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The research plan of the National Center for Geographic Information and Analysis

NATIONAL CENTER FOR GEOGRAPHIC INFORMATION AND ANALYSIS

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Abstract. In August 1988 the U.S. National Science Board established a National Center for Geographic Information and Analysis. This paper, which is adapted from the proposal of the successful consortium, describes a multi-year research agenda built around the recognition of impediments to the successful application of geographical information systems technology. The impediments range in nature from technical to institutional and are organized into five major areas: spatial analysis and spatial statistics, spatial databases, artificial intelligence and expert systems, visualization, and social and economic issues. The Center's research programme consists of a series of initiatives in specific areas, which are designed to last for periods of up to two years and to address the removal of recognized impediments.

1. Introduction

On 19 August 1988 the U.S. National Science Board voted to award the National Center for Geographic Information and Analysis (NCGIA) to a consortium led by the University of California, Santa Barbara, and including the State University of New York at Buffalo and the University of Maine. The process which led to this decision has already been described in this journal by Abler (1987). This paper describes the general research agenda of the Center, which is designed around the identification and removal of impediments to the adoption and application of geographical information system (GIS) technology.

The solicitation for the National Center (National Science Foundation (NSF) 1987 a) suggested that research might be directed to five major areas, or 'bullets':

- spatial analysis and spatial statistics
- spatial relationships and database structures
- artificial intelligence and expert systems
- visualization
- social, economic and institutional issues.

In the sections which follow we discuss impediments in all five of these areas, and suggest research directions which may lead to improvements in (GIS) technology and its use. References generally are omitted because of the complex multiple authorship of this paper and because of limited space, but a full bibliography is available from any of the three NCGIA sites (see footnote).

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Research at the NCGIA will be organized around a series of research initiatives drawn from these five major areas of research and designed to overcome specific sets of impediments. The structure of the Center is intended to welcome and facilitate involvement by researchers from outside the consortium. The schedule of initiatives will be revised regularly to reflect changing priorities and the accumulation of research results.

2. Spatial statistics and spatial analysis

Early GIS emphasized simple queries, reflecting the needs of urban planners and resource managers for basic record keeping and land inventory. They incorporated techniques—such as overlay mapping—that are simplistic, subject to indeterminate errors and easily abused. The future success of GIS technology will depend to a considerable extent on the development of more sophisticated analytical and modelling capabilities, on a better understanding of the nature of the data being analysed and on the ability of systems to handle increasingly large databases with reasonable speed.

Many of the mathematical findings that could provide the basis for advanced analytical capabilities exist already in the literature of spatial statistics, spatial analysis and spatial econometrics, but have yet to be applied. Several prominent spatial analysts have recently drawn attention to this persistent gap between theory and practice. For example, though retailing is a major application of spatial interaction models, no comprehensive calibration package is available for retail applications to apply the advances made since the 1960s in spatial interaction modelling. These problems of technology transfer are due, at least in part, to the extremely simplified (and hence unrealistic) spatial representations that underlie many models: the uniform plain, the isolated city, the square grid or matrix, or even the real line or circle. By providing ready access to realistic databases with detailed geographical resolution and appropriate data structures, GIS technology can support the development of much more effective methods. Comprehensive statistical packages such as SAS (Statistical Analysis System) have made statistical analyses easy to carry out on large non-spatial databases. There is no equivalent to such packages for spatial analysis, although there is a great need for GIS incorporating a comprehensive set of sophisticated techniques of spatial analysis. At the same time, extensive application will have a beneficial effect on spatial analysis by forcing a re-evaluation of models that fail to perform well and by identifying gaps in our current set of techniques.

Many forms of applied geographical analysis and modelling would be more powerful and useful if they were available within a GIS and if the data structures used in that GIS were more appropriate. These include such problems as optimally locating health care, retail, or emergency facilities in a region; determining optimal allocation of land-use and strategies for management in agriculture and forestry; accurately predicting runoff in hydrological modelling; assessing the susceptibility of a region to earthquake damage; delineating boundaries of school districts to meet prescribed goals; routeing vehicles for delivery of goods and services, and planning emergency evacuations. For all these problems, GIS capabilities are currently limited to simplistic analyses, and in many cases cannot represent the necessary topological relationships. Yet these systems potentially can couple sophisticated modelling with comprehensive data storage and display to create powerful decision support systems. This section focuses on impediments relating to the nature and analysis of spatial data. Many

impediments in this area are directly related to issues of data structure and visualization, but discussion of these will be deferred until the appropriate sections. We note in addition that, for many areas of spatial analysis and spatial statistics, the methods of artificial intelligence (AI) may be of value, particularly in the construction of expert systems (ES) that automate the application of certain procedures, For the sake of simplicity, we defer such a discussion until the section on AI/ES.

2.1. *Spatial statistics*

Despite the importance of spatial data, our understanding of statistical processes in space is still relatively limited. Research in spatial statistics is needed in two areas which are important to the successful development, adoption and utilization of GIS technology.

2.1.1. *Problems of spatial dependence and heterogeneity*

Many of the most popular techniques of inferential statistics assume the absence of spatial effects in the data. When a technique such as simple regression is applied to spatial data, the distortions produced by spatial autocorrelation (which is almost always present) and by spatial non-stationarity may lead to erroneous conclusions.

