal distance can be used as a basis for expressing relief, surface, or terrain dissectivity. Both terms roughness and dissectivity are closely connected. Roughness describes the general variability of the terrain on the earth's surface while dissectivity refers to the abruptness of changes between the hilltops and the valleys. The objective of this project is to develop a new tool for GIS users that would analyze terrain roughness and dissectivity in the study area globally and locally as well as compute additional statistics from any point data sets.

MATERIALS AND METHODS

Study area

The study area for this study encompassed four counties in east Texas. They were Angelina, Nacogdoches, San Augustine, and Shelby representing the piney woods region on the westernmost part of the forest biome in the South. An unsupervised classification was applied to a composite of Landsat multispectral satellite images that were acquired on different dates: leaf-on (07/18/02, 08/03/02, 09/28/02) and leaf-off (01/15/02) scenes. The above mentioned classification process resulted in five cover types, non-forest, pine forest, hardwood forest, mixed forest, and regeneration/clearcut with 72.78% overall accuracy. The acreage by cover type of the study area is shown on Table 1.

Table 1. Summary of area by cover type for the 4-county study area.

Class_Names		Acres	Hectares	Percent
Non-Forest (with Urban & Water)		581,876.60	235,477.00	27.76
Pine Forest		914,327.75	370,015.12	43.62
Hardwood Forest		347,398.70	140,587.21	16.57
Mixed Forest		163,986.92	66,363.12	7.82
Regeneration/Clearcut		88,450.48	35,794.62	4.22
	Total	2,096,040.45	848,237.07	100.00

A total number of 3,390 elevation points for the study area (Figure 1) was obtained from the Texas Natural Resources Information System (www.tnris.org). The elevation points are in GIS format and spaced irregularly on each of the 7.5-minute quadrangles from the U.S. Geological Survey (USGS) topographical map series. The elevation point dataset was prepared in ArcInfo coverage format. This point dataset was used in the moving window program to calculate newly developed terrain roughness and dissectivity indices.

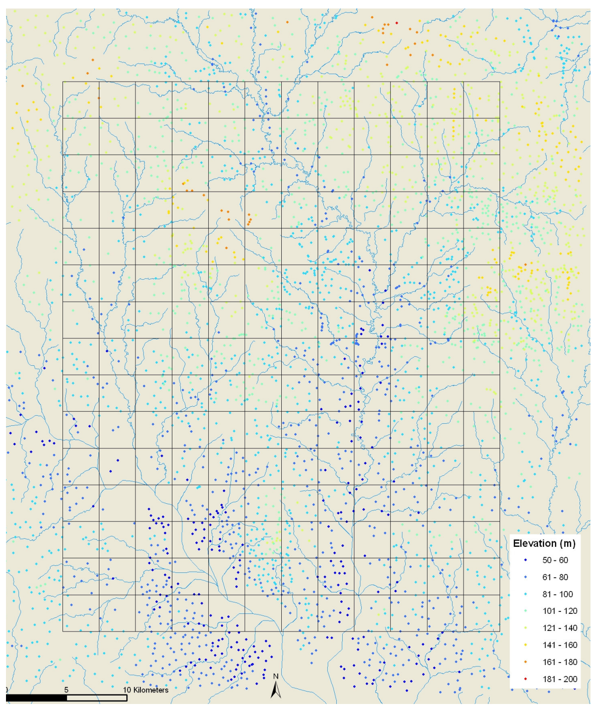

Figure 1. Moving windows superimposed on the study area in east Texas.

The adjustable "moving window" strategy is frequently used for computing local statistics from an area of interest. The advantage of this approach is in determining the local and sub-regional behavior of the studied phenomenon. For example, the general trend in the disease spread can be in a north south direction; however, the area of interest is localized in the western part and therefore safe from exposure to this disease. In order to evaluate terrain properties and the variation of terrain parameters in space, moving windows were used as a framework for computing numerous terrain and environmental properties deemed relevant for natural resource. In addition, the terrain parameters can be related to local environmental parameters using the results from the moving windows. In this program, a complete set of 58 parameters was computed and further analyzed in GIS and other packages. The set of 58 parameters can be divided into seven groups:

1) Traditional parameters (basic statistics such as mean, variance, range).
2) Moving window parameters (length, width, x,y coordinates for centroid)
3) Roughness index (mean, variance and range)
4) Hydrologic (length of streams, density of streams)
5) Landcover (type of landcover, percentage of landcover)
6) TIN surface (surface and basal area, number of triangular faces, mean slope of facets)
7) Dissectivity (Dissectivity mean, VH-ratio and Dissectivity Index).

