

ANALYTICAL CARTOGRAPHY

UCGIS Emerging Research Themes in GIScience

by

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DEFINITION AND SCOPE

Analytical Cartography was defined succinctly by Tobler (1976) as the mathematical and analytical parts of cartography that remain independent of technology that applies to both real and virtual maps. With origins in mathematical cartography, analytical cartography draws from the cognate fields of computer graphics, computational geometry, geodesy, surveying, image processing and geography, and the spatial data sciences in general. In recent years, much of analytical cartography has been subsumed into geographic information science. Yet GIScience is far broader in scope than analytical cartography. Analytical cartography, as a subdiscipline of cartography and the spatial data sciences, has been defined in terms of its development (Moellering, 1991; Tobler, 2000, Moellering 2000a), origins (Clarke and Cloud, 2000), scope and conceptual content (Kimerling, 1989, Moellering, 2000b) and applications (Franklin, 2000). We now propose that Analytical Cartography serve as a unifying theme within GIScience research, covering the essential link between GIScience and geographic theory on the one hand, and computer-based analytical mapping in the real and virtual domains on the other.

While GIScience has matured and expanded in scope (Goodchild, 1992; Clarke, 2001), even to include the role of technology in transforming society (Chrisman, 1999), analytical cartography has provided the "solid bedrock of theory upon which the field of geographic information systems is rapidly building" (Clarke, 1995, p.3). As such, the field is sufficiently specific as to constitute a distinct and related set of theory, methods, and applications; and at the same time broad enough to constitute a UCGIS theme.

Characteristics of the analytical cartographic conceptual approach are transformational geometry (Chrisman, 1999; Tobler, 1979), theories of data structures and models (Moellering, 1983; Nyerges, 1991), normative cartography (Cromley, 1992, p.18) and the sampling theorem (Tobler, 2000). Fields of interest include real and virtual maps, the specification of primitive objects, spatial frequency analysis, interpolation and neighborhood operators in the regular and irregular cellular domains, and analytical visualization (Moellering, 2000b). Applications have included the design and improvement of spatial data structures, analytical approaches to map annotation, generalization and transformation, including their inherent error, map annotation and numerical cartography. The collective benefits of years of research in these areas has led most of the algorithms, computer codes, and data structures embedded in specific geographic information systems, and inherent in further geographic theory. For example, Chrisman has reexamined Steven's classic work on measurement theory from the point of view of spatial data (Chrisman, 1998), and expressed GIS operations in terms of the transformational approach (Chrisman, 1999).

Briefly stated, analytical cartography is a mathematical sub-discipline of cartography and a part of the larger spatial data sciences that deals in the abstract with problems that are of great practical concern to GIScience. It has a distinct history, a finite suite of theoretical underpinnings, and many practical applications to analytical

mapping, real and virtual. We believe there are fundamental unsolved problems in analytical cartography that are both pressing and of use to the whole GIS field, and that are distinct from the other emerging research themes. For example, there is a great need to develop a general theory of spatial data. Currently it is thought that raster and vector data structures are vastly different things. Certain problems can be analyzed better with raster data than vector data, and vice versa, while a small class of problems could be solved with either of the structures. Both families of spatial data have their advocates and detractors, and there has been much debate in the field. This situation is very similar to the view of the particle and wave theories of light in physics during the 19th century. Various proponents of these two theories debated through the 19th century until a chap named Einstein developed the general theory of relativity which showed that the particle and wave theories of light were special cases of the general theory of relativity. Those in the spatial data sciences in the 20th century have been in an analogous position relative to spatial data organization. One suspects that raster, vector and relational structures are special cases of a more general theory of spatial data that is yet to be discovered. This possibility must be investigated by the brightest and most creative minds in the field. Furthermore, it is unlikely that such problems would be attacked either in a unified way, or even at all, without the attention that a UCGIS designation would bring.

RELATION TO THE 1998 UCGIS RESEARCH THEMES

Spatial Data Acquisition and Integration

This theme deals with the first two map transformations, those of measurement and representation. As such, analytical cartography offers this theme some new theory and interpretations of existing methods. For example, data structures on the database end have recently seen debate about which standard database indexing systems are most suitable for spatial data (e.g. R, R+ and S trees). Object orientation and new data capture mechanisms such as GPS and hyperspectral sensors have placed unprecedented strain on existing software systems, which can only be approached through new theory and heuristics. For example, Shannon's classic work on information theory may still hold advantages for understanding information flow during the capture and integration processes.

Distributed Computing

GIScience has been far more concerned with server-side applications in distributed systems, epitomized by ArcIMS and the Alexandria Digital Library. analytical cartography is more client-side oriented. New tools and standards for distributed architectures, such as Java, GeoVRML, OGC and XML, make this an exciting area for application of the methods and techniques from analytical cartography, especially computer mapping and analytical visualization. The relation to this theme is also one of a different approach, and access to new theory and algorithms.

