UC Santa Barbara
NCGIA Technical Reports

Title
A Research Agenda for the NCGIA Renewal 1993-1996 (92-7)

Permalink
https://escholarship.org/uc/item/7wk2r1xk

Author
The National Center for Geographic Information and Analysis (NCGIA)

Publication Date
1992-12-01

NCGIA

**National Center for
Geographic Information
and Analysis**

**A Research Agenda for
Geographic Information and
Analysis**

by

The National Center for Geographic Information and Analysis
Consortium

Technical Report 92-7

December 1992

A RESEARCH AGENDA FOR GEOGRAPHIC INFORMATION AND ANALYSIS

Preface

In our original NCGIA proposal to the National Science Foundation (NSF) in 1988, we presented a two-part research plan that responded directly to the solicitation document issued by NSF in late 1987. The first part (subsequently published as NCGIA, 1989) was a discussion of impediments to the successful use of GIS in geographic analysis, together with the research necessary to overcome these impediments. The discussion was structured within the five research areas suggested by NSF in its solicitation. This was followed by twelve specific Research Initiatives which described topics for which research was planned, in order to remove or reduce some of the impediments identified. This structure was used in order to respond to the need for a framework within which research would be conducted and managed, but also recognized the fact that most of the major, long-term issues must be addressed incrementally through a consistent, multi-year strategy. The proposal thus translated long-term goals into opportunities for research over one- to five-year time periods that would contribute to the solution of major long term problems. The discussion of long term issues provided a unifying framework for developing and executing a research agenda for GIS and geographical analysis, not only for the NCGIA, but also for the broader research community, in the United States and elsewhere.

The new research plan presented in this document preserves this structure and enhances it. The first 42 months of the NCGIA have demonstrated that a multi-institutional, multi-disciplinary center for the advancement of fundamental geographic and GIS research can function effectively. The new research plan builds on the previous one, but also reflects the advancement in our thinking. The five research areas listed in the original solicitation from the National Science Foundation, often referred to as "the five bullets", are herein replaced by three general research areas: spatial representation; spatial analysis; and spatial informatics. This new framework serves as the common base from which individual research efforts can be selected and planned, and into which they are integrated. The Research Initiative continues to be the NCGIA's principal vehicle for research, but is augmented by additional vehicles designed to provide greater flexibility and responsiveness to the Center's ability to conduct its mission and achieve its goals.

If NCGIA is to play a truly national role, it must coordinate its research activities with those of other individuals and groups, and act as a focal point and catalyst. The Specialist Meetings held at the start of each NCGIA Research Initiative have performed a useful function in bringing together researchers interested in each topic, and in establishing a common research agenda for the community as a whole. Our published research plan (NCGIA, 1989) has strong similarities to those GIS and GIA research agendas developed and published by other groups (Craig, 1989; Maguire, 1990; Masser, 1990). At its June 1991 meeting the NCGIA Board of Directors gave strong encouragement to undertake the development of a national GIS and GIA research agenda as an NCGIA activity. Thus we see the agenda that follows as a first step in building such a consensus, and as a statement of long-term, community research needs that extends well beyond the capabilities of our own resources. The research agenda should be read as a developing framework for research both within and outside the Center.

As was stated earlier, the mission of the NCGIA is the advancement of geographic research of lasting and fundamental significance. More specifically, we will continue to advance the theory, methods, and techniques of geographic analysis based on geographic information systems (GIS) in the many disciplines and professions involved in geographic research, and to interact with individual researchers and organizations on a national and international basis. Education and outreach missions are not discussed in this document.

Research at the NCGIA will continue to focus on the data-intensive modeling of spatial phenomena and spatial processes, both physical and human, within computational systems. This viewpoint is crucial for modeling of all spatial data, independent of the data source, their disciplinary nature, and the analytical methods used. We see this as the scientific goal of the NCGIA, and the sections which follow detail the specific fundamental scientific questions that we have identified within this overall objective.

In the remainder of this document, a research agenda for GIA is described under three broad headings. The first is concerned with the *representation of geographic information*. This is essentially a static view of phenomena in geographic space, reflecting the age-old concern with form and description, albeit in a formal and computational framework. The second part focuses on *spatial analysis*. Analytic models are representations of processes in geographic space, and build on the representations of geographic features. But technology is of little interest without use. The third part of the research agenda addresses the *use of geographic information and information systems*. Included are human-computer interaction, visualization and graphics, institutional and legal aspects of the technology, impacts on science and on society, and many other topics discussed in information sciences under the broad heading of *spatial informatics*. This term is popular in many countries (geoinformatics is also popular), but has not been widely adopted in the US to date; we use it here in the absence of other more suitable terms, and with some sense of discomfort, and define it in the relevant section.

Because of the amount of literature involved, we have chosen to limit references to the minimal set necessary to embed the discussion in the published literature. A suitable consolidated bibliography for GIS/GIA research to augment the references cited here can be found in D.J. Maguire, M.F. Goodchild and D.W. Rhind, *Geographical Information Systems: Principles and Applications* (Longman Scientific and Technical, 2 volumes, 1991). In order to prioritize Center research activities within the Research Agenda, indicate where the results of NCGIA Research Initiatives have already made significant advances, and identify areas where active and planned Initiatives are likely to contribute substantial new knowledge, but at the same time maintain the coherence of the document,

we have linked it to specific Center research activities through italicized, indented sections.

1. REPRESENTATION OF GEOGRAPHIC INFORMATION

1.1. The Nature of Geographic Phenomena

The search for appropriate representations (formal descriptions) for the phenomena and processes to be modeled is critical. It is paramount to any scientific discussion, and also is a prerequisite to the development of sound data storage methods, computer programs, and visual displays. Development of mathematical representations for geographic features and phenomena was a major part of the quantitative revolution in geography, and is exemplified especially in William Bunge's *Theoretical Geography* (Bunge, 1962).

It is important to recognize that models of the physical world, even formal mathematical models, are grounded in our basic daily experiences. Spatial experience forms the core of human cognition, and spatial concepts form source domains for many of the metaphors that we use to structure and understand more abstract concepts (Lakoff and Johnson, 1980). In order to understand basic concepts of space, one must investigate the observable manifestations, including natural language, spatial behavior, and spatial artifacts.

> *Results of Initiative 2 (Languages of Spatial Relations) identified this particular relationship toll forms of languages about geographic space. Aspects of metaphors for human-computer interaction with spatial data and geographic space are being pursued with high priority as ongoing efforts under Initiative 13 (User Interfaces for GIS). Likewise, Initiative 10 (Spatio-Temporal Reasoning) will investigate metaphors that apply to different temporal concepts (such as continuous time and non-monotonic changes) with the goal of identifying metaphors that are applicable for both geographic space and time.*

Scientific disciplines typically are based on specific selections of phenomena and their conceptualization within the framework provided by the theories of the discipline (Brodie *et al.*, 1984). Geography is somewhat atypical, however. Instead of focusing on a subclass of phenomena, such as plants or landforms or birds or markets, geographic research has a common concern with influences of distance, position, relative location, and other spatial factors on almost any phenomenon (Abler, Adams and Gould, 1971). This allows geographic researchers to share a common set of tools for modeling the spatial aspects of phenomena - and these common methods, and associated tools and techniques, may lie very close to the intellectual core of the discipline. Of course, tools are of use not only to geographers and surveying engineers but to all disciplines that study spatially distributed phenomena. Computational geography (Baerwald, 1991) can provide valuable integrating techniques to many of the social, behavioral, and natural sciences.

Recognition of the spatial context dictates a need to identify fundamental spatial concepts. In 1963, Nystuen (1968) proposed direction or orientation, distance, and connection or relative position, as three such fundamental spatial concepts. He also saw four basic classes of geographic problems, centered around historical tensions, dimensional tensions (points, lines, regions), time-space tensions, and "scale of observation and unit area". Phenomena are related to positions in space and susceptible to the influence of other phenomena at the same location or nearby. Phenomena in space are considered by different sciences at different spatial and temporal scales. In order to deal with the interrelationships of phenomena and processes in space, we must have tools to integrate the phenomena as modeled by the disciplines, that is, to handle multiple representations. Geographic location has great potential use as a basis for integrating data from many sources and disciplines.

The specification and formalization of representations of geographic phenomena and processes are needed before they can be properly modeled and analyzed within a computing environment (Mark and Frank, 1989). To this effort, two different approaches are possible. One approach involves the observation and identification of the spatial concepts which individual disciplines and tasks use, the description of them with formal methods, and perhaps the recognition of general underlying principles and even theories. The second approach first develops formal spatial models of more abstract (phenomenon-independent) representations, and then investigates where they apply. The first is a more inductive approach, and the second is more deductive. Of course, in practice both methods apply to some extent, and they often have alternating effects. Both methods are valid and potentially useful.

Research must progress in two distinct ways. First, it must provide the formal specifications for modeling spatial phenomena and spatial processes typically considered by geographers, social scientists, and other researchers. And secondly the research must incorporate the multiplicity of spatial models from the discipline, such as spatial interaction models, location-allocation models, cognitive process models, and physical process models, some of which are already implemented in special purpose programs. An important basis of the research agenda is that these two aspects of modeling must not be treated separately. The parameters, conditions, and constraints that develop when describing geographic phenomena must incorporate the realistic complexities of dependence on location and resolution. At the same time, data modeling considerations must be integrated comprehensively within the spatial modeling effort. We need much more powerful tools to model the complex spatio-temporal phenomena and their interrelationships in space and time; and wherever possible these tools must be generic and provide the integrating force across the disciplines.

> *In order to design appropriate user interfaces for GISs (Initiative 13), it is essential to know the user's conceptual models of geographic space and phenomena, or to be able to modify those concepts*

through training or experience. Many of the critical concepts were identified during Initiative 2 (Languages of Spatial Relations), and extending this conceptual work is part of the agendas for Initiatives 13 and 10 (Spatio-Temporal Reasoning).

