# *NCGIA* National Center for Geographic Information and Analysis

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# Research Initiative 3

# Multiple Representations

# Closing Report

By

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**CLOSING REPORT**

# MULTIPLE REPRESENTATIONS
## NCGIA RESEARCH INITIATIVE 3

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## ABSTRACT

This report describes the results of NCGIA Initiative 3 on Multiple Representations. It begins with a discussion of objectives and the process of developing a research agenda. Each of the major research activities is discussed. The initiative was active during the period 1988-1990. Since that time, research activities have continued, and include research following the original agenda as well as off-shoot research topics that have been subsequently refined to formalize NCGIA Research Initiative 8, "Formalizing Cartographic Knowledge". These transitional research activities will be briefly presented.

## OVERVIEW

The scope of concern in the use of the term "Multiple Representations" refers to changes in geometric and topological structure of a digital object that may occur with the changing resolution at which that object is encoded for computer storage, analysis and depiction. Cartographic and digital data arguably provide only a sample of the geographic features they are intended to represent. As discrete approximations of a continuous reality, each cartographic object may capture at most a subset of its geographic counterpart. The resolution at which features are captured by digital encoding methods will often bias the amount and types of details about the features that are encoded. The implications for geographic information and analysis formed the basis for prioritizing a research agenda.

In the context of GIS and geographical analysis, this is an important problem because the nature of geographic data renders changes in its appearance and underlying structure depending on the resolution at which it is digitally encoded. Topographic information and statistical phenomena with a spatial component both tend to exhibit characteristics of scale-dependence, and render more difficult the process of automating the mapping sciences as well as the analysis of geographical pattern. The expense and tedium of generating unique database information for every desired scale of representation continues to challenge data production, to inhibit research efforts, and to limit the reliability of many GIS applications involving spatial decision support.

Products of the initiative continue to develop since the Specialist Meeting in February 1989, and include research projects and publications, two research bibliographies, and generation of a multi-scale database for research and teaching. Details will be discussed briefly for each one in turn. A comprehensive discussion of the prioritized research agenda and products may be found in Buttenfield and DeLotto (1989).

It is important to realize this provides a starting point for research on multiple representations, an agenda of research priorities to be discussed, criticized, and expanded by interested researchers in many disciplines. Topics discussed and explored at the Specialist Meeting and in subsequent research are of course colored according to special interests and knowledge of the participating researchers. The formal closing date of the Initiative (June, 1990) is not intended as the terminus of the research, but rather as a point at which the establishment and refinement of a research agenda provide impetus for the rest of the research community. Research continues to focus on forming rules for map design, on error propagation for multi-scale computations such as coordinate conversion, distance computation in networks, and inference based on enumerated data.

## PROGRESS ON THE RESEARCH AGENDA

At the Specialist Meeting, attention focused on research questions that can be addressed now given the current level of technology and software engineering, and given the current state of knowledge. Two sets of issues surfaced for immediate research attention. These include Database Issues and Generalization Issues. A third arena for multiple representations research was determined to lie within the context of Spatial Modeling Issues, which has strong ties with NCGIA Research Initiative 1, Accuracy of Spatial Databases, and have been reported elsewhere (Goodchild, 1992, Final Report for Research Initiative 1). It is important to understand that these are not the only three areas where fruitful research topics may be discovered, but rather the three broad topics felt by the Specialist Meeting participants to be of highest priority and most realistically pursued given present knowledge and present research tools.

**Database Issues**

Database issues must be addressed to accommodate multiple representations in a single or multiple version data management strategy. Of central importance is the need to organize multiple topological and metrical versions for efficient access, and implementation of linkages between multiple representations. New strategies for maintenance of materialized database views is another important research topic. Rules to preserve consistency between database views generated at different levels of resolution must be refined as well. Projects developing from these topics include investigation of the following questions:

- What data models can best preserve multiple representations?
- How should multiple representations be linked to maintain consistency?
- How should multiple materialized views be organized for efficient queries?

Data Models of Multiple Representations. Current geographic information systems use only a single model or representation of the world and thus support only a single level of detail. GIS users need to organize multiple representations at different levels of detail and different map scales. While known multi-resolution metrical representations like strip trees are based on the primitive notion of topology used for geographical spaghetti, multiple geometrical representation are based on a complete notion of topology. Ongoing research includes work on integration of metrical and topological database information, as well as formulating hierarchies between topological cells (Bruegger and Frank 1989a; Bruegger and Frank 1989b; Bruegger and Frank 1990).

Linkages between Multiple Representations. Presently multiple representations are stored in our collection of maps. Representations of the coastline of Maine, for example, exist in the many historical renditions and current formats and scales of maps produced by different organizations. Other than sharing an approximate geographic location and a human cognitive association, these representations have no logical and explicit connections. Kate Beard has been exploring methods to explicitly and logically connect different representations of the same geography. Objects in different representations can be assumed to share some metric, topological or attribute information. Relevant work (Beard 1989; Beard, 1991) is focused on the formalization of operators which can yield or connect representations with different levels of detail.

Maintenance of Materialized Views. Materialized database views are derived from a database and stored in anticipation of providing fast response to future requests for that data. As a view is a derivation from the base data and generally must maintain consistency with it, one or more views over the same base data are a form of multiple representation. Dissertation research at Maine (Kate, citation please?) concerns re-establishing the consistency of the views after a change has occurred to the base data, by a technique called 'autonomous update computability'. Views generated by this technique may be materialized at remote sites, and subsequently updated by sending just the set of base data changes to the remote site. Portions of the view may be autonomously updated even when the entire view is not and some computational advantage may be extracted from this.

Other Research Questions. A related set of topics focuses on database queries. At the Specialist Meeting, particular interest was expressed about the stability of query processing in multi-scale database searches. How predictable is the variation in response to a database query made at different levels of resolution? Is the variation more readily predictable for particular data domains, or particular levels of resolution? What range of variation can be considered acceptable for specific types of spatial decision support? To what extent does the architecture of the database impact upon the stability of query processing?

A final topic relates to the determination of the scale of a given database. Depending upon the status of updates, database information should be derived from the amalgamation of scales from all data sources. The scale of a database is perhaps not meaningfully described by the simple numeric of a Representative Fraction (RF), for example as with USGS "1:24,000 hydrography" (one example from many cited). Asking the scale of a database is in fact making a query about the lineage of the database. The Spatial Data Transfer Standard addresses lineage as a data quality issue, but discussions during the Specialist Meeting indicate the issue should be more broadly defined to encompass generation and archival of geographic information.

**Generalization Issues**

Attention in this realm focused upon the nature and display of cartographic data. Generalization for analytical purposes must also drive the research agenda. Attention must be extended to representation and analysis of geographic terrain and higher dimensional objects, and not limited to the current primary focus on line simplification (DeLotto, 1989). Assessment of error in generalization continues to be an additional important research priority, as does generation and evaluation of digital cartographic database products (Fico, 1991).