The lack of readily-accessible packages capable of conducting inferential tests in the presence of spatial effects is a severe impediment to our understanding of spatially-distributed phenomena.

It would be difficult to build a spatial series module into the common statistical packages because of their inadequate data models, which cannot represent complex spatial entities. These models must be adapted and extended for incorporation into GIS accessible to applied analysts. GIS would also offer the ability to manipulate and display data in their spatial context, and to combine different forms of spatial analysis within one package.

2.1.2. *Statistical models of spatial data*

The precision of digital analysis is usually determined by the machine and frequently exceeds the precision of the input data. One of the consequences of GIS development has, therefore, been a new concern for the accuracy of spatial data and for associated error models and indices of uncertainty.

The lack of statistical models of complex spatial entities impedes the development of effective methods of determining accuracy in spatial databases and uncertainty in GIS products.

Our current lack of appropriate models and indices is a major impediment to the adoption of GIS, since it is impossible to provide measures equivalent to the confidence limits normally available for the products of statistical analysis. For example, the forest manager has no defence if GIS estimates of forest yield are shown to be in error.

Statistical models of spatial data also may be useful in developing more efficient GIS procedures and algorithms. Many of the design choices in GIS construction discussed in the next section depend on assumptions about the nature of the data to be stored and manipulated.

The uncertainty in the location of a point can be treated as a simple bivariate extension of the conventional model of measurement error. But uncertainty in a line or polygon requires models that represent not only the topology of the object and its relationships with other objects, but also the complex statistical dependencies present. In addition, many spatial objects are abstract representations for which no true, undistorted version exists.

Research in this area should be directed first at developing appropriate statistical models of complex spatial objects and the errors present in them. Methods are needed for estimating the parameters of these models and for designing numerical means of measuring accuracy and proportioning error among the contributing sources. Finally, each of the common GIS functions, such as area measurement and polygon overlay, should be analysed to develop appropriate confidence limits based on the underlying models.

2.2. *Spatial analysis*

We view the development of GIS as a stimulus to spatial analysis, with the potential to make existing techniques more accessible, stimulate the development of new techniques and applications, and give structure to what often appears to be an unco-ordinated body of material.

The lack of mutual awareness between spatial analysis and GIS is at present a major impediment to the dissemination and adoption of both technologies in critical application areas.

The examples in the following three sections have been chosen because they lie at the border between spatial analysis and GIS, and because in each case expertise in one area can be brought to bear on problems in the other. They represent a small part of the potential in the fertile intersection between the two fields.

2.2.1. *Resolution, consistency and spatial aggregation*

Because agencies that collect social data are constrained by confidentiality and cost and by conventional methods of data dissemination, the information they report is usually aggregated in space and frequently aggregated in time. The reporting zones used for spatial aggregation are rarely designed for research purposes and thus introduce uncontrolled and largely unpredictable bias; moreover, they are often subject to change. Information concerning the physical environment, collected by means of remote sensing or by direct observation at various levels of spatial resolution, is subject to variable standards of accuracy. Problems arise, therefore, in comparing data collected at different times, for different units, and often for different types of spatial objects. The capabilities of GIS for spatial analysis have enormous potential for assisting research by allowing overlay of incompatible units across different geographical scales, by supporting spatial and temporal interpolation, and by responding rapidly to new data.

The following research goals are proposed:

(1) Overcome the difficulties imposed on social databases by variable reporting zones.

Research is needed to develop estimation and interpolation procedures for overcoming traditional impediments in the use of social databases in demographic forecasting. This research has implications for public policy since there is increasing demand for data aggregated to units such as ZIP (postal) codes, which are far less permanent, well-defined and homogeneous than more traditional reporting zones.

(2) Reconcile social data collected for different time intervals.

For example, data on migration flows collected for a one-year period are incompatible with data collected for a five-year period. More sophisticated methods of translating data from one temporal unit to another need to be developed and implemented using GIS technology.

(3) Determine optimal or desirable levels of spatial aggregation in social data.

There is a trade-off in many models between the cost of collecting a large volume of data for calibration of a model and the accuracy of that model's predictions. Techniques are needed for evaluating this trade-off by taking advantage of the capability of GIS to move freely between different levels of spatial aggregation.

(4) Investigate the relationships between micro and macro socio-economic phenomena using microsimulation and other techniques.

GIS technology provides the ability to study processes at varying levels of aggregation and will facilitate this type of research and its application to such fields as labour markets, airline schedules and the spatial behaviour of consumers.

(5) Use data on the physical environment more effectively.

Global environmental problems are increasingly prominent, owing to programmes such as the International Geosphere–Biosphere Programme (IGBP) of the International Council of Scientific Unions (ICSU). Data for this programme will come from a variety of sources with different levels of completeness and spatial resolution and different standards of accuracy. Global data from remote-sensing instruments must be combined with the results of direct observation, often at irregularly distributed stations. The success of IGBP and similar programmes depends on the development of effective methods for handling these problems, on technologies for storing and accessing the enormous volumes of data required, and on models that address the full range of scales of spatial resolution, from local to global.