1.2. Data Models for Geographic Information

Every operation in a computerized GIS is based on a computational model, that is, a formal model of what should be achieved. If this computational model is *ad hoc* or implicit in the program, eventual failure of the system is very likely. Effective software engineering and data structure development thus depends on the development of formal models of the phenomena that the programs are to deal with (Boehm, 1987). Such models can be at different levels of abstraction, and may or may not be close to the concepts relevant to the user and the application. Low level models are typically used for storage of data in files or databases (Franklin, 1991), and also for the display of spatial data in the form of cartographic sketches. In these cases, users are required to translate the concepts in their high-level models of the phenomena under analysis, the data available, and the goals of the analysis into the low-level language which describes the data and operations of the system. The need for such translation is largely at the root of the high cost of learning to use a GIS. Ideally, a GIS would provide a coherent set of conceptual tools that approximate fairly closely its users' concepts of geographic space and phenomena, and thus enhance their efforts.

The spatial models used in current GISs are very limiting (Peuquet, 1989). In many cases they are constrained by the design of the data capture system (*e.g.* remotely sensed images, map scanners and digitizers) or by the storage medium. They typically employ a two-dimensional space, based on Cartesian coordinates and a Euclidean geometry and distance metric. This view of space has the advantage of conceptual simplicity, and provides the power of methods based on calculus. But since this view limits the nature, size, shape, location, and particularly the relationships and interactions among spatial objects, it is inadequate for many problems that GIS could otherwise address in social and economical sciences, ecology, climatology, hydrology, geology, and other disciplines. What is necessary are discrete spatial structures which can model, for example, the political subdivision of an area down to the census block, and still preserve such eminently spatial properties as adjacency and neighborhood (Saalfeld, 1985). Similarly, the geologist needs computational models to describe and represent such concepts as syncline, salt dome, fault, graben, *etc.*

Results of Initiative 2 (Languages of Spatial Relations) contain formalizations of topological relationships, cardinal directions, and order relations for bounded objects. It will be necessary to study in the future how close the formalizations come to human cognition. The formalizations of spatial relations will also be the basis for studies of temporal changes of spatial relations under Initiative 10 (Spatio-Temporal Reasoning in GIS).

1.2.1. Dealing with Multiple Representations

From the above, it is obvious that no single representation of a particular phenomenon or feature will be able to serve all users, models, or disciplines (Haggett, 1970; Harvey, 1968). If GIA is to advance, the development of computational systems for geographic information and analysis capable of supporting multiple representations of geographic information is crucial. And multiple representation is itself a multifaceted concept.

Modeling at Multiple Scales. The examination of phenomena at different scales is integral to geography, just as it often separates geography from cognate disciplines. To support multi-scaled analysis, we need models to represent objects at different levels of resolution. These models are needed to support reasoning across levels of resolution, and the propagation of modifications across resolution levels. Cartographers have long recognized the scale-dependent nature of the geometry of most geographic phenomena (Richardson, 1961; Mark and Aronson, 1984; Buttenfield, 1989), but the pervasive importance of this scale dependence has only recently been recognized more broadly. Scale-dependence applies to process as well as to form, as it is evident that geographic process will vary with scale, as does form and its description.

Results of research undertaken in NCGIA Initiative 3 (Multiple Representations) have improved our understanding of scale-dependent measures and models. We know now how to generate object-oriented descriptors of geometry, how to carry this knowledge within a database, and how to preserve links between objects whose topology changes with resolution. We know now that self-similarity is a special case of scale-dependence, and that automatic recognition of self-similarity can improve computational efficiency for many GIS computations.

Research is needed to formalize the ranges of scales at which particular human and physical processes operate, and at which the effects of those processes become evident. Research is also needed to determine the effects of using inappropriate scales, and the 'modifiable areal unit problem' in spatial analysis (Openshaw, 1984) is one direct perspective on this issue. But there is little formal theory dealing with the integration of models at different scales, and the issue is not studied in the mathematical background sciences (such as logic and algebra) that provide theory for the construction of modeling tools.

Proposed Initiative 15 (Multiple Roles for GIS in US Global Change Research) will address the integration of regional through global scale models in the context of global change research.

Cartographic databases often are acquired from maps published at several scales, or are used for production of maps at a series scales. In such data sets, it is common that representations for each scale are stored independently. The value of such databases could be greatly enhanced if representations were logically linked, so that changes in one data element could be propagated to others, either automatically or under operator control.

Modeling Temporal Aspects. Changes over time are important in investigations in geography (Langran and Chrisman, 1988), but we currently lack the tools to represent time effectively. Current GIS software does not allow temporal aspects of geographic information to be represented and manipulated effectively. Research is needed to address the logical foundations for the representation of spatial data with respect to time, and the logical inference methods applicable to such models. Several models of time are necessary, from models based on the concepts of time from physics, such as are often used in the natural sciences, to behavior-based and cognitive time models in the social sciences, to cyclic time models necessary to model processes that are cyclic over diurnal, tidal, annual, or longer time scales. Furthermore, models of time can exhibit the same scale dependency as spatial models, and the appropriate spatial and temporal scales may or may not be correlated. We expect that initially multiple methods for modeling time will be necessary.

> *Investigations of temporal aspects as they relate to geographic space will be a high priority in our future research activities. Initiative 10 (Spatio-Temporal Reasoning) will address discrete changes for bounded objects in geographic space. To get a better understanding of the different time models, we will study geographic applications which employ different temporal concepts and formalize them. The primary formalization methods will be algebras and logic.*

Modeling Multiple Disciplinary Views. The same object in a GIS can be studied by different disciplines, which may have very different conceptual models, or views, of the information. Database support for organizing the storage of several data units that describe the same object, but from different points of view, is necessary. Three very important cases must be considered, since the representations may differ in their level of processing (French *et al.*, 1990). *Primary data sets* are the raw data as collected by some sensors. *Secondary data sets* are produced by complex processing of various data sets from the primary database and some other ancillary data, but are not yet final products (*e.g.* vector data sets). And *tertiary data sets* consist of complex spatio-temporal objects that represent phenomena in the application domain. This classification indicates that during the modeling process, there is a progression of objects that are created, ranging from objects with a low explicit semantic content (raw data) to objects with a high degree of semantic content with respect to a given domain.

The integration of data, collected and used by different disciplines, involves observations at varying levels of resolution. Migration is not studied at the same scale as plate tectonics for the spatial processes involved operate at different scales. The analysis of their relations in space (primarily based on location) involve issues very close to the core of geography. It is an important research question to explore methods for building interdisciplinary models which integrate the models used by the different disciplines. Integrative models must show the interaction and interdependence of phenomena, as discussed by different disciplines at the same spatial location or within a spatial area of influence.

> *Research in global environmental change cuts across several disciplines and thus encounters the conflicts of domain specific models. Proposed Initiative 15 (Multiple Roles for GIS in US Global Change Research) must address the issues of integrating climate, hydrologic and ecological models in a policy-relevant context and with linkages to the human dimensions of global change.*

Integration of Error Treatment in Data Modeling. All data approximate reality. The difference between the data and the reality is often referred to as error. Models must include estimates of the data error, the quality of the data, and the effect of these errors on the inferences and analysis of the system. And, such errors must be assessed for every step and procedure, and carried along with the regular calculations. GISs are advocated as allowing the integration of data from many different sources, and for producing complex analyses useful for decision making.

With very few exceptions, current models do not include error assessment methods. And the exceptions usually are of limited scope, such as models of positional accuracy in surveying engineering, which may be very appropriate, say, for cadastral and legal applications, but may be almost irrelevant to retail market research. One is forced to assume, somewhat pessimistically, that at least some of the conclusions drawn from sophisticated GIS-based analyses are not justified if the error in the available source data is considered. Selection of a particular model determines what can be described or measured, and what other phenomena or attributes are excluded. Each model has limitations, both with respect to topic and resolution. This is the major reason why work to integrate models from different disciplines, and expressed in different formalisms, is important for further development of GIS.

> *Initiative 1 (Accuracy of Spatial Databases) developed models of error in categorical (multinomial) fields and made progress in error propagation. Research under Initiative 7(Visualization of Data Quality) focuses on representing error models and propagation to assist in monitoring error during GIS and GIA operations. For many GIS operations and GIA models, little is known about error propagation, or about sensitivity to source error, and*

GIS could also provide guidance to reduce error during data collection, through development of GIS-based procedures to implement a spatial sampling theory. Aside from some work in the geostatistical literature (Burrough, 1983; Cressie, 1991), there has been little work on how best to use multiscale geographic data to improve spatial sampling designs for both environmental and social phenomena. Known geographic information could provide valuable guidance in the location of long-term monitoring sites for global change research. Integration of traditional spatial sampling theory with GIS databases and software could form a basis for spatial sampling designs, but research is needed to bridge the gaps between the data models and concepts inherent in these different bodies of knowledge.

1.3. Data Structures and Database Issues

Without loss of generality, geographic information systems may be viewed as database systems, both in terms of their heritage and in terms of the most general definitions of database systems. It is generally assumed that a database system, and particularly the conceptual schema of the database, provides a model of the phenomena that are represented in the database. A cursory examination of current databases, however, reveals that they are very crude models (Silbershatz *et al.*, 1991). For example, consider the relational database that models a university or corporation. The standard commercial database is still primarily a simply structured repository of data which supports additions, deletions, and modifications of entries and little else.

If we assume that database applications may be viewed as modeling activities, then database development must be thoroughly integrated with phenomenon modeling, and use either the same languages, or languages into which descriptions of models can easily be translated. In the context of spatial phenomena, the database must be able to define and manipulate many classes of complex spatial objects and to access significant amounts of information about the objects based on spatial qualifications. In standard database
applications, significant domain modeling services have not been demanded, since both the domains and the queries have typically been extremely simple, and thus it is not surprising that GISs have also tended to be weak in this regard.