Clarifying the Concept of Resolution. The need to derive a comprehensive and flexible definition of resolution forms an important research direction. Variations in feature resolution that may occur within a single data set (e.g.., US county boundaries) must be explored to improve the efficiency and accuracy with which they are utilized for statistical and cartographic applications. Simplification algorithms must be designed that self-adjust according to the local resolution of objects (Buttenfield, 1989). Resolution of enumerated data is a topic of some interest to researchers in spatial statistics and spatial analysis, where it is commonly referred to as the "Modifiable Areal Unit" problem. Research in this area is discussed below.

Digital Feature Description. A second item placed on the research agenda involves formalization of digital feature description and categorization models. Digital models must accommodate the complexity of compound and hierarchical objects, and be sensitive to those aspects of geometry that may change with scale (Buttenfield, 1991). Measures of feature geometry and complexity must be evaluated in terms of robustness and redundancy (Jasinski, 1990). Conversion between digital models must be studied in terms of error propagation, to associate particular models with specific generalization operations (McMaster, 1989). Refined understanding of the properties and operations associated with a model or class of digital models (for example, terrain models) will improve decisions about which generalization algorithms will be appropriate for a particular model (DeLotto, 1989).

This research issue is not limited to simplification of map features (Walters, 1989). Problems of consistency in attributes and feature codes affect the transfer of data between federal agencies, and attest to the need for consistent attribute assignments in digital databases. Research on the logic of feature code assignments was ascribed a high priority at the Specialist Meeting. Categorization of digital data may be improved by attending to cognitive aspects of feature categories, in addition to the current emphasis on accuracy and (perceptual) recognizability so prevalent in database and cartographic research. There are implications for the logic of spatial query languages as well, and herein lies a link between Initiatives 2 and 3.

Formalizing Rules for Map Generalization. A third set of research topics involves rules for map generalization that must be defined explicitly to automate the cartographic process. Rules for setting and modifying tolerance values in feature or object simplification cannot be developed without improving techniques for encoding and manipulating those features and objects (Mark, 1990). A project funded by USGS (Buttenfield, PI) addressed tolerance modification for linear features at NCGIA-Buffalo (Buttenfield, 1991).

Rules for symbolic transformation of map information must also be derived (Beard, 1989) and evaluated (Mackaness, 1991). For example, the decision to collapse an urban area to a point is determined in part by scale, map purpose, and by dimensionality of the object at its source scale. Other symbolic operations such as coarsening of a categorical coverage, displacement of features during map reduction, etc. are understood only intuitively. Issues of conflict resolution must be defined and prioritized. A comprehensive typology of generalization operations must be formalized, and this marks an area of generalization research already being undertaken outside the NCGIA, and typified by researchers such as Robert McMaster (University of Minnesota) and Robert Weibel (University of Zurich).

A symposium to address substantive issues prerequisite to the development of a knowledge base for cartographic generalization was held in April 1990, and jointly sponsored by NCGIA and Syracuse University. The symposium was hosted by Robert McMaster (Syracuse) and Barbara Buttenfield (NCGIA-Buffalo). Participants were invited from universities in North America, Europe and New

Zealand and from the private sector (Intergraph, PRIME-Wild, and The Analytic Science Corporation, TASC). Each participant presented a paper focusing on a specific issue (for example, conflict resolution, or preserving the balance between artificial intelligence and amplified intelligence) that must be resolved in order to implement a knowledge base for automated generalization. Symposium participants are listed below.

NCGIA Participants:
Kate Beard, NCGIA - Maine
Barbara Buttenfield, NCGIA-Buffalo
William Mackaness, NCGIA-Buffalo
David Mark, NCGIA - Buffalo

Other Academic Participants:
Marc Armstrong, University of Iowa
Herbert Freeman, Rutgers University
Bob McMaster, Syracuse, University
Mark Monmonier, Syracuse University
James Mower, SUNY-Albany
Jean-Claude Muller, ITC, Enschede, The Netherlands
Brad Nickerson, University of New Brunswick, Canada
Tim Nyerges, University of Washington

Private Vendors:
Gail Langran, Intergraph Corp., Seattle, Washington
Stuart Shea, The Analytical Sciences Corporation, Reston, Virginia
Robert Weibel, PRIME, Zurich, Switzerland

Immediately following the symposium, two special paper sessions were held at the Association of American Geographers Meetings (Toronto, April, 1990). Both sessions included presentations condensed from the symposium (abstracts below). Follow-on research from the symposium was presented in two special paper sessions at GIS/LIS '90 in Anaheim, California, in November 1990, and several of the papers presented there were included in the proceedings (Armstrong and Bennett, 1990; Muller and Mouwes, 1990; Mark, 1990; Mackaness and Beard, 1990).

**Spatial Modeling Issues**

The effects of scale and zoning are being studied in the context of the Modifiable Areal Unit Problem, using multivariate exploration of Buffalo census tract data. Stewart Fotheringham leads this work at Buffalo, with particular interest in the sensitivity of parameter estimates to changes in the scale at which data are reported. The intention is to discover consistent findings with regard to scale-dependent sensitivities (Wong and Fotheringham, 1990). As a benefit of the work, block group boundaries for the Buffalo metropolitan area have been input to ARC/INFO for subsequent investigation of the urban density gradient over multiple levels of resolution.

A related issue concerns the scale at which various types of geographic process (for example, diffusion and aggregation) are likely to impact upon the structure of geographic features (for example, urban form and growth). Work proceeds applying fractal and chaotic models to the study of geographic process (Batty, Longley, and Fotheringham, 1989; Fotheringham, Batty, and Longley, 1989). Skepticism about the utility of fractal models has been discussed in an editorial by Fotheringham (1990). Batty (1990) has compared fractal models with Dielectric Breakdown Models in the context of modeling urban form.

## RESEARCH PRODUCTS AND DELIVERABLES

**Multi-Agency, Multi-Scale Database**

The discussions for the data base focused in part on the need to create a standard of reference upon which to benchmark generalization algorithms and database search and query operations. Without a standard data set, it remains difficult to compare the results of various algorithms and to improve our understanding of the nature of digital representations that may change substantially depending upon the resolution at which they are collected, archived, and mapped. A standard data set based on federal products that could be placed in the public domain would provide such a standard. Additionally, this data would provide a useful teaching aid, to demonstrate the use of federal agency data sets, and to explore the transferability of data from one agency format to another. Finally, it would provide researchers and students alike the chance to work with multiple digital views of the same area, produced according to the various digital specifications of participating US federal agencies.

The NCGIA was a logical agent to represent the academic perspective in the effort, as part of its mandate is to remove impediments to pursuit of research and education in GIS, and to support similar research and educational efforts at other academic institutions through its outreach program. Academic researchers do not always have resources to receive and process multiple digital data sets from federal data producers. Federal agencies do not often archive small data sets that can be compared with other data sets from other agencies.

Data to be included in the first set (Lee County, in southern Florida) was provided by US Census, USGS, and NOS. As time, funding, and the interest of the general community permit, up to four other data sets will follow. Tim Trainor of US Census has been in contact with NCGIA-Buffalo this spring to begin preparations for subsequent data sets. Each data set is intended to comprise 10 - 20 floppy diskettes and will have a small ASCII instruction file explaining how to unpack and load the data set. Data documentation will be a part of the packed data on the disks. NCGIA disseminates the data sets in the public domain on a cost recovery basis, in DOS fomat. Dissemination began in early 1990. Details on the database project were presented in NCGIA Technical Report 90-4 (DeLotto, Buttenfield, and Broome, 1990).