2.2.2. *Continuous monitoring*

Traditional methods of spatial analysis in human geography, demography and related disciplines have been geared to periodic data collection, led by decennial censuses but now augmented by annual and monthly surveys of various kinds. GIS-supported analysis is immediate by comparison, and can effectively use continuously-updated data. This situation already exists in health statistics in the form of individual mortality records, in data on emergencies and criminal activities, and in many areas of physical science including electrical storms, earthquakes, forest fires and weather records.

Largely because of traditional data constraints, we lack adequate methods of hypothesis-testing for continuously-acquired social data, as well as appropriate models and methods of storage and display. A GIS dedicated to the continuous monitoring of national cancer records, for example, would need to test hypotheses continuously to identify spatial hot spots as they develop and to respond to user queries on trends and forecasts. We propose to develop appropriate methods for testing hypotheses in such an environment and supporting GIS data structures and display methods.

A radically different approach to spatial analytical modelling will be required to deal with continuously varying parameters and associated methods of calibration. In the physical sciences, analytic techniques for continuous monitoring are comparatively well developed, and there is a need to facilitate the transfer of ideas from experts in the spatial analysis of geoscience data.

2.2.3. *Spatial decision support systems*

Spatial search algorithms are used to determine optimal locations for facilities based on defined criteria; potential applications include retailing, delivery systems, social services and health care. Although they have been applied extensively, impediments exist to the effective transfer of this technology to the sectors which can benefit most.

The simple data structures currently used in spatial search algorithms are inadequate, and subjective or intangible criteria cannot readily be incorporated into the decision-making.

A decision support system for spatial search based on a GIS would have several advantages that would lead in the long run to more extensive adoption of this methodology. It would combine tabular with graphic user interaction and would incorporate data from many sources at many different scales. It would also support the elicitation of preferences from which to construct objective multiple utility functions and would operate in a continuous dialogue fashion to incorporate changes in criteria and constraints. It could operate on uniform national databases, allowing the user to explore for suitable locations at any scale over any selected area from a single graphics terminal and using any available criterion.

There is a need to consolidate current research on this problem and to combine expertise in spatial search and GIS to design appropriate data structures for the area of application, along with appropriate user interfaces. Although this is treated here as an example of spatial analysis, progress can be made only by combining expertise in spatial search methods with research on the structuring of spatial data and on techniques of visualization, detailed in subsequent parts of this research agenda. In addition, the development of sophisticated spatial decision support systems (SDSS) will allow us to compare the effectiveness of various approaches for spatial analysis, such as exploration versus model-driven, parametric versus non-parametric, quantitative versus qualitative, and explanation versus policy-oriented.

2.3. *Conclusion*

The three preceding sections illustrate the benefits of merging spatial analysis with the capabilities of GIS technology. In addition, GIS provides the incentive and framework for organizing the body of spatial analytical techniques into a more logical scheme. A coherent taxonomy of GIS and spatial analytical functions would serve several purposes: it would lead to better organized GIS user interfaces, and thus be germane to the questions of human/machine interaction discussed below in § 5; it would provide the means for describing GIS workloads, an essential component of the benchmarking research discussed in the section on spatial databases, and it would help to set the research agenda for spatial analysis by identifying gaps and inadequacies in the current literature.

3. Spatial relations and database structures

Many of the shortcomings of current GIS can be attributed to problems of modelling spatial relationships or to their implementation in current systems. The summary of the NASA-sponsored conference on GIS held at Palm Springs in 1983 stated that

> The [present] lack of a coherent theory of spatial relations hinders the use of automated geographic information systems at nearly every point. It is difficult to design efficient databases, difficult to phrase queries of such databases in an effective way, difficult to interconnect the various subsystems in ways which enhance overall system function, and difficult to design data processing algorithms which are effective and efficient. As we begin [to] work with very large or global spatial databases the inabilities and inefficiencies which result from this lack of theory are likely to grow geometrically.
>
> While we can continue to make some improvement in the use of automated geographic information systems without such a coherent theory on which to base our progress, it will mean that the development will rest on an inevitably shaky base and that progress is likely to be much slower than it might be if we had a theory to direct our steps. It may be that some advances will simply be impossible in the absence of a guiding theory. (Smith 1983.)

The long-term research goal in spatial relations and database structures is threefold:

(1) to determine the spatial concepts human beings use,
(2) to develop a coherent spatial theory or comprehensive geometry, and
(3) to use this theory to design a comprehensive basis for computer algorithms in geographical information analysis (GIA) and GIS.

First, we discuss the cognitive and conceptual problems and describe theoretical methods to approach solutions. Then we assess the limitations of current implementations and strategies for building working systems with available computer technology. The approach proposed separates the abstract concepts of space, spatial relationships and spatial reasoning from the specifics of spatial objects of determined types or specific spatial processes. Such abstract spatial concepts can then be applied and restructured to explain specific spatial phenomena; their effectiveness is judged by the degree to which they simplify such explanations.