Parameters and their significance

Overall, these parameters can be valued as prime or secondary. The prime parameters were designed by authors and programmed in GIS. The secondary group consists of parameters that were developed by someone else, computed using an independent program either in GIS or outside of the GIS environment and then transferred to 'Dissect', the moving window AML program. One example is roughness parameter (Phillip and Watson 1986):

$$r = 1 - \frac{ap}{a} \tag{1}$$

where *r* is a coefficient of surface roughness, *ap* is the area of the triangle cluster surrounding the data point projected onto a plane that is normal to the vector sum of cross-products of the triangle cluster, *a* is the area marked by the baseline of the triangle cluster. The roughness index determines the regions where interpolation is more likely to be uncertain and more sampling is desirable to better define an interpolation surface. The roughness index also determines the slope change. The increasing roughness values indicate more rapid changes in the interpolation surface. This metric is computed from irregularly spaced data using the roughness program (Meyer 2001). Once the output file from the roughness program is loaded into GIS, the new program 'Dissect' computes the roughness statistics (mean, variance, maximum, minimum and range of roughness) for each moving window. Then the relationship can be studied between terrain roughness as measured by roughness index and other natural resource parameters such as drainage density, landcover or any other spatial data that were measured or computed elsewhere.

The first group of parameters consists of new dissectivity metrics that were designed by the authors and implemented in the 'Dissect' moving window program. The newly proposed dissectivity parameters depict the spatial variation of relief properties in different type of surfaces. These parameters were labeled as *Dm* (dissectivity mean), *Vh* (vertical-horizontal ratio) and *D* (dissectivity index). The *Dm* parameter is a sum of partial slopes inside each moving window divided by the number of non-repeating pairs:

$$Dm = \frac{\sum_{i=1}^{m-1} \sum_{j=i+1}^{m} \left| z_i - z_j \right| d_{ij}^{-1}}{N} \tag{2}$$

where z_i and z_j are attribute values (elevations) measured at locations i and j, d_{ij} is the horizontal distance between them, m is the number of point data in the moving window and N is the number of non repeating pairs used to calculate the hillslope:

$$N = {}_m C_2 = \binom{m}{2} = \frac{m!}{2!(m-2)!} \tag{3}$$

Vh parameter represents the ratio between the sum of non-repeatable vertical differences and the sum of horizontal distances between them as follows:

$$Vh = \frac{\sum_{i=1}^{m-1} \sum_{j=i+1}^{m} \left\| z_i - z_j \right\|}{\sum_{i=1}^{m-1} \sum_{j=i+1}^{m} d_{ij}} * 100 \tag{4}$$

The simplest dissectivity parameter computed in each window is labeled as *D* the dissectivity index and is represented as the ratio between the elevation difference of maximum and minimum values in each window and the horizontal distance between them as follows:

$$D = \frac{\left| z_{\max} - z_{\min} \right|}{d_{\max,\min}} * 100 \tag{5}$$

This parameter should not be confused with the maximum slope index that uses a similar formula and was computed for each window. Both parameters behaved differently and have significantly different relationships with other computed parameters.

The above described terrain parameters focus on measuring profile dissectivity. In reality, they measure the rate of vertical changes per unit of horizontal distance as detected by the point measurements of elevation. Therefore, the accuracy of these indices is limited to a profile marked by each individual elevation points. In order to complement these line-based metrics with the three-dimensional spatial measure, the TIN-based dissectivity parameter was used.

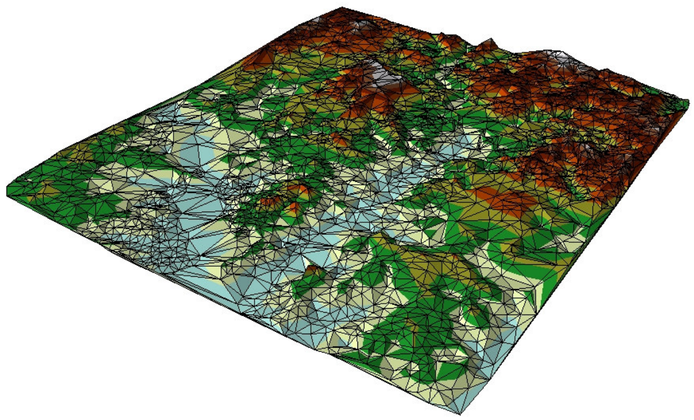

Figure 2. Triangular Irregular Network indicating the surface roughness-dissectivity.