**Multiple Representations Bibliography**

Incorporated into the bibliography (Buttenfield, DeLotto, and McKinney, 1989) are citations from journal articles, monographs and books, and technical reports on research in computer science, cartography, and spatial modeling. The common thread is the exploration of methods by which to generate and utilize a single detailed database to produce and analyze graphical representations at many different scales and resolutions. Implications for map representations include problems of appropriate simplification and symbolization of both features and attributes, as well as problems of maintaining consistency throughout database update.

The bibliography is intended as a tool for the general community, to provide an overview of research in a topical area that has to date not been identified in its own right. It became clear as the literature search was undertaken that the volume of research that has been reported is being catalogued under categories that are quite diverse, and little if any centralization to the topic now referred to as "Multiple Representations" has penetrated keyword generation to date. Publication of this bibliography should reduce redundancy of research efforts and alert individuals who do not commonly interact about the communality of efforts to understand the nature of things that change with scale, encourage interchange between researchers in many disciplines, and maintain currency in a field that is to date only crudely defined.

Information sources for this bibliography include the usual bibliographic tracing through published research reports and general reference. Online searches were performed through computerized bibliographic data bases and CD ROM archives of the Science Citation Index, INSPEC (Electrical and Electronic Engineering Abstracts) GEOBASE (GeoAbstracts) and GEOREF (Bibliography and Index of Geology). Several government abstracts and archives have been searched, including Government Reports Announcements and Index (GRA &I), Scientific and Technical Aerospace Reports (STAR), Energy Research Abstracts (ERA) and Monthly Catalog of US Government Publications.

**Visiting Scholars to NCGIA- Buffalo**

Professor William Mackaness, instructor at the University of Otago, Dunedin, New Zealand, accepted a 6 month post-doctoral appointment at NCGIA-Buffalo and arrived 15 February 1990. Dr. Mackaness' research interests focus in conflict resolution in expert systems, and in cartographic applications of GIS. He participated in the Syracuse Rule Base Symposium, and published with Center faculty and graduate students on work related to Initiative 3, as well as in planning and early publications for Initiative 7 (Visualizing the Quality of Spatial Data). Dr. Mackaness will return to NCGIA-Maine in September 1991 to pursue research associated with formalizing rules for map design (Initiative 8) and to direct production of a Compendium of Data Quality examples (Initiative 7).

# EXTERNAL FUNDING

## Research Grants Awarded

Three sources of external funds were identified in conjunction with Initiative 3, all of which involve federal agency support.

Buttenfield, B.P. "Automatic Methods for Cartographic Line Distinction". Research proposal ($39,081) funded by USGS (award announced August, 1989). Award period December 1989 - December 1990.

Buttenfield, B.P. "Multi-Agency Multi-Scale Database Project". Summer stipend ($3,000) for a graduate intern to develop data compression software. Funded by US Bureau of the Census; award announced April, 1989. Discussions in May 1992 with Census representative Tim Trainor have led to their verbal commitment to prepare subsequent datasets in the coming year.

Buttenfield, B.P. and McMaster, R.B. "Symposium Towards a Rule Base in Map Generalization" April 1990 in Syracuse, NY. Funds ($4,000) were provided by Syracuse University (and matched by NCGIA) to cover travel and lodging for symposium participants. PRIME-Wild Zurich has agreed to defray up to $1,000 for participant costs of Robert Weibel. AAG (Cartography Specialty Group) provided $360 to cover AAG conference registration costs for 3 European participants (Muller, Weibel, and Mackaness).

Kick, J.S. (in conjunction with Barbara Buttenfield) "Resource Inventory and Soil Surveys Using Geographic Information Systems" $ 47,500
USDA Soil Conservation Service. Funding includes $10,000 for NCGIA equipment, and commitment for 1 year paid residence at NCGIA-Buffalo for SCS representative to collaborate on research). (Award period January 1991 - December 1991)

# ASSESSMENT

Some topics in the agenda were focal points for Center research due to prior research interest, funding opportunities, and due to the specified priorities for research coming from Specialist Meeting discussions. In particular, the research on the modifiable areal unit problem and research in the area of map generalization have both continued, by members of the Center as well as by external researchers. The map generalization effort continues to be particularly active in North American federal agencies and in Europe, and these efforts will be drawn upon to assist in prioritizing a research agenda for Research Initiative 8, Formalizing Cartographic Knowledge, due to begin late in 1993.

This section presents a scientific assessment of Research Initiative 3, organized according to the five criteria established by the NCGIA Board of Directors.

**How has the research agenda been affected as a consequence of initiative activities?**

The NCGIA original proposal (NCGIA, 1988) cited several impediments related to resolution, consistency, and spatial aggregation:

- Models for digital representation of features must incorporate the possibility for scale-dependent geometry, to preserve recognizability and maximize storage efficiency.

- A GIS must be able to represent objects consistently at different resolution levels and to support modification across resolution levels.

- Reporting zones used for spatial aggregation are rarely designed for research purposes, and introduce uncontrolled and largely unpredictable bias; moreover, they are subject to change.

The Specialist Meeting refined these statements and proposed a research agenda addressing several classes of research topics. In database design and management, research addressed the need to formalize object descriptions at each resolution level, and formalize connections between resolution levels such that changes applied at one level can propagate to others, allowing multiple representations to be deduced automatically. GIS operations affected by this include map overlay and map comparison. In map representation, research addressed need to design and implement feature descriptors and generalization algorithms that preserve the realism of geographic entities and attributes that exhibit differing characteristics at different map scales. One can differentiate between aggregation of properties attached to objects, seen in the research published on the Modifiable Areal Unit Problem, and description and modification of object geometry, seen in the research on scale-dependent feature description and domain-dependent feature simplification.

**What do we know now that is new? What recommendations can be made to promote further advances of knowledge in the research area?**

We know now how to generate object-oriented descriptors of geometry and how to carry this knowledge within a database. The appearance of cartographic objects is both scale-specific and domain-specific, and carrying this knowledge in object data structures can improve the accuracy and visual realism of map representations. What is needed now is research to support decisions about which algorithm and which tolerance values will produce optimal results in both cases. This has direct implications for coordinate densification, aggregation of coordinates for dynamic segmentation, and selection of tolerance values for differential generalization.

We know now that the behavior of cart objects is both domain- and scale-specific, and this impacts modeling and analysis, in addition to illustration. For example, computation of the length of network links for location-allocation problems will be affected by scale in some (e.g.., hydrographic) but not all (e.g.., transportation) networks. Modeling procedures must be developed to compensate and correct for possible bias. This has direct application to spatial decision support.

We know now that self-similarity is a special case of scale-dependence, and that automatic recognition of self-similarity can improve computational efficiency. We know now that many of the measures designed to measure so-called “fractal dimension” or the rate of increased complexity across scales, are neither robust nor comparable, and this appears to be due in large part to embedded and limiting assumptions about statistical or geometric self-similarity. What is needed now is research to determine the ranges of scale within which self-similarity is bounded by scale-dependent change, to determine scales at which cartographic objects and attributes are particularly sensitive to modeling operations.