3.1. *Cognitive impediments*

Individuals, groups, disciplines and cultures have established different frames of reference or schemas for perceiving and communicating spatial concepts and relations, but the principles by which humans code, store, recall and use spatial information are not well understood.

Although people within such groups, disciplines and cultures can generally translate among systems, we lack a formal understanding of the methods involved and this impedes the construction of effective human interfaces for GIS. Cross-cultural translation is even more difficult. When an operator interacts with a system, the spatial concepts used by the system may clash with the natural cognitive structure of the human being. Examples occur in which the operator is surprised by a system action, or cannot see how to express a query in terms of the spatial relations offered by the query language. The lack of understanding of human spatial cognition also hinders the building of navigation aids. Such systems must present spatial information in a quickly assimilable form, often under conditions of moderate stress. Advances in our understanding of the concepts humans use to describe spatial situations will also help to improve graphic displays.

Research to understand the conceptual structures humans use to represent and reason about spatial relationships must be interdisciplinary. One can foresee immediate contributions from collaboration with cognitive and linguistic scientists. Cognitive science applies psychological and artificial intelligence methods to detect and describe human conceptual structures, and is being extended to large-scale spatial situations. Another promising area of investigation involves the constructions available in natural languages to express spatial relationships. Both single-language and cross-linguistic studies of spatial reference in language must be pursued through interdisciplinary research.

There are many research questions to be addressed. What reference frames and schemas are used in describing spatial relations, and are they relative to the observer or absolute in some sense? What roles do context and scale play in the reference problem? What spatial relationships are used? How do people deal with hierarchical systems (spatial reasoning in the large as compared with spatial reasoning in the immediate neighbourhood)? How is spatio-temporal reasoning used to describe and understand spatial processes?

3.2. *Conceptual impediments*

The design and coding of GIS software is currently limited by a lack of theoretical understanding of spatial relationships.

The many *ad hoc* solutions that have been used in lieu of a comprehensive formal model have made building GIS software slow and expensive. The query languages available for selective retrieval of data do not include a full complement of spatial relations. Owing to the lack of a theoretical base, systems from different vendors are very different. Exchange of data between GIS often requires expensive manual intervention.

There is a need for systems that can represent uncertain, imprecise or time-dependent spatial data.

Much current GIS methodology requires the precise (and hence expensive) collection of primary data, thereby discouraging its application. Moreover, many applications require systems that can deal with spatial change as it occurs over time, which current systems cannot readily do. The overall research goals are to represent spatial situations formally and to derive associated rules for reasoning about the locations and extensions of spatial objects and the relationships between them.

A formal approach is necessary to ensure that results can be translated into computer programs and to establish a firm base for translation between different systems. As a unifying method, multi-sorted algebras allow systems to capture the meaning of complex relations between things in a formal way, and are closely related to methods used in software engineering to write formal specifications. Algebraic specifications can be used for formal proofs of properties of the defined systems. From these formal representations one can derive associated algorithms, data structures and programs for implementation in spatial data handling systems.

3.3. *Representation of spatial objects*

Any GIS must represent the positions and extensions of spatial objects in a manner suitable for symbolic geometric reasoning.

The use of analytical geometry to compute geometric operations is hindered by the finite number schemes used in computers, which cannot represent continuous space precisely.

Spatial properties of objects can be represented in symbolic format using results from combinatorial topology, especially simplicial complexes. Representations that can be expressed in (first-order) predicate calculus are highly desirable, enabling the extension to include changes in time using modal and temporal logic and non-monotonic reasoning. A representation based on predicate calculus also simplifies the construction of expert systems, since inference algorithms (unification and Robinson

resolution) are known and readily available (e.g., in the PROLOG programming language).

3.4. *Multiple representations*

Geography studies objects of very different sizes, from land parcels to nations, and from small watersheds to continents. A GIS database must be able to represent objects at different resolution levels and to support modification across resolution levels. This point also applies to visualization of objects, and is discussed from that perspective in § 5 below.

A major impediment to full utilization of the GIS concept is the lack of methods to maintain multiple representations of the same objects.

Starting from object descriptions at each resolution level, we must describe formally the connections between them such that changes applied to one can propagate to the others, allowing other resolution levels to be deduced automatically. We can differentiate between methods that aggregate properties linked to geometric objects and operations that generalize geometric aspects of the objects. This problem, often called cartographic generalization, not only is useful for graphical display, but also assists spatial reasoning.

3.5. *Object-oriented versus spatial addressing*

Spatial data can be organized in raster or vector format. The first organizes the space itself, recording data values for each grid point or as an average for each raster cell; the second concentrates on objects, which have uniform values for selected properties, and records their locations as coordinates or their limits as vectors.

Current GIS are either raster- or vector-based and have limited abilities to combine the two.

These methods have fundamentally different theoretical models and different operations (raster processing versus analytic geometry). Human beings seem to use both concepts, depending on the problem. While current systems are built using one model or the other, an ideal GIS would offer both and allow full interaction between them. Moreover, there is a need to study the operations typical for each system (e.g., line intersection and point in polygon tests for vector; dilation, erosion and convolution for raster) using algebraic methods.