Whereas efficient relational database management systems (RDBMSs) have proven to be very successful for commercial applications, an NSF panel that recently studied the achievements and opportunities of database systems indicated that the next generation of applications, of which GISs are one set, will require more sophisticated support (French *et al.*, 1990; see also Guenther and Buchmann, 1990). This includes support for data access and data type management for large objects with a complex internal structure, as well as capabilities for processing large numbers of expert system rules, and the ability to handle new concepts such as spatial data, time, and uncertainty.

Research in database management systems *per se* is not part of the NCGIA mission, but GISs are critically interlinked with database management,and the NCGIA must extend and enhance its connections with the DBMS research community.

> *Under Initiative 5 (Very Large Spatial Databases), we have successfully started this dialog with the database research community. A new, biannual international conference series with a core of about 150 researchers has been launched that concentrates on the particular problems of very large spatial databases (Buchmann et al., 1989; Guenther and Schek, 1991).*

In the next subsections, we identify specific services a DBMS should provide to a GIS. The database research community is interested in very detailed description of such requirements, in order to study and provide appropriate solutions.

1.3.1. Modeling Complex Objects

GIS must deal with objects that have complex internal structures and are linked to multiple other objects. This is true even for the data that simply describe the spatial situation, but becomes far more important for the complex relationships between, say, hydrography, digital terrain models, and bridges in road networks. Current DBMSs can model such situations only with difficulty, and most of their intelligence must be captured in programs outside of the database.

> *Initiative 8 (Formalizing Cartographic Knowledge) will address knowledge representation both for cartographic objects and the geographic features represented by those objects. Extensionsto knowledge representation for more general geographic information may follow as extensions.*

1.3.2. Modeling Spatio-Temporal Phenomena

Current DBMSs cannot explicitly model time-dependent data, and only very limited support is available (Snodgrass, 1987) for a data type 'time' (often, only a data type 'date' is available). Support for spatial data types is completely lacking. The combination of spatial and temporal data poses exciting problems which were recognized early in the history of GIS (Sinton, 1978), but surprisingly little progress has been made since. Extensions for GIS are obviously necessary, but pose complex problems of trade-offs between the demands for the most flexible modeling support on one hand and efficient implementations on the other.

Modeling of spatio-temporal phenomena is a central part of the agenda for Initiative 10 (Spatio-Temporal Reasoning).

1.3.3. Access to Spatially Located Objects

Data in a GIS are related to locations in space, and the spatial dimension provides a common and uniform access method. For many applications, from analytical operations to cartographic sketches, it is necessary first to retrieve all data that relate to the area of interest. Past research has identified special data structures that allow fast access to data based on location (see Samet, 1989 for an overview). What has not been achieved, however, is the integration of these methods with large complete DBMSs, and the determination of which methods are best for realistic geographic data collections.

Assessments of the size of the data sets that will be available in this decade indicate that they will be extremely large (several terabytes), and that efficient storage and retrieval of large volumes of spatial data will be an issue of increasing importance. Retrieval methods must be efficient for data of varying spatial extents, for differing spatial scales, and for responsiveness to queries based on complex intersections of objects in space and time. Currently, the conflict between storage media and access methods that are essentially unidimensional on the one hand, and phenomena which exist and are interrelated in three (or four) dimensions of space and time on the other, represents a major impediment to progress in this area.

Initiative 5 (Very Large Spatial Databases) has focused on problems of data volume and access in GIS, and has made several important contributions to this literature.

1.4. Languages of Geographic Data Modeling

Language, in the most general sense, is a key element in the modeling of any phenomenon (Harvey, 1969); in particular, this applies strongly to the formal modeling needed in a computational environment. The formal languages used must be capable of representing adequately the objects and processes that arise in the domains being modeled. The languages must also be powerful enough to represent rules and theories of a specific domain. Finally, a language for representation must provide a meta level for the manipulation of the 'sentences' of the language - these may be the traditional inference rules of standard first-order predicate calculus, or the more complex rules of inference in a modal logic.

Issues of formal languages for geographic information were addressed under Initiative 2 (Languages of Spatial Relations). A dissertation at Buffalo on a language of spatial analysis is an outgrowth of that Initiative. The topic will be continued under Initiative 10 (Spatio-Temporal Reasoning).

Currently, we must deal with both domain-specific languages, developed by the domain scientists, and the quest for a general purpose GIS modeling language that is adequate for representing complex, multi-scale, spatio-temporal domains. For the former, the collection and formalization of the languages are the primary research issues.

Under Initiatives 2 (Languages of Spatial Relations) and 5 (Very Large Spatial Databases) we have studied the design of GIS query languages and identified their components, particularly as extensions of the database query language SQL.

The selection of languages for representation has immediate consequences for the effectiveness of the representation of phenomena and the computational efficiency of models based on those representations. Many languages must be investigated for their suitability for specific domains, and their computational efficiency must be evaluated. Of particular interest are classical first-order predicate calculus, modal and non-monotonic logics, calculus, and algebra. In general, a unification of various concepts can be observed within the framework of relational calculus, logic and algebra, and object-oriented design. Research in areas such as spatial and temporal reasoning and belief maintenance systems can contribute to the modeling of spatial phenomena.

1.5. Knowledge Representation

In their book *Building Expert Systems*, Hayes-Roth, Waterman and Lenat (1983, p.19) define knowledge as "facts, beliefs, and heuristic rules". Most of this section has been concerned with representation of facts about features and phenomena in geographic space. The distinctions among data, information, and knowledge are at times vague, but there is a tendency to view information and especially knowledge as having associated with it a higher degree of human interpretation. Also, the term 'knowledge' is often used in the context of expert systems, where knowledge engineering is the process of formalizing procedures for complex tasks by acquiring that knowledge from human experts (Hart, 1986; Armstrong, 1991). Knowledge may be acquired directly from experts through interview, or collaborative work between the expert and the program; it may also be acquired from textbooks or other publications, or by learning modules in interactive systems, where the expert performs a task using the system, and the system acquires rules or heuristics.

Under Initiative 2 (Languages of Spatial Relations), we have successfully developed knowledge representation schemes for geographic concepts such as cardinal directions and topological relations. We

will continue these efforts, considering their temporal changes, under Initiative 10 (Spatio-Temporal Reasoning in GIS).

GIS databases can be used to store everything from raw data to highly refined knowledge. Raw data may be of the greatest value to basic scientific research, while refined knowledge may be of the greatest value to decision-making and policy analysis (Parsaye *et al.*, 1989). The purpose of GIS technology may be to provide access to information, or to enhance the user's ability to explore information through the use of various tools, or to support analysis and the creation of knowledge from raw data. Each of these possibilities has implications for the structuring of information within the database, since refined knowledge requires much more sophisticated conceptual models. Some progress has been made in linking expert systems with information management (Brooks, 1987), and in developing knowledge-based information systems (Brodie and Mylopoulos, 1986), but much more remains to be done.

> *Many cartographic operations have aspects that are 'intuitive' or involve specialized expertise, and are difficult to formalize. The lack of formal cartographic knowledge impedes implementation of fully automated mapping, as solutions to cartographic automation have not been complete or general, and solutions to some mapping tasks have eluded even partialsolutions to date. Representation of digital cartographic data and implementations formalizing cartographic procedures will take priority in research addressed under NCGIA Initiative 8, Formalizing Cartographic Knowledge.*

2. SPATIAL ANALYSIS

2.1. The Nature of Spatial Analysis

Spatial analysis represents one of the core areas of research in contemporary geography and the main way in which geographic information and GIS can be extended to allow a greater understanding of the spatial world and how this understanding can be made relevant to various problem domains. The mission which the Center has set itself is entirely consistent with this broad aim of generating better understanding and applications for the development of data-intensive modeling of spatial phenomena within a computational system. Although the evolution of such analysis has gone hand in hand with the development of computers over the last 40 or so years, we are about to cross a threshold beyond which we will encounter a quantum leap in the applicability and relevance of spatial analysis to a vast array of real world applications. The Center's mission with respect to spatial analysis is to enable this leap to be made effectively.

In the development of spatial analysis, the first models were based on the application and adaptation of mathematical statistical theories to account for the particular effects posed by spatial configurations and adjacencies (Cliff and Ord, 1981). These models are based on identifying processes of growth and change from inferences concerning the distribution of various system properties across space and how these relate to one another (Cressie, 1991). Although the emphasis has been upon spatial structure, in econometrics and time series analysis there have been equally rapid advances and the field of spatial statistics now seems poised to incorporate time as well as space, thus engendering a whole new set of linked problems which can best be researched through data intensive computational modeling (Burrough, 1990).

Mathematical models, on the other hand, have also become central to geographical analysis. These models are based on theories of the system in question, on social and classical physics, on economic choice theory, on psychophysics, and on related disciplinary perspectives. Their essence is in linking deductive to inferential analysis and these too are best explored in data-intensive computational environments (Bennett and Haining, 1985; Anas, 1987). Finally, models of normative structure and behavior such as those involving welfare, utility, and energy, have been developed using various forms of optimization, heavily influenced by operations research. Recent developments in computation are also changing the structure and applicability of these types of model, making possible applications which hitherto were simply not envisaged. One of the central themes of this research agenda involves the application of new computational tools to these types of analysis (Harris, 1985).