This TIN-based metric uses the fact that the surface area of all triangles sharing a common point increases as the elevation of this common point increases per unit base area marked by the base of all triangles involved. In this project, the area of the moving window is considered to be the base area of triangles that were constructed from points inside each window. Therefore, the ratio between the total sum of the surface area of TIN and the moving window area increases as the surface roughness and dissectivity increases. TIN-based dissectivity parameter corresponds then more to terrain diversity than the indices described in equations 2,4 and 5. However, the parameter is not projected to the base, i.e. the triangles do not create a 'pyramid' above their base and have limited application as dissectivity metrics.

RESULTS AND DISCUSSION

As indicated earlier, the earth's relief is one of the most important components of the earth system having a profound influence on all elements of natural and socio-economic phenomena. Until now, numerous metrics have been developed to express terrain characteristics descriptively and mathematically (Ritter *et al*. 1995). However, the terrain is an extremely complex phenomenon and cannot be described and measured using one set of parameters. Geomorphometry began a new epoch in terrain analysis with the dawn of computerized technology: digital terrain modeling and analysis. GIS plays a significant role in this new trend. In this project the terrain analysis was performed on the east Texas study area and the results are summarized in Table 2 where the window size of 3000 m was used.

Overall 21 parameters were computed in GIS. These parameters ranked from the computation of mean and variance of elevation in each moving window to the roughness index (mean and variance), dissectivity parameters and the modified Martonne's parameter of terrain massiveness – coefficient of dissection:

$$M = \frac{\bar{z} - z_{\min}}{z_{\max} - z_{\min}} \qquad (6)$$

where z stands for elevation (Evans 1972). This analysis allows the user to study the local variation of terrain as it changes from place to place and relates them to any phenomenon of interest.

Table 2. Correlation coefficients between parameters calculated from moving windows.

Calculated parameter	*STD-METER*	*RMSE*	*RANGE-METER*	*MARTONNE*	*SUM-LENGTH*	*TIN-RATIO*	*Dm*	*MAX-SLOPE*	*VH*	*D*
MEAN-METER	0.3711	0.3164	0.4342	0.2652	-0.2692	0.2672	0.3282	0.2896	0.3322	0.2758
STD-METER	1.0000	0.8049	0.9163	-0.0287	0.0371	0.4421	0.8766	0.4850	0.9053	0.5698
RMSE	0.8049	1.0000	0.7152	-0.0229	0.1922	0.4485	0.7876	0.5001	0.7412	0.6387
RANGE-METER	0.9163	0.7152	1.0000	0.0325	-0.0788	0.4918	0.7649	0.6372	0.7658	0.6112
MARTONNE	-0.0287	-0.0229	0.0325	1.0000	-0.2561	-0.0383	-0.1048	0.0797	-0.0841	-0.0268
MEAN-ROUGHNESS	0.6525	0.6441	0.7396	-0.0549	0.0289	0.4934	0.6690	0.7516	0.5730	0.5776
STD-ROUGHNESS	0.4806	0.4019	0.5997	0.0029	-0.0483	0.3569	0.4755	0.7013	0.3934	0.4282
RANGE-ROUGHNESS	0.4281	0.3327	0.5720	0.0125	-0.0792	0.3426	0.4129	0.6824	0.3369	0.3947
SUM-LENGTH	0.0371	0.1922	-0.0788	-0.2561	1.0000	0.1021	0.0811	-0.0746	0.0285	-0.1212
NON-FOREST	-0.0811	-0.0254	-0.1904	-0.1832	0.2568	-0.1263	0.0081	-0.2285	0.0240	-0.0588
PINE	-0.0314	-0.0765	0.0601	0.1012	-0.4352	-0.0230	-0.0856	0.0912	-0.0682	0.0517
HARDWOOD	0.1561	0.1869	0.1054	-0.0325	0.5021	0.2165	0.1319	0.1047	0.0750	-0.0417
MIXED	0.1832	0.1685	0.2346	0.1639	0.5021	0.1987	0.1596	0.2518	0.1306	0.1013
REGENERATION	-0.0213	-0.0843	0.0631	0.1786	-0.2123	-0.0205	-0.0602	0.0677	-0.0539	0.0152
FOREST	0.0811	0.0254	0.1904	0.1832	-0.2568	0.1263	-0.0081	0.2285	-0.0240	0.0588
TIN-RATIO	0.4421	0.4485	0.4918	-0.0383	0.1021	1.0000	0.3546	0.4352	0.3319	0.2453
Dm	0.8766	0.7876	0.7649	-0.1048	0.0811	0.3546	1.0000	0.5266	0.9613	0.6121
MAX-SLOPE	0.4850	0.5001	0.6372	0.0797	-0.0746	0.4352	0.5266	1.0000	0.3918	0.5450
VH	0.9053	0.7412	0.7658	-0.0841	0.0285	0.3319	0.9613	0.3918	1.0000	0.5520
D	0.5698	0.6387	0.6112	-0.0268	-0.1212	0.2453	0.6121	0.5450	0.5520	1.0000

