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Geographic representation in spatial analysis

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Abstract. Spatial analysis mostly developed in an era when data was scarce and computational power was expensive. Consequently, traditional spatial analysis greatly simplifies its representations of geography. The rise of geographic information science (GISci) and the changing nature of scientific questions at the end of the 20th century suggest a comprehensive re-examination of geographic representation in spatial analysis. This paper reviews the potential for improved representations of geography in spatial analysis. Existing tools in spatial analysis and new tools available from GISci have tremendous potential for bringing more sophisticated representations of geography to the forefront of spatial analysis theory and application.

Key words: Spatial analysis, geographic information science, Euclidean space, distance, direction

1 Introduction

There is little doubt that spatial analysis has made tremendous progress since the so-called "quantitative revolution" of the 1950's. There is also little doubt that geographic information science (GISci) and its realization through geographic information systems (GIS) have tremendous potential to disseminate spatial analytical tools and allow a broad range of researchers, analysts and decision-makers to benefit from these techniques. A question that remains is "what can spatial analysts gain from GISci?" There are several answers to this question, some of which are addressed in other papers in this special issue. One answer that I will focus on in this paper is *representations of geography in spatial analysis.*

Spatial analysis mostly developed in an era when data was scarce and computational power was expensive. Consequently, traditional spatial analysis greatly simplifies its central objects of study, i.e., geographic space, geographic objects and geographic relationships. The rise of GISci and the changing nature of scientific questions at the end of the 20th century suggest a comprehensive re-examination of geographic representation in spatial analysis. Geographic information technologies and GISci have improved (to put it mildly) our ability to process digital geographic data that accurately represents empirical geography. Environmental problems, equity and access issues and increasingly scarce resources require integrative, global-level perspectives and tighter linkages between the human and physical sciences. Sensitive analysis of human behavior at a variety of scales requires a richer representation of the Earth as perceived and used by individuals.

This paper reviews the potential for improved representations of geography in spatial analysis. This review will illuminate existing tools in spatial analysis and new tools available from continuing advances in GISci. As will hopefully become clear, there is an existing undercurrent in the spatial analytical literature that addresses richer representations of geography. GISci has tremendous potential for expanding these efforts and bringing more sophisticated representations of geography to the forefront of spatial analysis theory and application.

2 Geographic representation in spatial analysis

2.1 Pregeographic space

Formal representations of geography are usually based on some model of *pregeographic space* (Beguin and Thisse 1979). Pregeographic space is a set of places (either finite or infinite) endowed with certain structural properties but devoid of any measured attributes. A key structural property is the *length-metric*. This is a relation defined over any two places and returns a value that we typically interpret as the *distance* between the places. The length-metric normally obeys the well-known metric space properties of *non-negativity, identity, symmetry* and *triangle inequality*.

Mainstream spatial analysis generally relies on a particular type of pregeographic space, namely, *planar Euclidean space*. This is defined when the set of places is a Cartesian n-space (typically, $n = 2$ although sometimes $n = 3$) and the length-metric corresponds to the Euclidean distance function. Planar Euclidean space is only one type of metric space: an infinite number of planar metric spaces corresponding to different types of shortest path travel. More general are *semi-metric* and *quasi-metric* spaces. In the former case, triangular inequality property no longer holds but symmetry still maintains. The latter case occurs when both the triangular inequality and symmetry properties are violated (see Smith 1989).

Non-Euclidean metric, semi-metric and quasi-metric pregeographic spaces are often more appropriate than Euclidean space for analyzing and visualizing geographic phenomena, particularly when spatial interaction does not follow straight lines or the metric space properties. Indeed, the argument by some non-scientific scholars that space is diminishing as a casual mechanism or critical medium holds mostly for Euclidean space: other pregeographic spaces still have substantial explanatory power (Cliff and Haggett 1998). There are several effective techniques for estimating non-Euclidean spaces from observed interactions or correlations (see, e.g., Cliff and Haggett 1998; Love et al. 1988).

Another type of pregeographic space is *spherical space*, i.e., a three-dimensional closed surface in which every location is equidistant from a given point (the center of the sphere). These spaces are critical for analyzing geographic phenomena at regional to global scales (Raskin 1994). Spherical spaces can be metric, semi-metric or quasi-metric depending on the length-metric. Some methods exist for spatial analysis on a sphere, including spherical statistics and interpolation methods (see Raskin 1994). In addition, advances continue in geocomputational algorithms for representing and processing digital representations of the sphere (e.g., Hodgson 1992).

Despite the promising developments in modeling and analysis of non-Euclidean pregeographic spaces mentioned above, these representations are still very much at the periphery of spatial analysis. Perhaps even more disturbing is a persistent lack of appropriate tools in GIS software. Concurrent development of non-Euclidean spatial analytical methods and geocomputational techniques for integration of these methods into commercial GIS software is required.