We know now how to generate and preserve links between objects whose topology changes with resolution, and how to maintain multiple views more consistently. We know now that object inheritance provides a robust mechanism for efficient database updates. What is needed now is research to implement the generation and maintenance of multiple views in both sequential and parallel architectures, to operate on very large databases such as those utilized for remote sensing and image processing.

We understand better the impact on statistical estimation caused by Modifiable Areal Unit enumeration, and need to refine development of statistical procedures to compensate for this as a possible bias. We need to develop map overlay and map comparison techniques that account for differences in topology and geometry in enumeration units. We need to develop inferential techniques to distinguish real differences caused by enumeration change from representational differences caused by processing geometry or topology.

We know now that statements reporting the scale of map data should require a statement of the lineage of objects contained in the database. Relationships between map data resolution and database data quality should be documented, and for a GIS user, knowledge about resolution requires knowledge about quality. What is needed now is to study variations in data quality under changes in scale. For example, we understand that conversion between coordinate systems has varying geometric effects depending upon the resolution at which the conversion is computed, and need to further explore optimal levels of computational precision that will best preserve critical map features and data quality.

**How has the education of GIS scientists been enhanced by the initiative?**

The first area where educational impacts are evident relates to research products of the initiative. The NCGIA-US Census dataset for Lee County Florida (described earlier in this report) is likely the most important pedagogic product in two ways. First, it was generated as a tool for the general research community, to expose students to multiple federal digital data products representing a single geographic region. Second, the project was conducted by Joe DeLotto, a doctoral student at SUNY-Buffalo, and required his internship in Washington DC for three months while securing data and for 8 months in Buffalo writing software to generate the final software product. The Center has had numerous requests for the dataset, particularly from smaller academic institutions where the expertise or technology to handle data pre-processing tasks is not readily available. US Census representative Tim Trainor has been in contact with the Buffalo site to plan for a second dataset.

A second area of educational impact includes pursuit of graduate theses on the multiple representations issue. Completed theses include research on automated classification of digital terrain (DeLotto, 1989), a critical comparison of fractal measurements on cartographic lines (Jasinski, 1990 ), presentation of automatic scale-changing operators that could be implemented in DMA's Digital Chart of the World (Fico, 1991), and a comparison of multi-scale operations in raster and vector GIS software (Soltyka, 1992).

A third area of educational impacts can be seen in publication of research bibliographies on various topics relating to multiple representation issues. These include a general scope bibliography on Multiple Representations (Buttenfield, DeLotto and McKinney, 1989) and a more focused bibliography on Fractal Geometry and Spatial Phenomena (MacLennan et al, 1991).

A final area where the Multiple Representations theme has provided educational enhancement can be seen in graduate coursework. This past spring at SUNY-Buffalo, the geography faculty collaborated in presenting a graduate seminar on "Fractals and Chaos" in the Geography Department, coordinated by Professor Michael Woldenberg. Faculty members led weekly discussions on topics related to specific research applications, including map generalization, simulation of urban growth, demographic modeling, and digital terrain representation. NCGIA faculty members who participated in the seminar included Professors Batty, Buttenfield, Fotheringham, Mark, and Rogerson and Woldenberg.

**What has NCGIA learned about the research initiative process?**

The Multiple Representations initiative was one of the first research initiatives to be pursued. It was important to create a level of awareness in the community before and during the initiative, in part because the Center was recently established, and in part because the initiative process was as yet not well-tested in practice. Perhaps the most important lesson learned from the first three initiatives is that direct involvement of researchers external to the Center provides the key to generating momentum on the research agenda outside the Center. For initiative 3, this momentum was maximized by federal agency efforts, notably at USGS National Mapping Division, and at US Census Geography Division.

Three things can be pointed out about the initiative process. The first relates to having a single initiative leader. The second relates to the Specialist Meeting format, specifically the focus on small group formats to generate a research agenda. The third relates to products of the initiative, including publication of research volumes and dissemination of software products.

Like initiative 1, initiative 3 was managed by a single leader, and unlike initiative 1, the leader was untenured during the active period of research. With advice from Ross MacKinnon, then Associate Director at Buffalo, the Specialist Meeting and subsequent research activities were purposefully kept much smaller in size and more tightly focused in scope than initiatives 1 and 2. In retrospect, this was a good management decision, because the amount of time required to coordinate multidisciplinary research at multiple sites increases as a function of the size of the research program. Subsequent to Initiatives 1 and 3, the NCGIA Science Policy Committee has assigned at least two individuals to co-lead every initiative, with the intention that initiative co-leaders should have some time free to pursue aspects of the research agendas they coordinate. The issue of tenure turned out to be a non-issue: in fact, the successful leadership served to strengthen presentation of the tenure case. Two subsequent initiatives have junior faculty co-leaders (I-6, Spatial Decision Support Systems, and I-10, Spatiotemporal Reasoning).

In contrast to previous initiatives, the venue for the I-3 Specialist Meeting iterated between meetings of the entire group each morning and small group discussions each afternoon. It was apparent that the small group format was exhausting, and yet proved to be one of the most effective parts of the meeting. The small group format has been adopted in some subsequent Specialist Meetings, with equal success. Its major advantage is summarized in recent electronic mail by the comment of an external participant (Bob McMaster, University of Minnesota) that "... you asked outsiders to help the Center prioritize a research agenda, and the small group format gave a strong indication that the input of outsiders was really important."

The third lesson to be learned relates to the products of research. In each of the first three initiatives, publication of a book has brought visibility to the research agenda, and laid groundwork for external offshoots to the original research. For initiative 3, the research volume **Map Generalization: Making Rules for Knowledge Representation,** co-edited by Barbara Buttenfield and Robert McMaster, resulted from a conference jointly funded by NCGIA and Syracuse University. The book reports research coming at the end of the initiative, and marks a transition between a conceptual focus on automating scale-change operations and map simplification to a broader focus on formalizing the entire cartographic design process (generalization, symbolization, and production). This conceptual transition has had impact on science within the Center as well, shown in part by the decision of the Science Policy Committee to revise research initiative 8.

Software products developed as a part of initiative 3 include the Multi-agency Multi-scale dataset for Lee County Florida (described above). This is currently available from NCGIA Central office as a box of DOS-compatible floppy diskettes, and also available on anonymous ftp from the NCGIA office in Santa Barbara.

# RESEARCH PUBLICATIONS

## Refereed Journal Articles

Batty, M. 1992 "Generating Urban Forms from Diffusive Growth." **Environment and Planning A,** forthcoming.

ABSTRACT. A formal model of diffusion-limited aggregation is presented and used to generate a continuum of urban forms from linear to concentric. A brief derivation of the continuum is presented, and related to potential theory. The forms produced by the model are subject to fractional power laws which relate occupancies of sites and densities to distances. Fractal dimensions can be derived from these fractional powers and conventional and fast methods of estimation are introduced.