> *An NCGIA Research Investigation into GIS and parallel processing has begun in the ongoing effort to improve the interface between spatial modeling, analysis, and decision support. This represents an important application of new computational techniques to both the use and further development of spatial analysis in a scientific as well as policy context.*

As well as the impact of new methods of representation on the types of spatial analysis we might develop and apply, the influence of various problem domains on spatial analysis must be explored. For example, new kinds of management and planning tools are emerging with distinct spatial orientations which in themselves are the product of new methods of computation applied to specific problem domains. New methods of spatial analysis do not emerge simply from the musings of researchers but from the volatile interaction of problem contexts with the tools available, and in this, new methods of computation through various types of GIS and GIA play a central part (MacMillan, 1989).

The key problem areas which lie at the base of our research efforts, and which will constitute a major research focus over the next several years, concern how we might best explore order and pattern in data, how we might best adapt and extend existing processes of spatial inference and models of spatial analysis in data-intensive computational environments, and how we might extend

the ways in which error and accuracy in spatial data and modeling can be incorporated in GIA and GIS. We will treat each of these issues in turn, under the headings of Exploratory Spatial Analysis (ESA), Spatial Inference Processes, Spatial Models, and Error Propagation and Lineage.

2.2. Exploratory Spatial Analysis (ESA)

The new tools of visualization, coincident with the current development of workstations, super- and parallel computers, and new ideas concerning graphics, have obvious applicability to spatial phenomena. But until quite recently, computers were simply not capable of providing visual exploration of data in a routine, user-friendly, interactive and low cost fashion. Moreover, what makes these ideas so important to geography is the development of computer mapping and GIS which enable spatial patterns to be explored not only the in the two-dimensional domain but in higher dimensional spaces, thus introducing the notion that patterns might exist in spatial data, not in two- but in higher orders of dimension (Haslett, Willis and Unwin, 1990).

> *Two major NCGIA Research Initiatives concern the immediate exploitation of new computing environments, particularly GIS, for visualization of spatial data. Initiative 7 (Visualization of Spatial Data Quality) focuses on spatial data quality, and is developing methods for modifying conventional cartographic displays to include information on the quality of data. Initiative 14 on GIS and Spatial Analysis will focus part of its efforts on the exploratory paradigm, and the development of new methods of spatial analysis which take advantage of the interactive, visual nature of the GIS environment.*

Exploratory data analysis (EDA) has existed in rudimentary forms for over 20 years (Tukey, 1977) and although almost always applied in a computational environment, its initial motivation depended upon the notion that patterns in data should be thoroughly explored before theories and models, which might explain such patterns, are formally developed. Such analysis is often accomplished informally in any case but with the evolution of computer mapping and GIS, our ability to undertake such informal exploration is greatly increased. We see ESA as a set of techniques for enhancing and refining intuitive approaches to spatial inference, allowing the analyst to combine data from different sources and to access tools that apply simple tests. What are now needed are systems which expand the power of existing GIS to incorporate exploratory functions, such as the simultaneous display of maps and graphs through linked windows, or stand-alone systems, or some coupling of the two (Gatrell, 1992). Developments are on the horizon, but there is much for the Center to do in developing ESA. It is likely that the formalized search for pattern in data, which is the obvious consequence of developing ESA, should produce new methods of analysis while modifying others so that the power of the new technology can be best exploited. Finally, ESA might enable the assumptions which are reflected not only in our models but also in our data and the way it is collected, to be explored so that their limitations in terms of their accuracy and relevance can be easily and swiftly assessed.

> *Exploratory spatial data analysis is rapidly becoming an essential methodology for the description and analysis of geographical data, and Initiative 14 (GIS and Spatial Analysis) is concerned with exploring the development of such methodologies within GIS for the examination of spatialpatterns and processes.*

2.3. Spatial Inference Processes

The development of spatial statistics and statistical processes in geography is founded on the basic notion that models must be as parsimonious as possible; only in this way can we evaluate the inferences to be made with respect to the relevance of such processes to one another and the impact of such processes on spatial structures (Ripley, 1988). The development of computer systems in general and GIS in particular to enable such functions to be used is both a major research and an applications task at the present time. Most GISs do not have any formal inference procedures incorporated into their structure as yet.

> *Initiative 14 (GIS and Spatial Analysis) will include an assessment of the impediments confronting the linkage between spatial statistics and GIS. In addition to a focus on how spatial statistics may be embedded into GIS, the Initiative will emphasize the development and improvement of existing and new statistical methods using GIS.*

These types of inference processes are not simply restricted to statistical analysis. Statistical models are the best developed to be sure, although methods based on logical inference are beginning to emerge and there are developments taking place using methods of graphical inference. One of the consequences of the development of graphics and visualization tools is the emergence of a new confidence in our innate abilities to interpret patterns intuitively and immediately, for through such display, there is the obvious possibility to see patterns which are greater than the sum of their parts, while developing new and unexpected inferences from existing patterns in various spatial distributions (Getis, 1991).

> *New methods of spatial analysis based on structured methods of inference through visualization are being explored under Initiative 7 (Visualization of Spatial Data Quality), where links between data representation, analysis, mapping and other forms of representation are being investigated.*

Our processes of inference are not only likely to be enriched, made feasible where they had not been before, and extended to deal with a wide array of phenomena, but new processes may emerge. The quest for exploration and inference in any case is a process of alternating between displaying the patterns and figuring out their meaning. It is also one of showing how patterns interact with one another and the development of better indicators of such interaction. Thus new forms of symbiotic inference might emerge from traditional inference in a data-intensive computational environment. Finally, and this is something we
will pick up again below, the ways in which exploration and inference are affected by the accuracy and error in data and model, and how such error is propagated through a series of steps which define the computational system, are issues which are highly relevant to the processes of inference which are used.

2.4. Spatial Models

Spatial analysis is by no means confined to statistical models although these emerged first. Mathematical models whose structure is built up around sets of formal relations from which various model properties can be deduced also form a large component of our domain, as do models based on optimization theory whose rationale and origins lie in normative problem contexts often with a distinct policy flavor (Wilson *et al.*, 1981). Exploratory spatial analysis and the development of appropriate databases usually precedes, and is sometimes concurrent with the development of these three model types, but the emphasis in their application is confirmatory rather than exploratory.

There are several themes which cut across appropriate representation and the development of spatial models. In particular, the type of computational environment in terms of database structure, scale and size, the ability and impact of disaggregating and aggregating data types across spatial and aspatial or non-spatial categories, methods for tracing accuracy and error, as well as methods for communication through visualization, all of these are instrumental in the development of appropriate spatial models (Openshaw, 1991). Moreover, dependence upon the problem domain is also of importance in model development especially where such problems are being researched or tackled using formal GISs. In such cases, there is always the need to link such systems to the range of models and analysis systems used. One of the major challenges for GIS research is to determine the various methods and means whereby spatial models in the generic sense can be related to GIS (Brail, 1990; Wise and Haining, 1991). So far there has been little formal research into such problems although it is already clear that the strength of the coupling will depend upon a wide range of practical to theoretical notions relating to the model in question and the problem context in mind.

> *While Initiative 14 (GIS and Spatial Analysis) is primarily involved with the analysis of spatial data, it will also investigate the integration of spatial models with GIS technology. Optimization routines for locational models seem especially well suited to such integration. A further Research Initiative on GIS and Spatial Modeling has been proposed.*

Statistical models are largely based upon either linear or nonlinear systems of relations which are developed using some econometric means of structuring, or upon distributional considerations which give rise to model forms which are fitted and tested directly (Anselin, 1988). In both sets of models, the effects of space (and time if relevant) are evaluated in terms of their autoregressive structures. Spatial data can be represented in terms of point patterns, networks, areal distributions and so on. The nature of the computational environment will determine our ability to test the assumptions on which such models are built, as well as testing their sensitivity to scale through aggregation (or disaggregation). At present, few if any integrated model systems exist in which such analysis can be broached directly and there are certainly no GISs which enable such analyses to be carried out easily and in a straightforward manner. This represents a central challenge for the NCGIA and the field, and it centrally involves the other two themes - representation and informatics, as we shall see.

Mathematical models on the other hand are likely to be rooted in much more substantive domains and problems than the statistical models. These types of models usually represent some set of causal relations in which there is feedback leading to nonlinearities and in which various impacts and effects can be deduced using *a priori* analysis. In the human realm, these models range from those based on gravitational analogies in social physics, to those based on micro and macro economic theory (usually in an urban and regional context), to transportation models, to psychological models of behavior and decision-making (Sheppard, 1979); in the physical realm, similar models encapsulate geomorphological, climatic, ecological and biological processes whose form is usually represented in terms of classical physical theory. Unlike statistical models which are parsimonious, these models are usually rich in structure, and their process of estimation is somewhat different from their statistical neighbors (Haining, 1990). Moreover, the possibility for error propagation through space and through different elements of the model structure gives rise to somewhat different types of visualization from those in the statistical domain (White, 1984). Such models to date have not been coupled to GIS or other forms of computer system, although there are many research problems involving in their coupling which are likely to change both model and GIS.

> *One of the foci of Initiative 6 on Spatial Decision Support involves the role of model-base management systems which complement the databases relevant to various spatial models. Algorithms for locational models are being decomposed into their base or atomic elements toform core data structures which support query, analysis and display. Such structures will greatly facilitate a close coupling of GIS and analytical operations.*

The last type of model is the most recent in that this class depends upon specifying the spatial modeling problem as one in which some function or set of functions needs to be optimized (Wilson *et al.*, 1981). The optimization may be physically observable or may define a future state of the system which is desirable in some way. These models are subject to many of the research issues already defined but there are important impacts in terms of the relevant computational environment. In principle, only a small fraction of the whole class of optimization problems are solvable and this makes their applications always problematic. In fact, new computer systems have meant that it is ever more likely that the class of models that can be solved will get larger although in many cases the problems are either not specified in enough detail or are intrinsically impossible to solve because of their structure. However, in the context of GIS and GIA, rapid strides are being made in applying Operations Research techniques, for example in the area of Spatial Decision Support Systems (SDSS) where the relevance to real problem domains is very great (Densham, 1991).