3.6. *Spatial relationships*

Basic relationships and rules must be defined and other relationships deduced from them. The spatial relationships humans use should be explained in terms of the basic relationships so they can be used in human interfaces to GIS.

In a GIS, we are interested not only in the positions, extensions and properties of the objects recorded, but also in their spatial relationships.

Euclidean geometry defines distance and direction as basic relations between points; humans generalize these terms to describe the relations between extended objects ('Canada is north of Maine'). Formal definitions of such relations will be required for natural language query systems and to support spatial reasoning. The inclusion relation ('Penobscot County is in Maine') forms a partial ordering of spatial subdivisions; humans often see such relationships as hierarchies. Research is needed to explore these orderings and use them to simplify reasoning, employing concepts from the cognitive and linguistic sciences.

3.7. *Uncertainty and ambiguity*

Current systems require exact determination and cannot cope with multiple and differing descriptions, even in situations that human beings can deal with unambiguously.

The geometric descriptions of objects in a GIS include errors of different types, and data from different sources may contradict each other. Formal systems to deal with inexact and vague data must be explored and applied to geometrical problems. One approach involves revision of belief in a semantic network and other methods, such as probability factors, fuzzy logic and category/prototype theory, will also be examined.

3.8. *Temporal problems*

Change is of primary interest in many applications, and in some applications the combination of data gathered during different time periods could aid interpretation.

Formal methods to handle situations that change over time are poorly developed in application areas. A small number of temporal logic systems exists; they must be assessed to determine which, if any, represent the conception of time used by humans in conjunction with geographical objects.

3.9. *Implementation*

The ideal GIS would include large collections of spatial data, together with values for a varying set of properties. It would accommodate multiple layers and types of data, as well as time dependency. Once the concepts for handling such data are clear, the major impediment is the size and variety of data. Current GIS can process limited amounts of data; users often must divide data into map sheets. Only a few map sheets can be handled at a time, precluding comprehensive queries over large areas. Because of their limited capabilities, current GIS are not true database systems, but are more accurately described as specialized file systems.

Current GIS do not protect data from abuse and erroneous entries or allow multiple users to access and change data simultaneously. This is a major impediment to GIS use in environments such as local government administrations.

The use of standard database management systems does not solve the problem since some of the requirements for data storage in an administrative environment are different from those of a GIS, or more generally from those of the scientific and technical domain. Data structures for non-standard or engineering databases are more complex; data access paths are different and are used in a different pattern. Consistency constraints are also more complex, and special data structures are sometimes necessary. It is assumed that engineering databases can be built from a common kernel but must include some special-purpose adaptations and optimization depending on the application area. Starting with the functionality of standard database management systems, research is needed to determine which kernel functions and GIS-specific adaptations are necessary.

Another major research problem is to understand the interactions among different GIS processes and the selection of optimal solutions for each. Building large systems, even if the separate problems have known solutions, is a major intellectual achievement. Understanding how components interact and in what order they must be combined is valuable, providing theoretical knowledge of eminently practical significance.

3.10. *Conceptual data models*

The data structures necessary to represent geometry in an object-oriented system are very complex.

Most current database systems cannot adequately model the geometry of spatial data. We can either extend the database structure or resort to special-purpose code (preferably over a common core of storage functions). The advantages and disadvantages of these methods for GIS have not been assessed and prototyping is needed.

The set of operations based on the relational data structure does not seem well suited for low-level GIS operations. It will be necessary to work with database researchers on a comprehensive new concept that includes basic results from artificial intelligence (knowledge representation) and software engineering (abstraction mechanisms).

3.11. *Transaction management*

The special programs that manage GIS data today do not include transaction management and therefore cannot deal with concurrent users, nor do they provide methods to enforce consistency constraints.

Transaction management in GIS databases differs from that in commercial database systems, since change operations are very complex, take considerable time to specify and affect large sets of data. A promising method might be to separate change operations into short and long transactions. For short transactions, the standard database management system (DBMS) transaction concept would be used; long transactions would be decomposed for processing. The operations permitted as short transactions must then fulfil a number of conditions (such as restartability and undo) requiring careful design.

Data are valuable and must be protected from corruption by either technical problems or user actions. This becomes exceptionally important when multiple agencies or user organizations share data. Responsibilities must be clearly defined, and the DBMS must provide technical means to enforce these policies. Current GIS do not provide this feature and thus are not suitable in a multi-agency situation where data are shared, but responsibilities for the data must be clearly defined.

3.12. *Query languages and user interfaces*

Current query languages are not designed for spatial selection and graphical output.

If GIS are to be used to answer questions and support decision making, users will require the means to express their information needs in the form of query languages. Future GIS must include user interfaces that are easy to learn, appear natural to the user and do not depend on the internal structure of the system.

3.13. *Parallel and distributed computation*

Most current GIS are designed for computing environments with a single central processing unit.

As new hardware architectures with multiple processing units become more widely available, the degree to which basic GIS algorithms can take advantage of parallel processing must be examined. New data structures and algorithms that perform better on parallel hardware must be developed. In the future, we expect GIS to move increasingly toward distributed workstations and central database servers. Overall architecture must be adapted to the distribution of tasks between central servers and workstations.