2.2 Geographic space

Geographic space emerges when we measure some attribute(s) within the framework provided by the pregeographic space (Beguin and Thisse 1979). Geographic space is a much richer concept than pregeographic space and corresponds better with our physical reality (which tends not to be empty).

When considering geographic space, the pregeographic concept of "distance" is too primitive: interaction is conditioned by physical and human-made attributes such as terrain or traffic congestion. The analogous geographic space concept is the *minimum cost path* through a *cost density field*, that is, an attribute or attributes that can be interpreted as an interaction cost.

Finding the minimum cost path through geographic space requires solving a variational problem that is difficult to evaluate for the general case. Fortunately, special cases of the problem are tractable, including *cost polygons in Euclidean 2-space* (e.g., Smith et al. 1989), *polyhedral terrain in Euclidean 3-space* (e.g., Mitchell et al. 1987) and *cost lattices* (e.g., Goodchild 1977).

Most theories, models and techniques in spatial analysis use the primitive view of interaction in pregeographic space, that is, as a function of distance. The richer view implied by geographic space is to characterize interaction by minimum cost paths through cost density surfaces. For example, spatial autocorrelation or spatial interaction models could replace the pregeographic concept of a distance function with the geographic concept of a minimum cost path to capture the mitigating effects of physical or human geographic features. This will require continued development of fast, parallel methods for computing these paths in appropriate special cases.

2.3 Geographic entities

Measuring geographic attributes within an appropriate pregeographic framework can generate entities with critical morphological properties. Properties such as shape, orientation, structure and pattern can strongly influence geographic processes (Medda et al. 1998). These properties can also guide the search for appropriate theory to explain geographic processes (Dobson 1992).

Measuring geographic attributes typically generates two types of geometric forms, namely, *objects* or *fields*. Morphological properties such as object shape and spectral signatures of fields were central to early conceptualizations of spatial analysis (e.g., Bunge 1966; King 1969). Treatments during the intervening decades have been uneven. Field-based representations of landscapes and landforms in quantitative physical geography are sophisticated, a tradition that GISci will continue if not expand. Object-based representations in human geography are frequently less satisfying. Some attention has been directed towards the mutual influences between object geometry and geographic processes (e.g., Medda et al. 1998). However, these factors are usually ignored due to the more common use of point-based representations of geographic entities.

Expanding the treatment of morphological properties in spatial analysis requires an expansion of appropriate GIS-friendly tools. Particularly critical are scalable techniques for shape analysis. Although shape can be a difficult and multifaceted concept, it is crucial as an indicator of forces that shape a geographic entity and as an influence on future evolution (Medda et al. 1998). While the spatial analysis literature offers several shape analytic measures, few are robust and can scale to handle the very large digital geographic datasets.

2.4 Geographic relationships

Nystuen (1963) identifies three fundamental relationships in spatial analysis, namely, *distance, connectivity* and *direction*. Spatial analysis generally treats the first two relationships in a very limited form and virtually ignores the third. An expanded view of geographic representation in spatial analysis requires a more complete treatment of these relationships.

2.4.1 Distance

We have already noted the reliance on the pregeographic concept of distance in spatial analysis and the need to expand this to the geographic concept of minimum cost paths. However, the concept of distance itself needs to be expanded, particularly when working with dimensional geographic objects. "Distance" in spatial analysis typically is a single measurement; for example, analysts often use a centroid-to-centroid measurement to characterize the distance between two polygons. In fact, a *distribution* of distances exist between two dimensional objects.

The centroid-to-centroid distance is often a poor summary of the distance distribution between two-dimensional objects. Other summaries of this distribution include: i) *expected distance*; ii) *average distance*; iii) *minimum distance*; iv) *maximum distance*, and; v) *Hausdorff distance*. The expected distance weights each distance in the distribution by the interaction probability. The average distance is a special case of the expected distance where interactions are equally probable between locations. The Hausdorff distance is the maximum distance between all locations in one object and the closest location in the other (therefore it is asymmetric).

Tools are emerging to allow spatial analysts to measure more appropriate distances between dimensional objects. Okabe and Miller (1996) formulate exact computational algorithms for calculating the average, minimum and maximum distances between pairings of points, lines and polygon stored in a vector format. The minimum and maximum distance algorithms are tractable while the average distance algorithms are limited to moderate problems. Required is continued research on exact or heuristic algorithms for average and expected distances and their appropriate use in spatial analysis as well as analogous procedures for minimum cost paths.