Batty, M. Longley, P. and Fotheringham, S. 1989 "Urban Growth and Form: Scaling, Fractal Geometry and Diffusion-Limited Aggregation." **Environment and Planning A**, vol.21, p.1447-1472.

ABSTRACT. A model of growth and form is proposed in which the processes are intimately linked to the resulting geometry of the system. The diffusion-limited aggregation or DLA model generates highly ramified tree-like clusters of particles or populations with evident self-similarity about a fixed point. The extent to which such clusters fill space is measured by their fractal dimension which is estimated from scaling relationships linking population and density to distances within the cluster. We suggest that the model provides a suitable baseline for the development of models of urban structure and density which manifest similar scaling properties.

Beard, M. Kate. 1991. "Theory of The Cartographic Line Revisited: Implications for Automated Generalization." **Cartographica,** forthcoming.

**ABSTRACT** The Theory of a Cartographic Line (Peucker 1975), described the width of a cartographic line as its essential characteristic. Digital representations have tended to ignore this basic attribute and in the context of generalization the oversight is detrimental. The theory claims that a set of enclosing bands captures the cartographic character of width and supports generalization. The Douglas algorithm, still one of the most commonly used algorithms for generalizing digital representations uses this model. Work of a Polish mathematician Perkal, provides the basis for another model of cartographic line width and a different generalization technique. This paper examines how effectively both models capture cartographic line width and succeed in producing generalized results, particularly for larger scale reductions. The two techniques are assessed by their ability to satisfy two objectives: capturing the essential and recognizable characteristics of geographic features and creating representations which can be legibly displayed at some smaller scale. This paper compares the behavior of the two methods as applied to digital coastline data.

Buttenfield, B.P. 1989 "Scale-Dependence and Self-Similarity in Cartographic Lines." **Cartographica**, vol.26(1), p. 79-100.

ABSTRACT. This paper provides a typology of two classes of geometry for cartographic lines, based on the well-known Richardson plots. The first class contains objects having self-similar geometry, features whose structural characteristics are replicated either precisely or statistically with changes in scale. Self-similar features

are currently described by fractal models, which some argue are appropriate for all cartographic objects. The fallacy of this statement will be demonstrated. The second class of features is fully scale-dependent, and contains cartographic objects whose geometry varies distinctly with changing scale. Both models are described and applied to examples of digital line features, to demonstrate their worth in encoding and preserving particular types of cartographic detail during automatic generalization.

Buttenfield, B.P. and DeLotto, J.S. (1992) "Multiple Representations of Digital Data: A Data Set for GIS Teaching and Research. **Photogrammetric Engineering and Remote Sensing** (under revision).

Fotheringham, A. S., Batty, M. and Longley, P.A. 1989 "Diffusion-Limited Aggregation and the Fractal Nature of Urban Growth." **Papers of the Regional Science Association**, vol. 67, p.55-69.
ABSTRACT. This paper introduces the mechanism of diffusion-limited aggregation (DLA) as a new basis for understanding urban growth. Through DLA, urban form is related to the processes of rural-to-urban migration and contiguous growth. In spite of their simplicity, DLA simulations are shown to incorporate properties found in most urban areas such as negative density gradients and ordered chaotic structures. The paper examines variations in the simulated urban structures produced by varying assumptions regarding the rural-to-urban migration mechanism. An important finding is that urban density gradients can occur independently of the presently accepted reasons for their presence. We also comment on boundary effects in the measurement of urban density gradients.

Fotheringham, A.S. and Wong, D.W.S. 1991. "The modifiable areal unit problem in multivariate statistical analysis." **Environment and Planning A,** vol. 23(7), p. 1025-1044.

Longley, P.A., Batty, M., and Sheperd, J. 1991 "The Size, Shape, and Dimension of Urban Settlements." **Transactions of the Institute of British Geographers**, vol.16, p. 75-94.

Mark, D. M., and F. Csillag, 1989 "The nature of boundaries on 'area-class' maps". **Cartographica,** vol. 26(1), p. 65-78.
ABSTRACT. Appropriate generalization methods for geographic data must depend upon the kind of feature being generalized. Most research on cartographic line generalization has concentrated on linear features such as coastlines, rivers, and roads; however, methods for the generalization of such linear geographic features may not be appropriate for the generalization of other types of cartographic lines. In this paper, we present a model of another type of cartographic line, namely boundaries between categories or classes which occur over contiguous regions of geographic space. We focus our attention on "natural" area- class data sets such as soil maps. In the model, such boundary lines are far more similar (mathematically) to elevation contours than they are to coastlines and rivers. Appropriate generalization methods may involve construction of surfaces representing probability of class membership, generalization or smoothing of such surfaces, and 'contouring' the probabilities to find boundaries.

McMaster, R.B. 1989 "The Integration of Simplification and Smoothing Algorithms in Line Generalization." **Cartographica**, vol.26(1), p. 101-121.

ABSTRACT. The cartographic generalization of vector data in digital format involves six distinct processes, including simplification, smoothing, enhancement, displacement, merging, and omission. This paper proposes a conceptual model for the geometric interaction of these components. It is proposed that sequential processing of line data base don this model will improve the quality of the original digital information, minimize database storage and database error, and produce aesthetically acceptable generalizations at greatly reduced scales.

Wong, D.W.S., and Fotheringham, A.S. 1990 "Urban Systems as Examples of Bounded Chaos: Exploring the Relationship Between Fractal Dimension, Rank-size, and Rural-to-urban Migration." **Geografiska Annaler**, vol. 72B(2-3), p. 89-99.

Abstract. Fractal structures appear to be closely related to systems whose growth to a large extent is the result of a series of unpredictable events. Examples of such structures include river networks, certain political boundaries, the growth of a city, and the development of urban systems. In this paper, we demonstrate how systems of cities have a fractal dimension and that this fractal dimension is related to a very commonly used index of urban systems, the rank-size parameter. Urban systems can be thought of as examples of ordered or bounded chaos in that the growth of a particular urban system results from countless, unpredictable decisions which makes it unique but the range of urban systems that we observe in reality is rather limited. We demonstrate a possible explanation for the bounded nature of urban system development which is based on rural-to-urban migration. It is shown that the controlling influence on the development of an urban system is the choice process by which migrants select alternatives. Both the fractal dimension and rank-size parameter of an urban system can be related to the parameters of a spatial choice model. Several examples are given of simulated urban systems, each of which is unique but yet has the same fractal dimension and rank-size parameter when derived from the same spatial choice model.

## Books

Buttenfield, B.P. and McMaster, R.B. (Editors) 1991 **Map Generalization: Making Rules for Knowledge Representation.** London: Longman.

ABSTRACT. This research volume focuses on development of a rule base for automated map generalization, addressing specific issues that must be resolved. Rudiments for some rules have been codified in recent efforts, but there is little consistency in current proposed solutions, making integration and coordination difficult. The book includes four sections: Rule Base Organization; Data Modeling Issues; Formulation of Rules; and Computational and Representational Issues. The editors have invited 13 chapters from disciplines of cartography, computer science, and surveying engineering, to present a broad perspective on the formalization of guidelines for digital map generalization. A Foreword to the book is contributed by Professor Herbert Freeman.