Extensions to Geographic Representation

Analytical cartography has always been related directly to the theory of data modeling. Again, new approaches are available, including object-relational data modeling, standards, and new primitives and behaviors (e.g. the nodes in GeoVRML), that can be exploited and investigated using analytical methods.

Cognition of Geographic Information

There is virtually no overlap with this theme, other than the fact that human vision characteristics and data models are determinants of cognition.

Interoperability of Geographic Information

Interoperability requires both standards and translations. We see the latter as another example of transformational geometry. Interoperability seeks to create transparent transformations of space and attributes that are complete and fully invertible. Analytical cartography offers some theory to interoperability, but clearly the importance of this theme as driving new research has been diminished by increased activity, standards and organizational attention.

Scale

Scale has been interpreted very broadly in GIScience. Analytical cartography uses the more specific cartographic definition of map and spatial scale, and so offers new approaches for automated map generalization

and spatial sampling in the regular and irregular cellular domains (See Tobler 2000). Geostatistics is closely related to analytical cartography through interpolation, and as such offers an alternative way to view and appreciate problems of scale (See Cressie, 1993).

Spatial Analysis in a GIS Environment

Most geographers see analytical cartography and spatial analysis as synonymous. This is probably because Tobler was a central figure in the development of the origins of both fields. Nevertheless, spatial analysis is to geography what analytical cartography is to maps. They intersect when virtual maps are used as the primary mode of analysis as in cartographic modelling (Tomlin, 1990). In analytical cartography the scope is usually more specific, while the applications are more specific to cartography.

The Future of the Spatial Information Infrastructure

We see the future of client-side computing as tightly tied to analytical cartography. Otherwise, the spatial information infrastructure as a repository is important in terms of data structure, compression and storage, and as an accessible resource presents important computing challenges that analytical cartographic methods can assist with.

Uncertainty in Spatial Data and GIS-Based Analysis

This theme is more central to current work in GIScience, yet when the error is geometric rather than thematic, or is a consequence of sampling, resolution or data structure, then analytical methods complement quite well the stochastic methods such as geostatistics and Monte Carlo simulation. This theme is complementary to analytical cartography.

GIS and Society

Reassessment of the early history of analytical cartography (Clarke, 2000), GIS (MacHaffie, 2000) and computational/quantitative geography have proven of great use for advances in understanding the discipline. While analytical cartography differs substantially in approach and method, nevertheless, its proponents have been among the first to advocate a revised and inclusive model of GIS as both reflecting and playing a role in shaping human society (Chrisman, 1998).

Overall, analytical cartography is not a subset of any of the original ten research themes, neither is it a superset. None of the existing themes need to be changed as written, yet use of theory and methodology from analytical cartography can add significantly to the breadth and depth of work in these areas. Generally speaking, analytical cartography's contributions will be to add new theoretical structures to existing approaches, strengthening and enhancing work in these fields.

ANALYTICAL CARTOGRAPHY AS A CROSS-CUTTING THEME

While analytical cartography is cross-cutting in its relationship to the original ten themes, it differs from both a unifying "grand problem" such as "Scale in GIS," and from those themes that speak closest to the application of technology. Instead, analytical cartography can be seen as the use of analytical approaches to solving map-related problems in the real and virtual domain. The compare and contrast approach, especially when it cuts across domains, is an essential component of analytical cartographic work. For example, various spatial data structures, such as the grid, topological vectors, and the TIN, can all represent terrain. From the point of view of application, we may wish to empirically describe the error associated with the use of a particular model, or for a particular type of data. Using direct comparison, theoretical or empirical, and then acting upon the results is the essence of analytical cartography.

The defining elements of the cross-cutting nature are a basis in mathematics, algorithms and analytical cartographic principles, in addition to the use of the scientific method, as applied to problem-solving, particularly in software and computation. This is the reason why the theme deserves separate status, that is because it does not overlap or subsume any existing theme, yet is cohesive in approach and method. Hence, work on topics like spatial ontologies will be left to others. We believe that this approach to analytical cartography can demonstrate from published papers, conference themes, and from research organizations a significant extant and clearly defined corpus of work.

THE ROLE OF UCGIS

The motives for adding Analytical Cartography as an emerging research theme are threefold:

First, we seek to encourage and advocate research using analytical cartographic methods, especially by young scholars. UCGIS plays a significant role in broadcasting the needs and goals of academic GIScience, one that has already influenced the allocation of funding and the careers of young scholars.

Secondly, since the demise of some of the key conferences that allowed concentrated activity in analytical cartography (GIS/LIS, Auto-Carto), there have been fewer opportunities for the community of scholars using analytical cartographic methods and approaches to interact. We see the addition of themes and extra days of papers and workshops at UCGIS-sponsored meetings and activities as an excellent way to remedy this. For example, there were several analytical cartographic papers at GIS 2000 in Savannah, yet they were interspersed with other papers on more general geographic issues.