We have already mentioned some of the cross cutting themes which run over the various types of spatial model and analysis noted so far in this and the last section. One of the biggest problems of research is in the effects of spatial aggregations, for models and analyses can be deeply limited in applicability if there is no invariance to scale. This problem is of prime import in that it occurs in data, in models, in terms of representation, and in terms of communication through visualization. Scale effects are only one of the generic problems of modeling spatial phenomena in a computational environment (Openshaw, 1984; Fotheringham and Wong, 1991; Flowerdew, Green and Kehris, 1991).

2.5. Data Quality, Error Propagation, and Lineage

At every stage of the representation-modeling-communication sequence where spatial information is processed, error can be introduced. There are both negative and positive consequences flowing from the existence of error in GIS and GIA. Error can exist in data through both measurement and conceptualization while the greater the numbers of processing stages in the computational environment, the more likely it is for initial error to propagate and new error to form (Burrough, 1986; Griffith, 1988).

New computational systems make possible the systematic observation and tracking of error,
particularly in formal methods for representing the lineage of data and information in such systems. Error is also concerned with processes of aggregation over space (and time), across space through interactions, and through various data and model operations. There are new possibilities for building error models and incorporating these into various statistical and mathematical models of spatial processes (Haining, 1990). So far, there has been little research into ways in which such integrations might occur. But with the growth in data-intensive contexts, in software to represent and model such data, and in new ways of communicating such material through visualization, it is essential to have clear and unambiguous statements involving error.

> *Two Initiatives have focused on the error problem. Initiative 1 (Accuracy of Spatial Databases) made substantial theoretical advances in developing error models for spatial data, and in tools for propagating error through GIS analysis into measures of uncertainty on products. Initiative 7 (Visualization of Spatial Data Quality) is currently developing tools for visualizing uncertainty, and carrying out research into the best methods for communicating spatial data uncertainty to users, and incorporating it into the decision-making process.*

Information about the origin and the quality of data is crucial for responsible use of data. Data must be stored and processed together with this quality information, and newly produced data must include linkages that trace their lineage. The increasing use of spatial data for policy formulation, by integrating information from multiple sources with different levels of reliability, requires the development of systems to track properties such as scale, date of creation, and authorship. Such systems must be capable of propagating and combining metadata as information is handled and processed (see chapters of Goodchild and Gopal, 1989).

Data quality information is only one very important type of metadata, or information about the parameters and properties of data rather than the data themselves. Current databases contain metadata in the form of the database schema. In the case of a relational database, the schema describes the contents of the database in terms of tables and the attributes they contain. But other critically important forms of metadata are typically not included in the schema. These include: data about the availability of data (*e.g.*, where is vegetation data available); data about the quality of the data (spatial resolution, date of data collection, *etc.*); data about the data collection methods; data about the classification methods used; and data about the cost of accessing data (price to purchase, time until delivery, availability of updates).

Initial studies indicate that metadata of many different kinds play an important role in the way people search for data in a GIS. This metadata must be available for processing and managed with other data. There is no clearcut boundary between metadata and data. They will both require database support for rules in the database, and an active database which triggers corresponding updates if base data is updated.

> *Research on metadata and its use in GIS and GIA has already occurred under Initiative 1 (Accuracy of Spatial Databases), where information on accuracy was incorporated with other forms of metadata into a suite of lineage tracing tools. It is a key component of Initiative 9 (Institutions Sharing Geographic Information), in view of the value of metadata to data sharing and standardization, and the Center is involved in ongoing debates over metadata formats and standards within the spatial database community.*

3. SPATIAL INFORMATICS

The term *informatics* has been adopted in several research communities in North America and Europe to characterize the merger between data processing and information transfer (Dizard, 1989; Gonzalez-Manet, 1992). The American Society of Information Science identifies the domain of informatics as the study of the impact of the semiconductor upon society. The term has gained wider acceptance in European scientific circles than in North America to date, although disciplines including Communication and Computer Science have adopted the tenets and the name in recent research (Duijvestijn and Lockemann, 1981; Huib and Jaeger, 1989). The merger of processing and transmission results from developments in telecommunications, as transmission systems require connection by increasingly intelligent nodes. Informatics researchers maintain that similar paradigms can be used to study both cognitive transferral and technological transmission (Beniger, 1986). The more conservative view unifies the two domains within the broadest context of interaction between human and machine information processing.

With continuing efforts to manage and control burgeoning volumes of spatial information about society and the environment, informatics has become relevant for GIS and the spatial sciences as well. There exist clear social implications at three levels for the adoption and use of GIS technology. At the personal level, human-computer interaction studies are directed to improve GIS interface design, to evaluate graphical defaults, and to implement innovative visualization techniques including tools for animation, hypermedia and virtual reality modules.

> *Initiative 13 (User Interfaces for GIS) has discussed the use of virtual reality modules as a means of improving access to spatial databases.*

At the organizational level, studies of spatial decision support are directed to better understand policy-making and decision management for a range of problems from facility allocation to monitoring natural resources.

> *Initiative 6 (Spatial Decision Support Systems) has identified this as one of its four major research themes.*

At a societal level, the use and value of GIS technology impacts issues of public and private access to spatial information, and the sharing of spatial data between agencies and institutions. The diffusion of GIS technology and its adoption by western or developing societies forms a societal response to the need to control and manage information about the local and global environment. There is a need for objective research that reflects on the meaning of GIS adoption for society at large.

> *Research Initiatives 4 (Use and Value of Geographic Information) and 9 (Institutions Sharing Geographic Information) have used a combination of theory and case studies to examine processes of GIS adoption and diffusion. Proposed Initiative 16 (Law, Public Policy and Spatial Databases), while still in the planning stages, may develop a research thrust in the meaning of GIS adoption for society.*

Much of the agenda of spatial informatics lies in the domain of social and behavioral science. Much of it requires a different paradigm than those traditionally used in geographic research, involving an emphasis on case studies and a general awareness that general results may be difficult to find. In many ways the agenda of spatial informatics is the most critical of our three areas, since it has often been said that human and societal factors are the most important in impeding progress in the adoption and use of new technologies. At the same time real progress in this area may be the most difficult to achieve.

3.1. Human Factors

The computing environment acts in many ways to facilitate the organization, retrieval, analysis, and display of spatial data. User interaction with GIS is often hampered by efficiencies of system design and implementation. Current systems burden users to understand system implementation details that may be isolated or even irrelevant to the substantive context of a particular problem (Falzon, 1990). Data structures and system commands may preserve efficient system performance at the expense of efficient performance of the user. System access and data manipulation are unnecessarily obscured with details that are more relevant to the implementation programmer than the user.

3.1.1. Human-Computer Interaction

Use of the computer as a tool for storage, analysis, display, or any other function is impeded by lack of a flexible interface. Until interaction with GIS tools is made easier, wide adoption of the tools will not follow. Two approaches must be adopted. Current interfaces should be simplified and reduced to the primitive set of operations and concepts. Achieving a standardization of interface designs will facilitate adoption and use of GIS, because mastery of the interface for one package will shorten the learning curve for other packages. Second, interface command sets must be designed to incorporate logical connections for the user, closer to the concepts the user is familiar with. In both cases, research should concentrate on the conceptual levels of interface design and use the best user interface toolboxes available.

Research Initiative 13 (User Interfaces for GIS) is focussed on human-computer interaction. The Initiative includes interface design, including metaphors, and is also concerned with task analysis and user testing.

3.1.2 Reasoning and Cognitive Inference

Spatial reasoning is so common in everyday life that it proceeds without conscious effort. Introspection to understand unconscious process is very difficult to formalize; yet this is the prerequisite to implementation of automatic reasoning algorithms in GIS and spatial analysis packages. Reasoning in spatial analysis may be used to process topological relations, measure elusive spatial concepts such as proximity and connectivity, and improve robotics, vehicle guidance and navigation, and to better understand human way-finding behavior.

Cognitive theory predicts that results of daily experience with common spatial behaviors are integrated into solving navigational tasks in geographic space, with varying degrees of success. Formal systems must be constructed to model large- and small-scale spatial reasoning in an effective and consistent way. What is most important for spatial informatics is that the conceptual models in the user interface to geographic software be as similar as possible to the conceptual models that the user has when acting in the real world.

3.1.3. Spatial Decision Support

At present, GIS technology provides only rudimentary support for policy- and decision-making (Rhind, 1988). More sophistication must be incorporated for full integration of the technology into spatial decision support. Optimal schemas for decision support must be developed in areas of ill-defined problems, for example location and allocation of resources. Data requirements for modeling the decision process are not yet in place, as the organizational requirements are not readily formalized. Spatial decision support involves highly interactive systems to allow users to examine alternative solution scenarios (Densham and Rushton, 1988). New technologies for Computer Supported Cooperative Work (Greif, 1988) will have high impacts on many aspects of GIA, but especially on Spatial Decision Support Systems.

Initiative 6 (Spatial Decision Support Systems) concerns the integration of GIS and GIA to support decision-making. Research has focused on four themes identified at the Specialist Meeting: decision-making processes and SDSS; the role of modelling and data within a SDSS; the technology and implementation of SDSS; and user requirements and organizational issues. The Research Investigation on "Parallel Computation and GIS" builds on several of the themes associated with Initiative 6. Parallel algorithms for locational modeling are being developed and coupled with GIS to investigate transformations between exploratory resolution spaces for ill-defined problems; the forms of representation and visualization needed to support spatial decision-making; and human-computer interaction in a decision-making environment which is both data-rich and computationally-intensive. Initiative 14 (GIS and Spatial Analysis) takes up several topics from the modelling theme of Initiative 6. Specifically, Initiative 14 will continue and broaden research into the modifiable areal unit problem and the propagation of error in linked spatial models.