3.14. *Physical storage*

Because GIS data collections are often very large, data structures must be found which are effective when data are stored on relatively slow mass storage devices.

Most database-oriented processing is dominated by the time taken to access data from disk (and not by processing in main memory). Operations in a GIS are dependent on spatial proximity, as consecutive accesses to data usually occur within a limited area. The data structure, and possibly the buffer strategies, must respect this. Several strategies are already known and should be compared and evaluated.

Work in this area will be of particular importance to agencies that collect and manage very large spatial databases. Data management is an increasingly important aspect of remote-sensing systems, as data volumes rise with the precision of instruments and as analysis and use of remotely-sensed data become more sophisticated. The problems of very large spatial databases are also apparent in topographic mapping and in utility systems.

3.15. *Benchmarking*

Most agencies acquiring GIS lack the resources to make informed decisions about the performance of proposed configurations.

The National Center might perform a significant function in developing and disseminating tools for the evaluation of systems. Assessment must not be based solely on technical grounds but must take into account the full range of user requirements in a modern GIS. Evaluations today are hindered by the lack of a set of standardized test cases which can be used with a variety of systems, and by the lack of an accepted methodology for defining GIS workload and evaluating systems against it. This is particularly true for interactive systems requiring user/machine dialogue and immediate response, alphanumeric and graphical output, and multiple concurrent users.

4. Artificial intelligence and expert systems

Artificial intelligence (AI) and expert systems (ES) offer a set of techniques to overcome impediments arising in the context of computer-based analysis of geographical information. AI may be defined in two distinct yet complementary ways. From an engineering perspective it is a set of computational techniques that may be employed to find acceptable answers to problems that humans can solve, but for which exact solutions either are not defined or are computationally intractable; from the perspective of cognitive science, AI uses the computer to reveal principles of intelligence in general and of human thought in particular. AI involves the study and application of special data structures, procedures, control structures and computer architectures, together with heuristic domain-specific knowledge, that allow problems to be solved by computational means. Expert systems form a subfield of AI concerned mainly with building computational systems that incorporate expert human knowledge.

As a body of techniques and methods for problem solving, AI/ES cuts across the topically-based organization of the other components in this research agenda, contributing in substantial ways to all of the other major research areas.

Many impediments involving both computational and cognitive aspects of geographical problem-solving may be overcome using AI/ES approaches.

Many problems in geographical analysis can be solved using relatively well-known analytical approaches. For other problems, however, no currently available theories, techniques, or even research procedures provide adequate solutions. For some such problems, AI/ES techniques may prove valuable. In particular, these techniques may be usefully applied to overcome some of the more difficult impediments that arise in the areas of spatial analysis, spatial relationships and data structures, and visualization.

Building a large ES from scratch is both time-consuming and costly. There has, however, been great interest in constructing ES shells—very high-level programming languages that greatly reduce the cost of constructing ES. It is important to determine whether ES shells with special applicability to spatial analysis exist and, if not, whether they can or should be constructed. If such shells become available, the cost of building relatively complex geographical information and analysis systems might be significantly lowered. Special-purpose ES can be constructed that partly automate some aspects of the following:

(1) the statistical analysis of spatial data, including the selection of the statistical tests to be employed and warnings in the case of inappropriate use;
(2) the modelling of certain spatial phenomena;
(3) the interpretation of images, such as the detection of change and the extraction of features;
(4) the procedures used by human experts for making decisions concerning location/allocation;
(5) cartographic design, including the placement of labels and the selection of colours, and
(6) cartographic generalization.

5. Visualization for display and analysis of spatial data

The report of the NSF panel on graphics, image processing and workstations defines visualization as

> a method of computing. It transforms the symbolic into the geometric, enabling researchers to observe their simulations and computations... Visualization embraces both image understanding and image synthesis. That is, visualization is a tool both for interpreting image data fed into a computer, and for generating images from complex multi-dimensional data sets. It studies those mechanisms in humans and computers which allow them in concert to perceive, use, and communicate visual information. (NSF 1987b, p. 3.)

Visual displays can thus be used to analyse as well as to illustrate information and to generate hypotheses as well as to interpret the results of scientific research.

Methods for visualizing spatial data form a major component of the long-established discipline of cartography. Visual displays in the form of graphic and cartographic products are one of the most important research tools in spatial analysis, and it is appropriate that many geography curricula require students to study cartographic principles. Fundamental geographical variables (e.g., spatial coincidence, proximity, contiguity) are difficult to interpret in the purely numerical context of conventional computing environments, yet their patterns become obvious in appropriate graphic depiction. Visualization provides capabilities to explore spatial patterns that are not directly accessible, for example in statistical landscapes where topography is determined by population density, travel accessibility or volumes of fiscal transfer. We may also visualize in order to simplify the interpretation of patterns that exist in more than three dimensions, such as multivariate distributions changing simultaneously in space and time. Visualization in spatial analysis can be accomplished more efficiently with the aid of computer technology, but requires a clear understanding of human and machine cognition.