Thirdly, we will evaluate and aggregate national curriculum in analytical cartography. While many Universities offer classes in GIS, and computer cartography, few teach the principles necessary for analytical cartography (Clarke, 1987). We will seek to use UCGIS as a vehicle for disseminating information about teaching the methods and theory of analytical cartography, possibly with areas such as computer science and mathematics, including cross-disciplinary advising where necessary. Thus we see research on teaching as valid research under this initiative.

IMPORTANCE OF THE EMERGING THEME TO NATIONAL RESEARCH

Analytical cartography has played a key role in serving national needs, from defense and intelligence during the Cold War to serving the needs of civilian federal agencies today. Much research on analytical cartography in the past took place as part of directed federal efforts, for example by the USGS or the US Census Bureau. Today, the commercial world develops new algorithms and techniques for mapping and spatial analysis largely for competitive advantage. As a consequence, some of the analytical cartographic literature in the formal, scientific research sense, has been characterized by gray and black literature (Clarke and Cloud, 2000). There is a critical need for open research in the peer-reviewed literature that includes descriptions of algorithms and methods as well as theory and approach (Franklin, 2000). We believe that developing such a body of literature is critical to advances in Geographic Information Science, and is critical to the interdisciplinary nature and outreach of spatial scientific methods. Scientists working in analytical cartography typically have a narrower background than those in GIScience, and include mathematical, computer science and engineering elements in their backgrounds. As such, there is a need by both government and industry for students and professionals with a background in analytical cartography to maintain the United States edge in the emerging fields of geographically enabled mobile communications, in GIS and in spatial science.

The needs of this initiative are minimal. Success of this thematic endorsement by UCGIS will be demonstrated by:

1. Increases in the submissions of papers to journals using the methods and approach of analytical cartography;
2. Increases in the number of undergraduate students being exposed to curricula reflecting the analytical cartographic approach;
3. Increase in the number of advanced students working in the area and;
4. Raising the awareness of Federal and other bodies of the importance of funding research in analytical cartography.

Benefits will include meeting national employment needs to sustain US leadership in the field, increased technical benefits from the science, patents, etc.

PRIORITY RESEARCH AREAS

Areas of research that fall under this theme are reviewed thoroughly by Moellering (2000b). We separate them here by priority:

In the short term, research should focus on cross-fertilization. Analytical cartographers should review (and submit their reviews and surveys to journals) recent developments in theoretical computer science and mathematics. Similarly, traditional mapping sciences such as computer graphics, civil engineering, surveying, geodesy and planning should be surveyed so that developments can be shared. For example, Mike Worboys recently surveyed developments in theoretical computer science and assessed their utility for mapping and GIScience at the Hong Kong Spatial Data Accuracy symposium. This research can be completed in two to three years, culminating with a track to be added to a forthcoming GIScience meeting, hopefully the sequel to this years meeting in Savannah.

In the medium term, UCGIS could work toward both encouraging more research based on the theory in analytical cartography, and substantiating the curriculum at institutions of higher education in the United States. A UCGIS web-site should serve the role as a clearing-house for curriculum and teaching information in much the same way that the NCGIA site garnished the GIS Core Curricula. This should not be a "model curriculum" effort, but more of an information sharing and self-help framework, targeted at supporting instructors who teach analytical and computer cartography at the college and university level.

In the long term, work should proceed toward the design and execution of a definitive textbook in analytical cartography, such that the material could fit into any curriculum in computer science, geography, engineering school or the likes. Similarly, after a decade, it would be time to hold a conference aimed at international participation, perhaps a revival of the International Conference on Computer-Assisted Cartography (Auto-Carto) sequence, still owned in name by the American Congress on Surveying and Mapping. Similarly, some accountability information should be forthcoming, in the form of a report to UCGIS on the numbers of papers attributable to the initiative, number of dissertations completed, patents developed, and curricula approved.

EXAMPLE RESEARCH PROJECTS

Example research project in the short term have been provided by Franklin (2000), who reviewed projects in terrain visibility, map overlay, use of partial information for analytical purposes, mobility, interpolation and approximation, and drainage analysis. Franklin also reviewed current challenges, including the proper representation of terrain, database use, three dimensional analysis, error metrics, "just good enough" computations, and theory of algorithms. To these, Saalfeld has added significant and profound problems and challenges in tractability and complexity (Saalfeld, 2000).

POSSIBLE SHOWCASE DEMONSTRATIONS

The authors of this document are available to gather together a suite of showcase demonstrations when necessary. We will concentrate on demonstrations that have proven to be of importance to federal agencies, such as the USGS, the Census Bureau, NIMA, and the Department of Defense. We see the Digital Earth and other such initiatives as an excellent way to focus attention of the need for research in analytical cartography.

CONCLUSIONS

We request UCGIS to endorse Analytical Cartography as an Emerging Research Theme in GIScience. We have demonstrated that the body of literature defining the scope and content of analytical cartography is substantial and relevant to GIScience and to the larger spatial data sciences. We seek to accomplish goals relating to the encouragement of research, raising national awareness about analytical cartography, especially among the federal government users of GI Technology, and goals that will establish a more solid and interdisciplinary educational framework around which to build in the future.

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