3.2. Societal Impacts

GIS forms part of the communications infrastructure which is emerging in the transition to the postindustrial society. There is every prospect that even this sort of technology will eventually find its way into every home in the nation. Its impact is therefore likely to be immense and this puts a heavy responsibility on those concerned with its promulgation. One must consider both the positive and negative effects of its impacts on society. On the positive side, the layperson's access to electronic information will improve awareness of political and environmental affairs, and may preserve a healthy level of interest in global and local governing policies. One may envision a network of consumers of spatial information, who require appropriate education including the skills to access. Research on the use and value of such access, and the ethics associated with access and privacy, are clearly needed. Wider access to spatial information for individuals will create societal change, which may take forms ranging from land records modernization to impacts of access to satellite downlinks from international news services.

At the scale of the organization, once again, both positive and negative impacts may be discerned (Cleveland, 1985). Government expenditures appear to be declining, along with a decentralization of societal responsibilities, and this tends to increase the complexity of societal infrastructure, as private and grassroots public interest groups seek to fill the gaps in support for the poor, the infirm, children and the elderly. Demands for access to centralized repositories of information will continue to increase. In his presentation to the International Cartographic Association meetings in Bournemouth, England, in September 1991, Jack Dangermond of ESRI proposed the concept of an Electronic Democracy to guide the introduction of GIS technology in response to these demands. Research to facilitate large database access, to protect and/or aggregate sensitive or private information, and to mediate the update of demographic and socioeconomic data must be pursued, to accommodate smooth transition into an electronic democracy (Warren, Thorwaldson and Koball, 1991).

It is important for the research community to develop GIS technology within the context of these perspectives, to know the correct moments and circumstances when such technology should be transferred from theory to implementation, and to forecast the needs for research to advance the technology (Chrisman, 1991). It is clear that such technology can be divisive in some contexts, and

integrative in others. It can create new class divisions between the information-rich and the information-poor, and it can exacerbate existing tensions and divisions and magnify differences between the haves and the have nots (Westin, 1971). In the context of the more prosaic development of GIS, we must research the broader social context in which the technology is developing (Rhind, 1992; Osborne and Gaebler, 1992). There are important questions of ethics to resolve with respect to who has access to such technology. Moreover, access is likely to be a consequence of the existing power structures in society and in a world where competitive advantage is frequently seen as involving the power to manipulate, deny, and monopolize information, it is essential to look at both information technology in general and GIS in particular in as wide a context as is possible (Maffini, 1990). Moreover, questions of access and privacy relate very strongly to GIS and it is important to set these developments into the wider legal context.

3.2.1. Adoption, Diffusion, and Technology Transfer

The legal, social, and institutional environments in which GIS technology is used produce a complex set of requirements. It is important for the practical success of GIS usage to understand these requirements and to be responsive to them in system design. Understanding these requirements is currently hampered by lack of systematic research on factors and processes affecting the diffusion, utilization and impact assessment of geographic information technologies and by a variety of conceptual and methodological problems (Rogers, 1983; Zwart, 1986). Although progress has been made, further research is needed in identifying the determinants of adoption outcomes, isolating critical adoption factors for particular classes of users, assessing utilization success, determining levels in the organizational structure where GIS products are used and to what extent, identifying the forms of decision making which have utilized GIS, investigating the stages at which change agent, opinion leader, and champion influences are most critical, identifying processes and factors leading to rejection of previously embraced GIS, and identifying organizational and societal consequences of GIS (Onsrud and Pinto, 1991). Theory-focused empirical research using multiple methodologies (for instance, carefully planned case studies in tandem with multivariate statistical analysis of survey responses) has proven an effective paradigm for advancing knowledge of the desired parameters (Benbasat *et al.*, 1987; Williams *et al.*, 1988). Using this approach, a body of research observations more logically consistent, rigorous, and systematic than that which currently exists may be developed. Models incorporating validated parameters derived from such studies should allow geographic information technologies to reach their maximum potential use within an organization or throughout an entire societal class of users (Wellar, 1988).

> *Research Initiative 4 on the Use and Value of Geographic Information has contributed to an understanding of the application of diffusion models within GIS technology transfer environments, has addressed several conceptual and methodological problems in accomplishing behavioral and organizational research within GIS applications environments, and has contributed to the initiation of a theory-focused empirical research tradition within the GIS community.*

3.2.2. Legal Issues, Privacy, and User Access

As evidenced by the rapidly growing computer law literature, society and the legal system are having great difficulty in dealing with the ramifications of technological advances. Nowhere is this more evident than with citizen reaction to spatial databases. Privacy has become a major concern and has already caused abandonment of multi-million dollar database development projects (Reitman, 1991). Recovery schemes for the costs of developing public GIS databases have caused a significant increase in concern over the citizen's right to know what government knows (Graham, 1984; Archer and Croswell, 1989). The ineffectiveness of the legal system to deal with a public employee who abused access rights to a spatial database for personal gain was cause for lengthy commentary recently in the legal literature. Difficulties in copyrighting databases and protecting the investments in them (*i.e.* the leading costs in any GIS project) have caused major rewrites of those laws (Samuelson, 1992). Higher hurdles have been set for the admissibility of computer-generated evidence in court (Onsrud, 1991). The need to write contracts with all who might access a database in order to protect oneself from legal liability has created significant impediments to the sharing of geographic information. The inability to track and communicate errors as well as the ease of altering data without detection make most GIS databases and the products generated from them particularly susceptible to rejection by the legal system. Growing legal and public policy concerns raise the issue of whether many current GIS databases are being built on foundations of sand which will eventually cause loss of much of the investment in those systems. The limits of all these concerns need to be explored.

There is a need to observe the effects of law and public policy in action. Comparative studies of differing legal arrangements in dealing with the above issues in spatial database environments are called for. We need to develop and assess alternative strategies that might be used in accommodating legal uncertainties in each area.

> *The goal of proposed Research Initiative 16 on Law, Public Policy and Spatial Databases, which is still in the planning process, is to identify the legal and public policy issues arising out of the use of GIS technology and related databases and to contribute to the empirical and analytic work necessary to resolve them.*

In regard to user access, an interplay of technical and institutional hurdles must be overcome before we may empower the average citizen to readily make queries of a typical spatial database. The geographic academic community also complains about the difficulty of determining data availability, utility, access and transfer. To improve access to extensive databases, easy to use catalog

systems (comparable to a library catalog) must be constructed and made available, preferably in a standardized format common to all data sources, so the potential user is not forced to learn the producer's specific catalog language for each potential data source.

> *Identification of access issues, both human and technical, and exploration of institutional models for widespread sharing of geographic information are included within the agenda of Research Initiative 9 on Institutions Sharing Geographic Information. Improved, intuitive user interfaces are critical in providing direct public access to geographic information. The conceptual basis for such easy-to-use interface design is part of the agenda for Research Initiative 13 (User Interfaces for GIS).*

3.2.3. Institutional and Organizational Issues and Impacts

The most widely accepted contemporary model of the impact of computing on society suggests that organizations of all types are undergoing profound change with respect to computing. No longer is the cutting edge of computing at hardware or even software. The greatest resources are being expended on developing ways in which to embed such technology into the wider organizational environment. A review of the GIS literature readily confirms the validity of the rationale behind such expenditures. When attempts are made to share spatial data among organizations or among the divisions of a single organization, those involved often report the most significant impediments to be institutional, organizational, or behavioral in nature rather than technical (Croswell, 1991). Technical capabilities and safeguards which could readily allow transfer and sharing may already exist but typically are not facilitated due to one or more of these impediments. Theory-focused investigations need to be carried out in existing GIS operational environments to build a knowledge base regarding such issues as organizational structure, cross-functional cooperation, corporate culture, bureaucratic practices, standard operating procedures, political environment, individual differences, effects of technology champions and opinion leaders, and turf battles. From this base, prescriptive strategies need to be hypothesized and tested. Such testing requires systematic observations in real settings. The processes of sharing data, using the technology, and assessing the impact of such systems on the wider organizational environment all need to be studied.

> *Sharing relationship variables, formal methods for studying and identifying behavioral and organizational factors, the exploration of prospective models, and formal methods for testing the hypotheses generated from empirical investigations are included in the agenda of Research Initiative 9 on Institutions Sharing Geographic Information.*

3.2.4. GIS and the Social, Environmental, and Policy Sciences

One of the Center's goals is to develop Initiatives relating to the use and value of geographic information in science generally, as well as in the many applications contexts in which geographic information is used. So far, we have begun to develop models of the way geographic information and related computer systems have been adopted, how such systems are gradually diffusing through the public and private sectors, how GIS might be useful in a variety of non-geographic, traditionally non-spatial research areas.

There are also important implications of the development of GIS, spatial analysis and spatial databases for other disciplines. We are conscious of the great potential of GIS to the advancement of knowledge in the social sciences. Without access to the tools of GIS and resources and knowledge to develop large spatial databases, researchers in the social sciences have made little progress in realizing this potential. The increasing exposure to GIS and spatial analysis methods, however, promises to provide a context for the diffusion of GIS to other social science disciplines. The Center is conscious of the role it can play in this process. At a minimum, it is helpful to this process through the advancements in GIS resulting from its Research Initiatives. Beyond this, however, the results of GIS research can be a catalyst for improved social science through a process of mapping the basic spatial analysis concepts developed in GIS to the evidentiary requirements of evolving theories in social science. In addition, the policy sciences are increasingly being asked to research the spatial pattern of resource requirements of given policies or the spatial pattern of effects of policies. Disaster preparedness, for example, is one application area where GIS concepts and techniques will increasingly be adopted. The Center will consider the potential for further research in this area.