2.4.2 Connectivity

In traditional spatial analysis, the concept of "connectivity" is binary, i.e., two geographic entities are either connected or not. This is a very limited view of the possible connectivity relationships between two geographic entities, particularly if one or both is dimensional. Egenhofer and Herring (1994) analyze the possible topological relationships between points, lines and areas in Cartesian 2-space. They discover a rich set of possible connectivity relationships between dimensional geographic features. Experiments by Mark and Egenhofer (1994) demonstrate that these relationships correspond well to the natural language descriptions of real-world geographic features by human subjects. Since the connectivity relationships can be computed through simple binary topological relationships, they are scalable to large spatial databases (see Egenhofer and Herring 1994).

2.4.3 Direction

Directional relationships can influence the interaction among geographic entities. This is intuitively obvious in physical geography where the flow of material, biomass or energy can vary by direction. Directional relationships can also be important human geography, for example, in human environmental knowledge and spatial behavior.

Spatial analysts should incorporate and expand computational techniques for analyzing directional relationships. A fairly extensive (although not complete) suite of *directional statistics* is available for statistical inferences from directional observations. Also available are *spherical statistics*; these are the special case of directional statistics on the sphere. Measures of central tendency, dispersion, goodness of fit to theoretical distributions and sample difference tests are available (see Raskin 1994). However, these techniques are only available for point objects and do not necessarily scale. Continuing advances in computational procedures for assessing directional relationships among dimensional geographic objects could serve as the basis for scalable directional and spherical statistics for line and polygon objects.

3 Conclusion

We now have the ability to process detailed digital representations of the Earth. A closer match between formalizations of geography in spatial analysis and available GISci techniques for processing digital geographic representations can enrich spatial analysis, making it more relevant to the critical scientific questions emerging at the turn of the century. The research agenda outlined in this short paper is to identify the appropriate domains for expanding geographic representation in spatial analysis and continue the development of tools to support these expanded representations.

References

Beguin H, Thisse J-F (1979) An axiomatic approach to geographical space. *Geographical Analysis* 11:325–341

Bunge W (1966) *Theoretical Geography*. Lund Studies in Geography, Series C, General and Mathematical Geography number 1, 2nd edition

Cliff AD, Haggett P (1998) On complex geographic spaces: Computing frameworks for spatial diffusion processes. In: Longley PA, Brooks SM, McDonnell R, Macmillan B (eds) *Geocomputation: A Primer*, John Wiley, New York, pp. 231–256

Dobson J (1992) Spatial logic in paleogeography and the explanation of continental drift. *Annals of the Association of American Geographers* 82:187–206

Egenhofer MJ, Herring JR (1994) Categorizing binary topological relations between regions, lines and points in geographic databases. In: Egenhofer MJ, Mark DM, Herring JR (eds) pp 1–28

Egenhofer MJ, Mark DM, Herring JR (eds) (1994) The 9-intersection: Formalism and its Use for Natural-language Spatial Predicates. National Center for Geographic Information and Analysis Technical Report 94-1

Goodchild MF (1977) An evaluation of lattice solutions to the problem of corridor location. *Environment and Planning* A 9:727–738

Hodgson ME (1992) Rapid k-neighbor identification algorithm for the sphere. *Cartography and Geographic Information Systems* 19:165–174

King LJ (1969) The analysis of spatial form and its relation to geographic theory. *Annals of the Association of American Geographers* 59:573–595

Love RF, Morris JG, Wesolowsky GO (1988) *Facility Location: Models and Methods*. North-Holland, New York

Mark DM, Egenhofer MJ (1994) Modeling spatial relations between lines and regions: Combining formal mathematical models and human subjects testing, In: Egenhofer MJ, Mark DM, Herring JR (eds) pp 29–82

Medda F, Nijkamp P, Rietveld P (1998) Recognition and classification of urban shapes. *Geographical Analysis* 30:304–314

Mitchell JSB, Mount DM, Papadimitriou CH (1987) The discrete geodesic problem. *SIAM Journal of Computing* 16:647–668

Nystuen JD (1963) Identification of some fundamental spatial concepts. In: Berry BJL, Marble DF (eds) *Spatial Analysis: A Reader in Statistical Geography*. Englewood Cliffs, N.J., Prentice-Hall, pp. 35–41

Okabe A, Miller HJ (1996) Exact computational methods for calculating distances between objects in a cartographic database. *Cartography and Geographic Information Systems* 23:180–195

Raskin RG (1994) *Spatial Analysis on a Sphere: A Review*. National Center for Geographic Information and Analysis Technical Report 94-7

Smith TE (1989) Shortest path distances: An axiomatic approach. *Geographical Analysis* 21:1–31

Smith TR, Peng G, Gahinet P (1989) Asynchronous, iterative, and parallel procedures for solving the weighted-region least cost path problem. *Geographical Analysis* 21:147–166