UNCOVERING THE GLOBAL AND LOCAL STRUCTURES OF URBAN NETWORKS VIA POINCARE EMBEDDING

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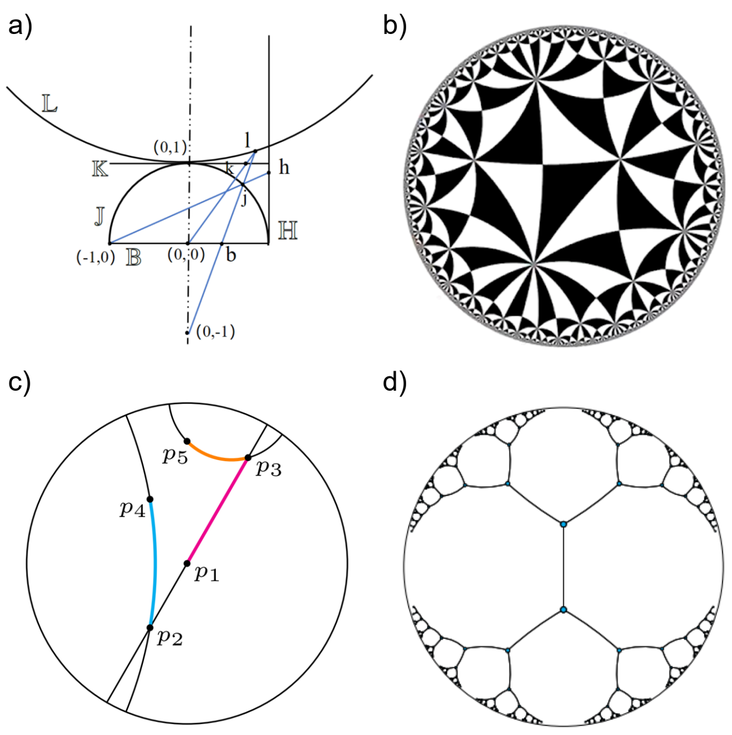
Introduction

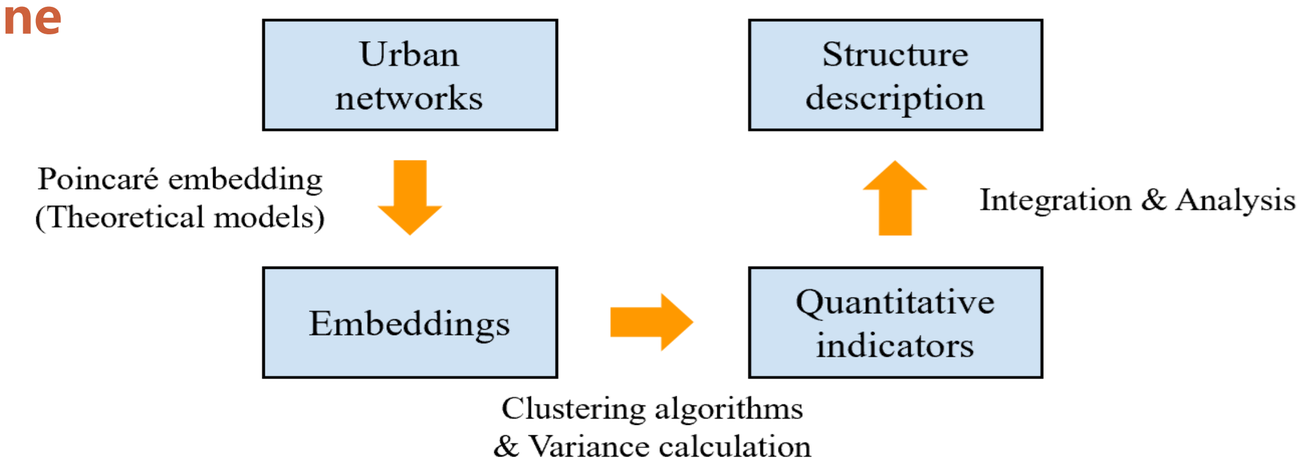
Understanding spatial structures of urban net works is of great significance for the spatial planning of urban and regional development. Traditionally, researchers often provided limited descriptions characterizing urban networks by indicators at the city-level, e.g., population, economic output, and income levels (Berry and Garrison 1958, Taylor 1997). However, these approaches fail to capture the complex relationships between cities that are embedded in the external relations to other cities. With the emergence of urban flow data and advanced techniques in the complex networks approach, methods have been developed to examine either local or global structures, but they cannot capture both global and local structures simultaneously (Derudder and Taylor 2018, Newman 2006, Rombach et al. 2014). This paper proposes a novel geospatial artificial intelligence (GeoAI) method for urban network analysis, which effectively reveals the global hierarchy and local proximity of urban networks by learning the relational embeddings of cities in a Poincaré space. In addition, a series of measures based on the Poincaré embeddings are presented to quantify the global and local network structures. By using human movement flows between cities in China over the past years, the structures of urban networks are analyzed, and the preliminary experiments demonstrated the validity of the new method.

Theoretical models



a) Relations of different hyperbolic spaces; b) Visualization of the Poincaré disk; c) Geodesics in the Poincaré disk; d) Embedding of a tree in the Poincaré disk (Nickel and Kiela 2017).

Pipeline



Results

* Different colors indicate different provinces in China.

Methodology

(Poincaré ball) Let $B^d = \{x \in \mathbb{R}^d | \|x\| < 1\}$ be the open d-dimensional unit ball. The Poincaré ball model can be regarded as the Riemannian manifold (B^d, g_x), i.e., the open unit ball equipped with the Riemannian tensor:

$$g_x = \left(\frac{2}{1 - \|x\|^2}\right)^2 g^E,$$

where $x \in B^d$ and g^E means the Euclidean metric tensor. Then, the distance between points $u, v \in B^d$ is given as:

$$d(u,v) = arcosh\left(1 + 2\frac{\|u-v\|^2}{(1-\|u\|^2)(1-\|v\|^2)}\right).$$

The distance changes smoothly with respect to the location of u and v. When we place the root node and leaf nodes of a tree at the origin and boundary of the Poincaré ball respectively, the entire system is stable. This property allows us to learn embeddings that simultaneously capture the hierarchy of objects as well as their similarity. Assuming that we embed the urban networks into the Poincaré ball, we can easily observe the global and local structures, with higher levels of cities located closer to the center of the ball, and conduct a quantitative analysis.

Conclusive discussions

The proximity and hierarchy of cities are presented above (Results). The blue arrows indicate the measurement of three indicators from different perspectives on embedding results. Firstly, we use the hyperbolic clustering algorithm to cluster cities and intuitively study the meso-structure of urban networks through the number of clusters. Secondly, we calculate the variance of the distribution on the core-periphery axis and this measurement reflects the global hierarchical strength of the structures. In addition, the distribution of embeddings in various circles is analyzed, which indirectly reflects the degree of closeness between cities.

This study aims to produce a new methodological approach to analyze the global and local structures of urban networks. By embedding the urban networks into the Poincaré ball, the global and local structures of the networks are effectively maintained, and comprehensive quantitative analysis can be carried out. The preliminary experiments demonstrated the validity of our method.

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