The global change research initiatives within US Government agencies and the broader scientific community will involve remotely-sensed data sets of unprecedented size and complexity. Spatial data handling and computational geography will form a key base for global environmental modeling (a theme explored in September 1991 at the Center-sponsored First International Conference/Workshop on Integrating GIS and Environmental Modeling), and for studies of both the physical and human dimensions of global change.

3.3. Technological Issues

Data-intensive environments that are the product of recent advances in computation are rapidly becoming the norm in the applications of science and technology as well as other forms of social intervention and action in postindustrial society. Already there has been a rapid transition to the use of computers for many routine communications but so far involving mainly word and speech processing. In one sense, the emergence of GIS in particular and computer graphics and mapping in general represents an obvious consequence of the fact that computers are now powerful enough to enable pictures to be processed, but we are only just at the threshold where such picture processing is likely to become routine. The remarkable growth of GIS attests to this fact and it is one of

the main tasks of the Center to urge these developments to embrace the best possible functionality for the tasks in hand. Areas in which these developments are most evident include data integration and visualization tools.

3.3.1. Data Integration

The integration of GIS data and products at the societal and organizational levels poses substantial challenges to basic research. The provision and maintenance of spatial data for multiple user groups and diverse purposes promises important savings; one good example is the utility and adoption of topographic maps and related products in a wide range of applications.

Diffusion of GIS technology will rapidly become dominated by the evolution of the network society in which computing is no longer seen as a resource which is fixed by location. With the emergence of electronic superhighways operating at gigabyte speed, networking will become the norm as a new style of economics of networks and information begins to evolve. This will have a profound impact on the development of GIS, on copyrighting and access to software and on the many agencies and firms who will grow up around these networks and who operate as purveyors of information. Adding value to information will become one of the most likely of all work pursuits, and GIS will be one part of this milieu.

3.3.2. Visualization Tools

Use of spatial data in a GIS is of little value if at the end no output is made available to inform the user of the results. Cartographers (Bertin, 1983; Dent, 1990; Imhof, 1982) have developed sophisticated methods of graphically encoding spatial information to accommodate the limitations of the human visual system, which is extremely efficient for pattern detection, recognition, and interpretation. Digital technology can provide visualization tools to extend the bandwidth of human vision, to see the unseen, and create models describing both terrestrial and statistical landscapes (Upson *et al.*, 1989). Access to the intangible landscape allows analysis of phenomena at scales too small or too large to measure directly, and the use of visualization to extend the range of scales of geographical inquiry can improve comprehension and understanding of results from numerical analysis.

> *Initiative 7 (Visualization of Spatial Data Quality) research develops techniques to visualize the multidimensional and abstract nature of spatial data quality. Understanding of data quality can improve the reliability of interpretation, analysis, and decision-making.*

Visualization remains "a form of computing" (McCormick *et al.*, 1987), several years after the beginning of the NSF ViSC initiative. Cartographic presentation of phenomena provides an additional form of modeling (Board, 1967). The rules governing such models and the products that can be generalized from them are only partially understood.

> *Initiative 8 (Formalizing Cartographic Knowledge) research will formalize cartographic knowledge required for map production and cartometric analysis. Aspects of this knowledge are at present poorly articulated or intuitively applied.*

Rules for the design and simplification of static maps may be applied to more fully automate the cartographic process, and lead to expert systems and intelligent solutions to mapping problems. Non-conventional representations such as hypermedia, map animation, and virtual reality provide a wealth of opportunities to explore spatial and temporal pattern (Parsaye *et al.*, 1990; Laurini and Thompson, 1992).

4. Summary

As noted at the outset, the purpose of this Research Agenda is to provide a domain for NCGIA research, and a first draft for a national research agenda for GIS/GIA. While the italicized sections have described linkages to past and planned Research Initiatives, only brief summaries of the progress made on each of these topics over the past four years have been included. More comprehensive assessments of progress can be found in NCGIA Annual and Closing Reports. The agenda has been developed as a statement of research needs for the entire GIS/GIA research community, and commentary is encouraged. There is no implication that the Center intends to work on all of these topics, either now or in the future, or to somehow 'reserve' these topics. On the contrary, our intent is to encourage as much research on these
topics outside the Center as possible, since we believe that this will be beneficial to all concerned.

REFERENCES

Abler, R., Adams, J. and Gould, P.R. (1971) *Spatial Organization: The Geographer's View of the World.* Prentice-Hall, Englewood Cliffs, New Jersey.

Anas, A. (1987) *Modeling in Urban and Regional Economics.* Harwood, New York.

Anselin, L. (1988) *Spatial Econometrics: Methods and Models.* Kluwer Academic, Dordrecht.

Archer, H. and Croswell, P.L. (1989) Public access to geographic information systems: an emerging legal issue. *Photogrammetric Engineering and Remote Sensing* 55: 1575-1581.

Armstrong, M.P. (1991) Knowledge classification and organization. In Buttenfield, B.P. and McMaster, R.B. (eds.) *Map Generalization: Making Rules for Knowledge Representation*. Longman, London.

Baerwald, T. (1991) Computational needs and opportunities in geography. *ARC News* (Fall 1991) pp. 40-42.

Benbasat, I., Goldstein, D.K. and Mead, M. (1987) The case research strategy in studies of information systems. *MIS Quarterly* 11(3): 369-386.

Beniger, James R. (1986) *The Control Revolution: Technological and Economic Origins of the Information Society*. Harvard University Press, Cambridge, 493 p.

Bennett, R.J. and Haining, R.P. (1985) Spatial structure and spatial interaction models: modelling approaches to the statistical analysis of geographical data. *Journal of the Royal Statistical Society* B48: 259-279.

Bertin, Jacques (1983) *Semiology of Graphics*. University of Wisconsin Press, Madison, WI.

Board, C. (1967) Maps as models. In Chorley, R.J. and Haggett, P. (eds.) *Physical and Information Models in Geography*. Methuen, London, pp. 671-725.

Boehm, B. (1987) Improving software productivity. *IEEE Computer* 20(9): 43-57.

Brail, R.K. (1990) Integrating urban information systems and spatial models. *Environment and Planning B* 17: 417-427.

Brodie, M.L., Mylopoulos, J. and Schmidt, J., eds. (1984) *On Conceptual Modelling*. Springer-Verlag, New York.

Brodie, M.L. and Mylopoulos, J., eds. (1986) *On Knowledge Base Management Systems*. Springer-Verlag, New York.

Brooks, H.M. (1987) Expert systems and intelligent information retrieval. *Information Processing and Management* 23: 367-382.

Buchmann, A., Guenther, O., Smith, T.R. and Wang, Y., eds. (1989) *Symposium on the Design and Implementation of Large Spatial Databases*. Lecture Notes in Computer Science, Vol. 409, Springer-Verlag, New York.

Bunge, W. (1962) *Theoretical Geography*. Lund Studies in Geography, Series C, Volume 1, Lund.

Burrough, P.A. (1983) Multiscale sources of spatial variation in soil. The application of fractal concepts to nested levels of soil variation. *Soil Science* 34: 577-597.

Burrough, P.A. (1986) *Principles of Geographical Information Systems for Land Resources Assessment*. Clarendon, Oxford.

Burrough, P.A. (1990) Methods of spatial analysis in GIS. *International Journal of Geographical Information Systems* 4: 221-232.

Buttenfield, B.P. (1989) Scale-dependence and self-similarity in cartographic lines. *Cartographica* 26(1): 79-100.

Chrisman, N.R. (1991) Institutional and societal components of cartographic research. In Muller, J.C. (ed.) *Advances in Cartography*. Elsevier Applied Science, London, pp. 231-242.

Cleveland, H. (1985) The twilight of hierarchy: speculations on the global information society. *Public Administration Review* 1: 185-195.

Cliff, A.D. and Ord, J.K. (1981) *Spatial Processes: Models and Applications*. Pion, London.

Craig, W.J. (1989) URISA's research agenda and the NCGIA. *Journal of the Urban and Regional Information Systems Association* 1(1): 7-16.

Cressie, N.A.C. (1991) *Statistics for Spatial Data*. John Wiley, New York.

Croswell, P.L. (1991) Facing reality in GIS implementation: lessons learned and obstacles to be overcome. *Journal of the Urban and Regional Information Systems Association* 3(1): 43-56.

Densham, P.J. (1991) Spatial decision support systems. In Maguire, D.J., Goodchild, M.F. and Rhind, D.W. (eds.) *Geographical Information Systems: Principles and Applications*. Longman, London, pp. 403-412.

Densham, P.J. and Rushton, G. (1988) Decision support systems for locational planning. In Golledge, R.G. and Timmermans, H. (eds.) *Behavioural Modelling in Geography and Planning.* Croom-Helm, London, pp. 56-90.

Dent, B. (1990) *Cartography: Thematic Map Design* (2nd edn.). W.C. Brown Publishers, Dubuque, IA.

Dizard, Wilson P. (1989) *The Coming Information Age: an Overview of Technology, Economics, and Politics* (3rd edn.). Longman, London, 250 p.

Duijvestijn, A.J.W. and Lockemann, P.C., eds. (1981) Trends in information processing systems. *Proceedings, 3rd conference of the European Cooperation in Informatics, Munich, October 20-22, 1981.* Springer-Verlag, Berlin, 348 p.

Falzon, P. (1990) *Cognitive Ergonomics: Understanding, Learning and Designing*. Academic Press, London.

Flowerdew, R., Green, M. and Kerhis, Z. (1991) Using areal interpolation methods in geographic information systems. *Papers in Regional Science* 70: 311-325.

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

Franklin, R. (1991) Computer systems and low-level data structures for GIS. In Maguire, D.J., Goodchild, M.F. and Rhind, D.W. (eds.) *Geographical Information Systems: Principles and Applications.* Longman, London.

French, J., Jones, A. and Pfaltz, J. (1990) Summary of the Final Report of the NSF Workshop on Scientific Database Management. *SIGMOD Record* 19(4): 32-40.