Much of the effort in computer-assisted cartography over the past quarter of a century has been concerned with automating traditional cartographic representations and techniques; there has been too little concern for cartographic methods that go beyond what was possible on the static printed map. Graphic portrayal of three-dimensional data, of time-varying spatial data, of geographical flows and of uncertainty or fuzziness in geographical information all present substantial research challenges.

5.1. *Impediments to visualization*

Three types of impediments to research on visualization in geography are evident.

We are impeded by the sheer volume of available data and by the lack of appropriate representational models.

New approaches must be developed to enable scientists to comprehend the masses of data that can now be collected and stored. Researchers tend to think of a data set as a snapshot of reality and to view data structures as static; this is a subtle trap that constrains the variety of research questions and the way they are posed. It is difficult to encapsulate the visual complexity of real-world objects in data matrices, yet the commands contained in most computer graphics libraries are constrained to matrix manipulation (rotation, translation, pan and zoom). As discussed in an earlier section, researchers also must determine formal expressions for the kinds of data structures and spatial objects we manipulate and analyse.

Current technology and hardware limit visualization research.

Within two decades, topographical and other geographical data for the entire world will be available at high spatial and temporal resolutions, presenting major challenges to analysis and visualization. Getting the graphics hardware and software tools into the hands of the scientists who study phenomena represented in such large databases is a primary goal whose accomplishment will require continuing collaboration between industry and research centres.

Research on visualization is based on an incomplete model of underlying processes.

Neurological, physiological and, to a lesser extent, behavioural models clearly fall beyond the scope of most geographical research. However, formal expression of graphical design principles remains a prerequisite to automating the construction of effective visual displays. Of particular relevance to problems of visualization is the discipline of computational vision which focuses on machine vision and on modelling human vision. Overcoming impediments regarding both types of vision operations requires research collaboration between geographers, psychologists, computer scientists and others.

5.2. *Impediments involving data and data models*

The lack of realistic models which would allow multiple scales of graphic depiction to be constructed from a single digital database impedes the generation of maps and integrated software systems.

Operations affected by this impediment include map overlay and map comparison; consistency of operations to simplify features may also be compromised. Digitizing and archiving data repeatedly are time-consuming and expensive. Models for digital representation of features must incorporate the possibility for scale-dependent geometry, in order to preserve recognizability while maximizing efficiency of storage. A means to label features within a digital file as scale-free, self- similar or scale-dependent would provide automatic flags for applying a particular model (e.g., fractal) for feature representation, and also provide markers to guide automatic modification of tolerance values during map generalization.

Use of GIS data is limited by inadequate methods for visually depicting data errors and related measures (reliability, uncertainty, fuzziness).

Standard reliability diagrams as seen on topographic sheets cannot reflect the complexities of error propagation nor the associated probabilities on an overlay surface. Most depictions do not distinguish between positional and attribute error and do not indicate errors of omission or of logical consistency, confounding problems of reliability for the map viewer.

5.3. *Limits of technology*

In the past, the load-dependent speed of mainframes and the limited processing speed of microprocessors have impeded real-time processing and display for interactive visualization.

Although a new generation of computers—including graphics workstations—may have largely removed this technological impediment, software development has lagged behind. New technology is expected to supplant, to some degree, the use of printed maps and images for the support of navigation and for archival storage of spatial data. Hardware developments, including the size and resolution of screens, video refresh rates and dedicated graphics memory, provide means for increased accuracy, precision and complexity of visual display. Useful improvements would expand digital holograms (for direct visual exploration of three-dimensional objects) and faster access from mass storage.

Software developments, including polygon fill, hidden line removal and ray tracing, have enabled more realistic visual presentations of spatial data and relationships to be provided. Standardized graphic storage formats (e.g., PostScript) will improve the portability of constructed images between applications. A means to transmit imagery efficiently over long distances is now needed: recent developments in transmission of high-quality text by electronic mail systems should be complemented by similar techniques for high-quality graphics.

5.4. *Human vision considerations*

Increasing reliance on special-purpose electronic disposable graphic displays has displaced much of the demand for general-purpose printed maps and charts.

Appropriate guidelines for map design must now be formalized as defaults for mapping and GIS software, to allow researchers to focus on the substance of their data rather than the mechanics of constructing data displays. Recent technological improvements have facilitated cartographic research on the use of colour in thematic map design; these results must now be incorporated into new cartographic software. Tektronix has recently developed a directly viewable three-dimensional display device based on stereovision. The impact of this and related technology on map use and image analysis remains to be explored.

Non-traditional visual displays will provide a means to expand the types of research questions we ask.

Map animation, for example, allows the exploration of patterns that vary simultaneously over space and time, representing real time with temporal symbology. Patterns of traffic volume within a city, of the recency of regional seismic activity and of changing land use and ownership may easily be intepreted in animated form. Real-time animation plays an important role in electronic navigation systems.

Visual tools are of clear utility in cybernetic interfaces, as is demonstrated by the common use of screen menus, mice and picking operations in the design of integrated graphics software.

Visualization helps researchers to interpret the results of statistical testing and conduct sensitivity analyses. Graphic display of changes and interaction between variables may facilitate real-time guidance of computations. Just as we do order-of-magnitude calculations in our heads to validate arithmetical work, graphical depictions may help us to avoid spatial nonsense and errors. Research into human factors to determine the impact of visual interfaces on initial learning curves, user fatigue and performance in spatial analysis is of obvious importance in the development of user shells and on-line documentation for large GIS packages, especially in educational applications.