## Book Chapters

Batty, M. 1990 "Cities as Fractals: Simulating Growth and From." In **Fractals and Chaos,** edited by R.A. Earnshaw. New York: Springer-Verlag, p. 41-69.
ABSTRACT. The morphology of cities bears an uncanny resemblance to dendritic clusters of particles which have been recently simulated as fractal growth processes. The analogy is explored, presenting deterministic and stochastic models of fractal growth, and suggesting how these models might form an appropriate baseline for urban models. In particular, the diffusion-limited aggregation (DLA) models and dielectric breakdown (DLM) models are outlined. Comparisons are made between simulated clusters and the form of medium-sized towns. Using the DBM formulation to illustrate constraints and distortions, the model is applied to the town of Cardiff, Wales.

Batty, M., Fotheringham, A.S. and Longley, P.A. (in press) "Fractal Geometry and Urban Morphology". In Lam, N. and DeCola, L. (Eds.) **Fractals in Geography**. Englewood Cliffs, N.J.: Prentice-Hall.

Beard, M. K. 1991 "Constraints on Rule Formation". Chapter 7 in: Buttenfield, B.P. and McMaster, R.B. (Editors) **Map Generalization: Making Rules for Knowledge Representation.** London: Longman House, p. 121-135.
ABSTRACT. Generalization has traditionally been practiced as an individual artistic skill and as such it lacks a universal and consistent definition. Although some general procedural steps can be identified, the diversity of cartographers' approaches to the task has defied formalization and hindered automation. Formalism requires specification of some well-defined and unambiguous rules, but anticipating rules to cover every possible condition is not practical. This paper explores the specification of generalization as a set of constraint-based transformations, and develops in the following sequence: (1) specification of an exhaustive set of operations to abstract the spatial and nonspatial aspects of a representation; (2) description of the essential information needed to support each operation in the set; (3) development of a model to support the information as defined and facilitate operations in the set; and (4) design of an interface allowing users to specify conditions (constraints) which must remain invariant during generalization.

Buttenfield, B.P. 1991 "A Rule for Describing Line Feature Geometry." Chapter 9 in: Buttenfield, B.P. and McMaster, R.B. (Editors) 1991 **Map Generalization: Making Rules for Knowledge Representation.** London: Longman House, p. 150-171.
ABSTRACT. Automatic methods are presented to determine locations in a coordinate file where the geometry of a line feature changes, to enable automatic tolerance value modification. Tolerance values must be modified periodically to insure both accuracy and recognizability of graphic details on a generalized map. Any automatic solution requires formalized description of the amount and type of details that occur along the extent of the digital file. This is complicated by the need to accommodate scale-dependence in the formal descriptions. Previously developed methods for digital description of line characteristics that are scale-dependent are discussed in the context of formalizing rules for generalization.

Mackaness, W.A. 1991 "Integration and Evaluation of Map Generalization." Chapter 13 in: Buttenfield, B.P. and McMaster, R.B. (Editors) 1991 **Map Generalization: Making Rules for Knowledge Representation.** London: Longman House, p.218-227.

ABSTRACT. There are about ten techniques that are invariable used when generalizing a map. The factors governing their applicability are many. To date, generalization techniques have been researched in isolation of one another, and appraised using mathematical techniques. It is becoming increasingly apparent that the combination and degree of application of these techniques are interdependent of one another, and need to reflect the geographical character of features, the map type, user knowledge, and also encompass the objectives of aesthetics. This paper attempts to summarize these qualitative attributes using an "attribute-rose diagram". Attributes typically used to describe a map are represented by spokes. The distance up the spoke is proportional to the strength with which that adjective describes the map. The problem thus becomes one of pattern recognition, namely associating generalization techniques according to the shape of the rose. This approach is holistic, and for use in establishing the combination and degree of application of generalization techniques and as a way of evaluating the success of the graphic.

Mark, D.M. 1991 "Object Modeling and Phenomenon-Based Generalization." Chapter 6 in: Buttenfield, B.P. and McMaster, R.B. (Editors) 1991 **Map Generalization: Making Rules for Knowledge Representation.** London: Longman House, p.103-118.

ABSTRACT. This paper proposes that support of phenomenon-based ("geographical") generalization requires three high-level classes of objects. One class would be made up of geographic objects, features of the real world such as shorelines, settlements, roads, lakes, etc. Another class would include cartographic objects, such as the symbols and features that are shown on topographic maps. The third class includes data-structure objects, such as points, pixels, line segments, images, etc. If the classes are properly linked, then generalization rules may be applied in one domain, and the effects propagate through to the others. Since generalization rules and principles in the data-structure domain are fairly well known, this paper concentrates on object-class definitions and rules for the geographic domain.

Walters, D.K.W. 1989 "Discrete Contour Descriptors." In **From Pixels to Features**, edited by J.C. Simon, North Holland Elsevier, p 287-298.

ABSTRACT. A set of discrete contour descriptors is proposed. The descriptors are able to describe discrete contours, such as those found in digitized maps, using parameters which are independent over the similarity transformations of scaling, rotation and translation. As the descriptors are based on discrete geometry, they do not have the implementation problems of descriptors based on continuous geometric concepts. In addition, the descriptors are perceptually valid: contours which humans perceive to be similar have similar descriptors. The descriptors are much simpler than spline-based or related descriptions, and thus can lead to more compact representations that maintain all of the perceptually relevant information.

Weibel, R. and DeLotto, J.S. 1989 "Automated Terrain Classification for GIS Modeling". Chapter 2 in: Weibel, R. (Editor) **Contributions to Digital Terrain Modeling and Display.** Zurich: University of Zurich Geo-Processing Series, vol.12, p. 25-50.
ABSTRACT. Automated terrain classification involves the partitioning of an area into homogeneous topographic regions through quantitative interpretation of a digital terrain model. By evaluating geometric parameters extracted from raw elevation values, it is possible to characterize the nature of topography either in general terms such as roughness, or in terms of a specific application, such as hydrology or geomorphology. In recent years there has been a growing interest in the use of automated terrain classification to provide meaningful information to a number of modeling and processing tasks. This paper reviews the conceptual basis for areal classification of topography and examines specific difficulties for performing this task automatically from digital terrain models.

## Monographs and Technical Reports

Buttenfield, B.P. and DeLotto, J.S. 1989 **Multiple Representations: Report on the Specialist Meeting**. Santa Barbara, CA: NCGIA Report 89-3.

Buttenfield, B.P. and DeLotto, J.S. and McKinney, J.V. 1989 **Multiple Representations: A Bibliography.** Santa Barbara, CA: NCGIA Report 89-11.

DeLotto, J.S. Buttenfield, B.P. and Broome, F. 1990 **Multiple Representations Data Set Project: Lee County Florida**. Santa Barbara, CA: NCGIA Report 90-4.

Fico, F. 1992 **Generalization of the Digital Chart of the World.** Santa Barbara, CA: NCGIA Report 92-x (forthcoming).

Jasinski, M.J. 1990 **A Comparison of Complexity Measures for Cartographic Lines.** Santa Barbara, CA: NCGIA Report 90-1. (abstracted below, under section 3.7.6, Graduate Thesis research).