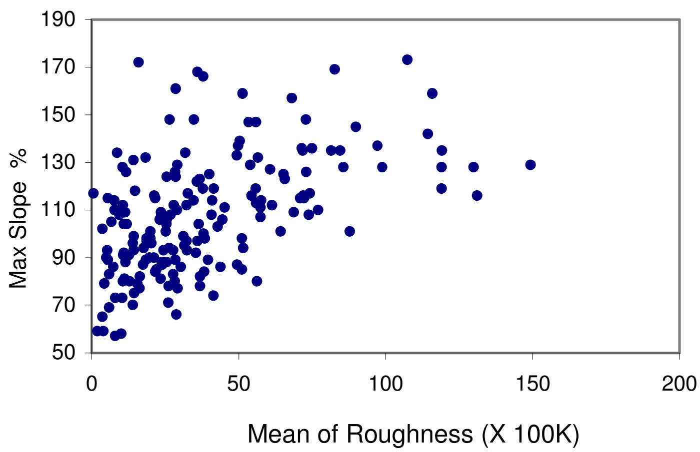

Figure 3. The correlation between roughness index and slope.

For example, in this project the root mean square error (RMSE) of kriging interpolation and mean absolute error in each moving window were correlated with the roughness and dissectivity parameters. As the results indicated, there appears a significant correlation between the kriging interpolation errors and all dissectivity metrics especially the newly developed parameters *Vh*, *Dm*, and *D* that correlate well with the magnitude of interpolation errors. This relationship suggests that the interpolation is strongly influenced by variation in relief in the study area (Figure 4).

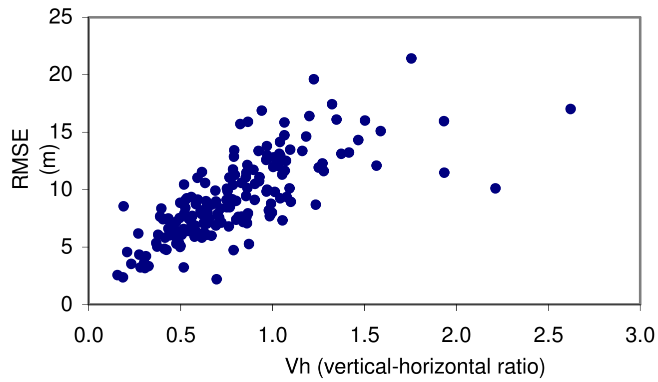

Figure 4. Correlation between dissectivity and kriging errors.

In addition, other parameters were calculated such as stream length and the percent of cover type (pine, hardwood and mixed). As the results indicated, a moderate correlation can be observed between the stream length in each moving window and the vegetation (landcover parameter.) One would expect a stronger relationship between the vegetation and terrain parameters. The results from this analysis indicated that there is a very weak or no impact of terrain on the vegetation. This is primarily due to human influence (forest management) and insignificant terrain variation in the study area (Figure 2 and 5). The mean elevation value was less than 200 meters and the standard deviation of elevation points was 25 meters.