Gatrell, A. (1992) Spatial point process modeling in a geographical information systems environment. Initiative 14: GIS and Spatial Analysis, Papers Presented to the Specialist Meeting, NCGIA, Buffalo, NY.

Getis, A. (1991) Spatial interaction and spatial autocorrelation. *Environment and Planning A* 23: 1269-1277.

Gonzalez-Manet, Enrique (1992) *Informatics and Society: the New Challenges*. Translated by L. Alexandre. Ablex, Norwood, NJ, 201 p.

Goodchild, M.F. and Gopal, S., eds. (1990) *Accuracy of Spatial Databases*. Taylor and Francis, London.

Graham, J.M. (1984) Note: Fair administration of the Freedom of Information Act after the computer revolution. *Computer/Law Journal* 5: 51-76.

Greif, I., ed. (1988) *Computer-Supported Cooperative Work: A Book of Readings.* Morgan Kaufmann, San Mateo.

Griffith, D.A. (1988) Estimating spatial autoregressive model parameters with commercial statistical packages. *Geographical Analysis* 20: 176-186.

Guenther, O. and Buchmann, A. (1990) Research issues in spatial databases. *SIGMOD Record* 19(4): 61-68.

Guenther, O. and Schek, H.-J., eds. (1992) *Advances in Spatial Databases, Second Symposium, SSD '91*. Lecture Notes in Computer Science, Vol. 525, Springer-Verlag, New York.

Haggett, P. (1970) Scale components in geographical problems. In Chorley, R.J. and Haggett, P. (eds.) *Frontiers in Geographical Teaching* (2nd edn.). Methuen, London.

Haining, R.P. (1990) *Spatial Data Analysis in the Social and Environmental Sciences*. Cambridge University Press, Cambridge, UK.

Harris, B. (1985) Some notes on parallel computing: with special reference to transportation and land use modelling. *Environment and Planning A* 17: 1275-1278.

Hart, A. (1986) *Knowledge Acquisition for Expert Systems*. McGraw Hill, New York.

Harvey, D.W. (1968) Pattern, process and the scale problem in geographical research. *Transactions, Institute of British Geographers* 45: 71-78.

Harvey, D.W. (1969) *Explanation in Geography*. St. Martin's Press, New York.

Haslett, J., Willis, G. and Unwin, A. (1990) SPIDER: an interactive statistical tool for the analysis of spatially distributed data. *International Journal of Geographical Information Systems* 4: 285-296.

Hayes-Roth, F., Waterman, D.A. and Lenat, D.B. (1983) An overview of expert systems. In Hayes-Roth, F., Waterman, D.A. and Lenat, D.B. (eds.) *Building Expert Systems.* Addison-Wesley, Reading, MA, pp. 3-29.

Huib, Ernste and Jaeger, Carlo (1989) *Information Society and Spatial Structure*. Belhaven Press, London.

Imhof, E. (1982) *Cartographic Relief Presentation*. Walter de Gruyter, Berlin.

Lakoff, G. and Johnson, M. (1980) *Metaphors We Live By*. University of Chicago Press, Chicago.

Langran, G. and Chrisman, N. (1988) A framework for temporal geographic information. *Cartographica* 25(1): 1-14.

Laurini, R. and Thompson, D. (1992) *Fundamentals of Spatial Information Systems.* Academic Press, New York.

MacMillan, W., ed. (1989) *Remodelling Geography*. Basil Blackwell, Oxford, UK.

Maffini, G. (1990) The role of public domain databases in the growth and development of GIS. *Mapping Awareness 4(1): 49-54.*

Maguire, D.J. (1990) A research plan for GIS in the 1990s. In Foster, M. and Shand, P.J. (eds.) *AGI Yearbook 1990*. Taylor and Francis, London: 267-277.

Mark, D.M. and Aronson, P.B. (1984) Scale-dependent fractal dimensions of topographic surfaces: an empirical investigation, with applications in geomorphology and computer mapping. *International Journal of Mathematical Geology* 16(7): 671-683.

Mark, D.M. and Frank, A.U. (1989) Concepts of space and spatial language. *Proceedings, Ninth International Symposium on Computer-Assisted Cartography, Baltimore, Maryland*, pp. 538-556.

Masser, I. (1990) The Regional Research Laboratory initiative: an update. In Foster, M. and Shand, P.J. (eds.) *AGI Yearbook 1990*. Taylor and Francis, London: 259-263.

McCormick, B.H., DeFanti, T.A. and Brown, M.D. (1987) Visualization in scientific computing. *SIGGRAPH Computer Graphics Newsletter*, Vol. 21.

NCGIA (1989) The research plan of the National Center for Geographic Information and Analysis. *International Journal of Geographical Information Systems* **3**(2): 117-136.

Nystuen, J. (1968) Identification of some fundamental spatial concepts. In Berry, B.J.L. and Marble, D.F. (eds.) *Spatial Analysis: A Reader in Statistical Geography*. Prentice-Hall, Englewood Cliffs, NJ.

Onsrud, Harlan J. (1991) Evidentiary admissability and reliability of products generated from GIS. *Proceedings of the ACSM Annual Convention, Baltimore, MD*, Vol. 1, pp. 197-201.

Onsrud, H.J. and Pinto, J.K. (1991) Diffusion of geographic information innovations. *International Journal of Geographic Information Systems* 5(4): 447-467.

Openshaw, S. (1984) *The Modifiable Areal Unit Problem.* Concepts and Techniques in Modern Geography 38, GeoBooks, Norwich, UK.

Openshaw, S. (1991) A spatial analysis research agenda. In Masser, I. and Blakemore, M. (eds.) *Handling Geographic Information*. Longman, London, pp. 18-37.

Osborne, D. and Gaebler, T. (1992) *Reinventing Government: How the Entrepreneurial Spirit is Transforming the Public Sector*. Addison-Wesley Publishing, Reading, MA.

Parsaye, K., Chignell, M., Khoshafian, S. and Wong, H. (1989) *Intelligent Databases: Object-Oriented, Deductive Hypermedia Technologies*. John Wiley, New York.

Peuquet, D. (1989) Representations of geographic space: towards a conceptual synthesis. *Annals of the Association of American Geographers* 78: 375-394.

Reitman, V. (1991) Firm scraps plans to sell database with personal details on consumers. *The Philadelphia Enquirer*, Jan. 24, front page.

Rhind, D.W. (1988) A GIS research agenda. *International Journal of Geographical Information Systems* 2: 23-28.

Rhind, D.W. (1992) Data access, charging and copyright and their implications for GIS. *International Journal of Geographical Information Systems* 6(1): 13-30.

Richardson, L.F. (1961) The problem of contiguity: an appendix to the statistics of deadly quarrels. *General Systems Yearbook* 6: 139-187.

Ripley, B.D. (1988) *Statistical Inference for Spatial Processes*. Cambridge University Press, Cambridge, UK.

Rogers, E.M. (1983) *Diffusion of Innovations* (3rd Edn.). The Free Press, New York.

Saalfeld, A. (1985) Lattice structure in geography. *Proceedings of AUTOCARTO 7*, pp. 482-497.

Samet, H. (1989) *The Design and Analysis of Spatial Data Structures*. Addison-Wesley Publishing Company, Reading, MA.

Samuelson, P. (1992) Copyright law and electronic compilations of data. *Communications of the ACM* 35(2): 27-32.

Sheppard, E.S. (1979) Geographic potentials. *Annals of the Association of American Geographers* 69: 438-447.

Silberschatz, A., Stonebraker, M. and Ullman, J. (1991) Database systems - achievements and opportunities. *Communications of the ACM* 34(10): 110-120.

Sinton, D. (1978) The inherent structure of information as a constraint to analysis: mapped thematic data as a case study. In Dutton, G. (ed.) *Harvard Papers on Geographic Information Systems*. Addison-Wesley, Reading, MA.

Snodgrass, R. (1987) The temporal query language TQUEL. *ACM Transactions on Database Systems* 12(6): 247-298.

Tukey, J.W. (1977) *Exploratory Data Analysis*. Addison-Wesley, Reading, MA.

Upson, C., Faulhaber, J.T., Kamins, D., Laidlaw, D., Schlegel, D., Vroom, J., Gurwitz, R. and van Dam, A. (1989) The application visualization system: a computational environment for scientific visualizatio*IEEE Computer Graphics and Applications* (July), pp. 30-42.

Warren, Jim, Thorwaldson, J. and Koball, B., eds. (1991) *Computers, Freedom, and Privacy*. IEEE Computer Society Press, Los Alamitos, CA.

Wellar, B. (1988) Institutional maxims and conditions for needs-sensitive information systems and services in local governments. *Proceedings of the 26th Annual Conference of the Urban and Regional Information Systems Association, Los Angeles, California*. Urban and Regional Information Systems Association, Washington, DC, Vol. 4, pp. 371-378.

Westin, A.F. (1971) *Information Technology in a Democracy*. Harvard University Press, Cambridge, MA.

White, R. (1984) Principles of simulation in human geography. In Gaile, G. and Wilmott, C. (eds.) *Spatial Statistics and Models*. Reidel, Dordrecht, pp. 384-416.

Williams, F., Rice, R.E. and Rogers, E.M. (1988) *Research Methods and the New Media*. The Free Press: New York.

Wilson, A.G., Coelho, J.D., McGill, S.M. and Williams, H.C.W.L. (1981) *Optimization in Locational and Transport Analysis*. John Wiley, Chichester, UK.

Wise, S. and Haining, R.P. (1991) The role of spatial analysis in geographical information systems. Paper presented to the Annual Conference of the Association for Geographic Information (AGI), Birmingham, UK.

Zwart, P. (1986) User requirements in land information system design - some research issues. *Surveying and Mapping* 46: 123-130.