MacLennan, M., Fotheringham, A.S., Batty, M. Longley, P. 1991 **Fractal Geometry and Spatial Phenomena: A Bibliography.** Santa Barbara, CA: NCGIA Report 91-1.

## Conference Proceedings

Armstrong, M.P. and Bennett, D.A. 1990 A Knowledge Based Object Oriented Approach to Cartographic Generalization. **Proceedings** GIS/LIS 90, Anaheim, California, p. 48-57.

ABSTRACT. Digital cartographic data are encoded from source documents that determine the degree of accuracy that can be obtained from a database. In practice, data may be needed at different levels of generalization. Two main problems must be addressed: how to determine the required level of abstraction for a given application, and how to generate that level of abstraction. Past approaches are unsatisfactory because they fail to specify a mechanism for generalization and its parameterization for a given application. Object-oriented programming provides a mechanism for overcoming this problem. The geometrical description of an object and its representation are encapsulated in the description of the object. This knowledge is bundled with the object and can consist of facts or rules about the behavior of the object for a wide range of applications. This approach is consistent with modern software engineering principles.

Barrera, R. and Vasquez-Gomez, J., 1989 "A Shortest Path Method for Hierarchical Terrain Models", **Proceedings**, AUTO-CARTO 9, Baltimore, Maryland, p. 156-163.

ABSTRACT. An algorithm is presented for obtaining the shortest path between two points on a terrain represented by a triangular-faced polyhedron. The terrain model is hierarchical, i.e. it has several level of precision, the representation at each level refining the previous one. The proposed algorithm consists of two phases. In the initial phase, terrain representations at increasing precision levels are searched for regions where no optimal paths can trespass; these regions are not to be considered any further. In the final phase, a standard shortest path algorithm is applied on remaining areas.

Beard, M.K. 1989 "Design Criteria for Automated Generalization" **Proceedings** International Cartographic Association Conference, Budapest, Hungary, August 1989 (forthcoming).

ABSTRACT. The history of automated generalization spans approximately 25 years, but solutions developed to date have not yielded satisfactory results. It seems timely to evaluate reasons for this limited success. Although limitations of early computer technology are partially responsible, other factors are hampering progress. These factors include difficulties in formalizing the process, the graphic map and the physical mindset, and introduce persistent hardware and software problems. This paper investigates factors which have hindered both progress and success in automating generalization and to explore directions for advancing efforts in this area.

Beard, M. K. and Mackaness, W.A., 1991 "Generalization Operations and Supporting Structures" **Proceedings,** AUTO-CARTO 10, vol. 6, p. 29-45.
ABSTRACT. Current GIS do not support wide flexibility for the performance of map generalization operations so users have limited opportunity for creating views of data at different levels of resolution. This paper describes a context for computer assisted generalization and reports on a set of generalization operators. The generalization operators are embedded within a larger scheme for a map design system which could be attached to a GIS. The selection and sequencing of operations is not fully automated but relies on user interaction. This approach is adopted to allow users maximum flexibility in tailoring maps to their individual needs. The system, however, is designed to provide substantial support for the user in negotiating this process. The final section of the paper describes data structures for supporting the operations within the context of this interactive environment.

Bruegger, B.P. and Frank, A.U. 1990 "Hierarchical Extensions of Topological Data Structures" **Proceedings,** 17th Annual International Surveyors Conference (FIG), Helsinki, Finland.
ABSTRACT. Humans maintain multiple mental models to reason about the world. They use models appropriate to given situations in order to avoid getting lost in detail. GIS normally feature only a single representation for their reasoning process in a given domain. This paper present multiple topological representations designed to improve reasoning efficiency of GIS.

Bruegger, B.P. and Frank, A.U. 1989 "Hierarchical Cell Complexes." **Proceedings**, 12th Applied Geography Conference, Binghamton, New York, p. 238-240.
ABSTRACT. Multipurpose GIS offer considerable cost savings due to the sharing of data acquisition and maintenance efforts among several user groups. The paper demonstrates how a single topological representation impedes the implementation of such a system by causing response times to be unacceptably high when relatively large spatial objects are involved. In order to solve this problem, additional representations with reduced detail have to offer higher level views of the spatial objects. Lattice structures under spatial inclusion and hierarchies over topological cells are shown as examples for such higher level representations.

Bruegger, B. P. and Frank, A. U. 1989 "Hierarchies over Topological Data Structures" **Proceedings**, ASPRS/ACSM Annual Convention, Baltimore, Maryland, vol.4, p.137-145.
ABSTRACT. The paper describes a system of multiple, ordered topological representations connected by hierarchical relationships between topological cells. The lowest level representation organizes all spatial objects in detail, while the higher order representations contain only large and important objects represented with less detail. This structure makes the implementation of multipurpose GIS possible, where very small (e.g. parcels) and very large spatial objects (e.g. nations) co-exist. The response time to queries is independent of the size of the objects in contrast to present topological data structure. The spatial objects can be displayed in several resolutions.

Buttenfield, B.P., Weber, C. R., Leitner, M. Phelan, J. J., Rasmussen, D. M., and Wright, G. R. 1991 "How Does a Cartographic Object Behave? Computer Inventory of Topographic Maps." **Proceedings** GIS/LIS 91, Atlanta, Georgia, October, 1991.
ABSTRACT. Implementation of formal rules for cartographic generalization requires several types of knowledge describing map features. Collection of knowledge may proceed empirically, by trial and error application of various algorithms to features in various domains, or by interviewing cartographers with expertise in map compilation, or by systematic inventory of existing map series to determine the presence of consistent treatment of cartographic objects. This paper presents an empirical study using the last approach, generating an inventory of cartographic objects appearing on topographic map series.

Chitambaram, R. K. Beard and R. Barrera. 1991. "Skeletonizing Polygons for Map Generalization" **Proceedings** Annual Meetings of the American Congress on Surveying and Mapping, Baltimore, MD. vol. 2, p. 44-55.
ABSTRACT. Cartographic generalization plays a key role in enhancing the use of computer assisted map production systems and Geographic Information Systems. In recent times, considerable effort has been directed toward the development of tools of generalization that will give users flexibility to create maps at different resolutions. One such tool is the collapse tool used to transform areas to lines or points, and lines to points at lower resolutions. This study proposes the use of the polygon skeleton as an acceptable generalization of elongated areal objects at lower resolutions. The study includes the development, implementation, sand evaluation of a method for skeletonization. The methods uses the properties of the Voronoi diagram.

DeLotto, Joseph S. 1989b "Elevation Matrices as a Data Source for Automated Terrain Classification" **Proceedings**, International Cartographic Association Conference, Budapest, Hungary.
ABSTRACT. Parametric descriptions of terrain geometry have been proposed by a number of authors as a path to automating terrain classification, including measures of slope angle, aspect, hypsometry, and local convexity. Gridded topographic data (DTM's) remain the most widely used format for digital terrain, but are limited as a source for quantitative interpretation of terrain. Because sampling for production of DTM's does not vary with complexity of terrain, DTM's often contain inadequate representations of geomorphically significant features. A number of parameter extraction techniques are compared to demonstrate this limitation.