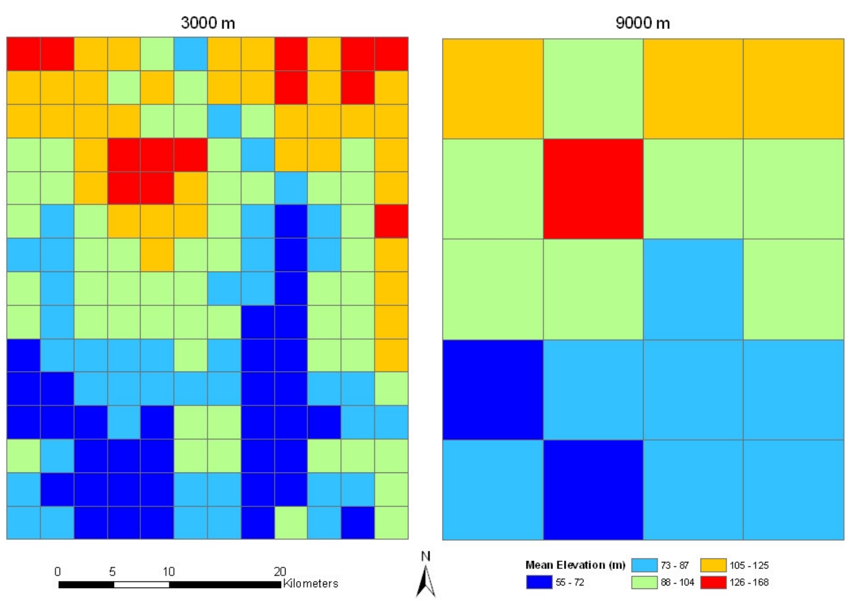

Figure 5. Local variation of elevations using moving windows of different sizes.

Another significant aspect in the digital terrain analysis that requires attention is associated with local variation as related to the scale. The variation of elevation values usually changes with distance and it may be connected to the character of general geomorphic features such as valleys, mountain flanks, erosional-depositional plains, coastal areas, basins, canyons, etc. Any study area can be viewed as containing a set of different geomorphic entities that would indicate changes in shape, size and terrain properties with scale. The same surface attributes such as the mean and variation of elevations, roughness and dissectivity parameters may significantly change with resolution and scale. Therefore, spatial oriented studies in natural resource management should pay close attention to regional changes of studied phenomenon with the scale. In order to account for the local variation of studied phenomena and the scale, the adjustable moving windows strategy was designed and implemented (Figure 5). It allows a researcher and practitioner to investigate and compare local versus global terrain variation and compute parameters based on different window sizes, provided there are enough data points in the windows. In addition, this strategy can be applied to any data set and the correlation can be established between the terrain parameters and the variables of interest. For example, in this study the relationship between surface (terrain) characteristics and a number of other variables were determined. These non-terrain parameters include vegetation, stream density, kriging interpolation errors and forest resource parameters such as the tree basal area, merchantable volume and tree density. The results indicated that in general there is a weak or no correlation between all terrain parameters and natural resource data such as the basal area, merchantable volume of trees, tree heights, and density. Similar results were obtained when correlating hydrologic parameter and landcover. Therefore, the results clearly indicated that relief is not an influential factor in the study area. Human activities have the greatest impact on natural resource, vegetation, and the forest ecosystem. Especially forest management, agriculture and urban development appear to have the most significant influence on spatial distribution of natural resource phenomena.

CONCLUSION

Computerized technology gave a new dimension to the terrain analysis and modeling. Today, geographic information package is frequently used for generating surfaces, computing slope, aspect and terrain curvature. In this paper we introduced new enhancement to digital terrain analysis. The new program was developed and new parameters for terrain analysis were tested. The already existing and new parameters were computed for east Texas region and correlated with natural resource data and interpolation errors. The program and the terrain analysis introduced in this paper are a valuable resource application for computation of surface parameters and establishing relationship to any natural resource variable of interest. The results indicated that the terrain roughness-dissectivity is closely correlated to ordinary kriging interpolation errors. The correlation to vegetation and forest parameters was weak or close to zero indicating that in the east Texas area the terrain does not play significant role in distribution of natural resource phenomena. Its variability and diversity as measured by a number of parameters is not correlated to landcover and forest parameters. This is primarily due the low surface diversity and human impact (forest management). The moderate correlation was determined between hardwood and mixed forest percents and the stream length i.e. as the total length of streams increases the percentage of hardwood and mixed forests tends to increase.

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