McMaster, R.B., and Mark, D.M. 1991 “ The Design of a Graphical User Interface for Knowledge Acquisition in Cartographic Generalization.” **Proceedings** GIS/LIS 91, Atlanta, Georgia, October 1991, vol. 1: 311-320.
ABSTRACT. This paper presents a research project designed to elicit the procedural knowledge used in generalizing maps. the project is based on the development of a specific graphical user interface (GUI) for map generalziation. The interface consists of pull-down menus that provide selection of algorithms, operaters, and parameters. Users may select individual objects or entire areas to be generalized. Eventually, the interface will be incorporated with log-keeping functions, and used with the NCGIA Multiple Representations data set to gain procedural knowledge on generalization from trained professional cartographers.

Mark, D. M.. 1990 Competition for Map Space as a Paradigm for Automated Map Design. **Proceedings,** GIS/LIS'90, Anaheim, California, p. 97-106.
ABSTRACT. This paper explores the concepts that competition for space on the display is the dominating process in the compilation and design of graphic maps. It is proposed that such competition can be regarded as a paradigm for the automation of the map design process, which includes feature selection, abstraction, symbolization, generalization, and displacement, as well as label placement and the positioning of non-geographic map elements (such as legend, title, scale bar, etc.). Competitive interactions between map elements could be managed through importance factors attached to every map symbol. Importance values could range from 1.0 (must show if there is space) to 0.0 (never show; delete from the graphic). Initial importance factors may be part of a database, or assigned based on other attributes. Rules then may modify importance values through 'inheritance' of importance through spatial relations, using methods based on propagation of certainty factors through an expert system. The centrality of spatial competition to expert systems for map design also puts high emphasis on efficient data structures and algorithms from computational geometry for the detection of overlaps and proximity relations.

Mark, D.M. 1989 "Conceptual Basis for Geographic Line Generalization." **Proceedings**, AUTO-CARTO 9, Baltimore MD, April 1989, p. 68-77.
ABSTRACT. Line generalization is an important part of any automated map-making effort. Generalization is sometimes performed to reduce data volume while preserving positional accuracy. However, geographic generalization aims to preserve the recognizability of geographic features of the real world, and their relations. This essay discusses geographic generalization at a conceptual level, and introduces the position that generalization is phenomenon-based, that is, different types of features (transportation, hydrographic, etc.) may require differing treatment because of the nature of their geometric and geographic characteristics.

Muller, J.C. and Mouwes, P. 1990 Knowledge Acquisition and Representation for Rule Based Map Generalization: Logistical Aspects and Pragmatisms. **Proceedings** GIS/LIS 90, Anaheim, California, p. 58-67.

ABSTRACT. Rules and procedures for generalization of topographic maps was collected from three sources, including national surveys' written guidelines, topographic map series and interviews with professional experts. Attempts to represent the collected information in formalisms useful for implementing a rule based generalization system are discussed. Facts and rules expressed in English-like language or in graphical form can be translated into alternative constructions, including frames, predicate calculus, and semantic networks. The extent to which these constructions may guide the geometrical and conceptual aspects of map generalization are also discussed.

Mackaness, W.A. and Beard, M.K., 1990 "Development of an Interface for User Interaction in Rule Based Map Generalization", **Proceedings** GIS/LIS 90, Anaheim, California, November 1990.

ABSTRACT. Map generalization has long been regarded as a subjective process. Since the early 1950's researchers have been attempting to remove the subjective component and render generalization as a strictly objective process. Some degree of user interaction seems necessary and desirable. The success of a rule-based approach is dependent upon an interface allowing users to intuitively investigate different map design solutions. Unconstrained by the time and cost of manual productions techniques and supported by new technologies, a user-interactive approach will allow for creation of products unique to individual uses or applications. This paper describes development of a prototype user interface for selection and application of various generalization techniques and suggests ways to convey rule constraints, and to provide for interaction of rules. Optimal interface design will have critical impact on the way in which rules are formalized and represented in a knowledge base. The discussion is centered around the design of topographic maps.

Weibel, R and DeLotto, J.S. 1989 "Automated Terrain Classification for GIS Modeling." Proceedings, GIS/LIS '88, San Antonio, Texas, vol. 2, p. 618-627.

ABSTRACT. Automated terrain classification involves the partitioning of an area into homogeneous topographic regions through quantitative interpretation of a digital terrain model. By evaluating geometric parameters extracted from raw elevation values of a DTM, it is possible to characterize the nature of topography in either general terms, i.e., roughness, or in terms of a specific application, i.e., hydrology or geomorphology. A recent interest in terrain classification can provide meaningful input to modeling and GIS processing tasks.

**Other Publications**

Fotheringham, A.S. 1990 "What's the Fuss About Fractals?" Guest Editorial in **Environment and Planning A**, in press.

## Graduate thesis research

DeLotto, J.S. 1989 "The Role of Scale in Automated Terrain Classification." MA thesis, completed August 1989.

ABSTRACT. Recent efforts to integrate techniques of automated terrain classification into geographic information systems are hindered by inadequate application of existing knowledge in fields of numerical taxonomy, image processing, and image understanding. The thesis reviews principles of terrain classification and geomorphometry, identifies problems that may occur when classification is performed from gridded elevation data, and proposes techniques to accommodate the scale dependent nature of topography.

Fico, F. 1991 "Generalization of the Digital Chart of the World." MA thesis, completed August 1991. Forthcoming as NCGIA Technical Report.

ABSTRACT. The Digital Chart of the World (DCW) is a database built from 1:1,000,000 scale source maps by the Defense Mapping Agency (DMA), scheduled for public release in early 1992. Nearly 200 feature types are included in 17 data layers. A layer-by-layer examination of features included in a prototype area of the DCW is accomplished for the purpose of investigating the feasibility of building a smaller scale database via generalization. Opportunities for feature generalization are identified and specific generalization operations are described. A number of the operations are performed or simulated using ARC/INFO, and the results are graphically displayed. It is found that meaningful small scale feature representation can be achieved through the application of tailored generalization operations with a significant savings in the amount of data required.

Jasinski, M. 1990 "Comparison of Complexity Measures for Cartographic Lines." MA thesis, completed February 1990. Also Published as NCGIA Technical Report 90-1.

ABSTRACT. Existing geometric measures commonly applied to cartographic line features will be examined for statistical redundancy. The goal is to determine a quantifiable definition of 'line complexity', or specifically to discover the components of a quantifiable definition. It is hypothesized that components will include aspects of distance, angularity, and density of detail, and that redundant measures are being applied by various researchers. A test data set comprised of both cultural and naturally-occurring line features will be measured and compared statistically to evaluate the geometric measures.

Soltyka, N. 1992 "A Comparison of raster and Vector GIS Functions Using Digital Terrain Data". MA thesis, complete January 1991.

ABSTRACT. This research compares GIS functions commonly utilized in monitoring natural resources. One goal is to compare systems using different methods (raster and vector) to store this information. The systems are ARC/INFO and GRASS. The benchmark selection of GIS functions includes volumetric measurement operations, and systems are compared on the basis of system performance, command sequence and complexity, and overall ease of system use.