5.5. *Machine vision considerations*

Principles of computational vision implemented on machines could overcome many factors impeding automated acquisition of GIS data.

Abstraction forms the core of the research process; in the context of visualization, this points to the importance of pattern recognition as an analytical tool. Pattern recognition is also required to restore topology to scanned data and raster displays, and must be applied to implement operations of automatic feature labelling within a digital database. Finally, the application of machine vision to decision making, as shown by advances in robotics and ballistic strategy, demonstrates the need for continued interaction between industry and research centres.

6. Social, economic and institutional issues

An information system is an assembly of human and technical resources which captures, analyses, represents and delivers data and information. GIS are potentially extremely useful to a wide variety of users in the private and public sectors who assemble land-related data and draw conclusions based on information derived from them. This varied group includes planners, developers and investors, as well as scientists and engineers who study spatial patterns and processes. Decisions resulting in rational use of physical and human resources are most likely to occur when users have information about land, water and other resources in appropriate form and at the appropriate time. The desire to reduce uncertainty in these decisions creates a demand for improved information products.

Adoption and implementation of geographical and land information systems is a dynamic process characterized by mutual adaptation between products and services and user needs. Adaptation is not an automatic or instantaneous process, but can be promoted by various intervention stategies. Social, legal, economic and institutional factors—both real and perceived—all affect the pace and extent of adoption. Research on these factors will not only provide greater knowledge of the adaptation process, but also yield feedback relevant to the design and development of GIS.

The incorporation of advances in GIS into the operations of government and private industry will create numerous problems, some of which are unpredictable. Of those which are currently evident, some are considered critical impediments to the adoption of GIS technologies, and will be among the first problems addressed by the National Center. The primary research effort will be directed at developing methodologies and bodies of knowledge which government, private industry and other institutions will find valuable as they cope with the societal ramifications of GIS technologies.

6.1. *The adoption of GIS technology*

A central research problem is to understand the process by which users adopt and accept GIS technology.

Research topics include the identification of direct and indirect users of land and geographical information, the manner in which users arrive at an understanding of GIS technology, the demand for geographical information, and the means by which attributes of useful products are determined. Mechanisms for the acquisition of products from GIS technology are also critical.

In order to study the use and value of geographical information, models of the adoption process, including barriers and feedbacks, will be needed, along with a methodology to identify and measure the benefits of using geographical information. Elements of the process include adaptation of economic theories of information to geographical information, characterization of geographical information as a public good, distinguishing between tangible and intangible benefits, understanding the legal regime regarding rights to information, and modelling the benefits and costs.

6.2. *Use and value of geographical information*

The benefits of GIS technology are difficult to assess in the absence of a theory of value for geographical information.

The theory of the use and value of geographical information is poorly developed. However, economic, psychological, sociological and other existing social scientific methods will be applied to this problem. The role of information in decision-making, the mechanisms and processes by which information is defined and utilized and the economic theory of information must all be addressed. Economic value is a demand-initiated concept. The desire to reduce uncertainty creates demand for information, yet its value is difficult to assess because of the distribution of benefits, variation in the value of information by culture, location and decision, and changing community standards.

6.3. *Institutional structure*

There is a need for research on the institutional effects of adopting GIS technology.

Changes in the activities of people, agencies and professions brought about by specific changes in GIS technology must be identified and formal arrangements developed appropriate to these altered activities, including changes in rules, laws and standards for individual, agency and professional activity. It is also important to identify the impacts of institutions on GIS technology.

6.4. *Liability*

Uncertainty over legal liability impedes wider adoption of GIS technology.

Geographical information products—traditionally maps—often contain errors, are sometimes used in unintended ways, may be inappropriately combined and may be misused. Furthermore, including data in a GIS almost certainly increases the chances of misuse. Such situations can result in conflict and, ultimately, in litigation when an injured party blames those who produced and relied upon the product. Map-based information is used as scientific or technical evidence and is particularly subject to litigation involving people's rights and value in real property.

Research at NCGIA will identify, analyse and characterize the legal regime and professional standards for the use of geographical and land information, especially as scientific and technical evidence within courts and agencies, and apply the legal regime to the development of criteria for designing GIS technology and products. Recommendations and professional standards will result from such research.

6.5. *Access to, and availability of, geographical and land information*

Current rules of access to geographical information products are unclear and inconsistent.

Reasonable access to geographical information is a technical, legal, social and economic concern. Freedom of information laws, federal and state, elicit a bias in favour of full disclosure of publicly-held data and information in a manner convenient for the citizen. Automated recording makes it possible to ask questions that could not be asked previously, but control of information is a political issue, especially in cases where public access without professional assistance is limited when the development of a system is inhibited because costs cannot be recovered owing to pricing law and policy. Finally, equity and fairness are questioned when systems provide large amounts of accurate data and information about some areas and not about others.

The status of laws of freedom of information and records in relation to GIS must be assessed, especially at the state and local levels. The attitudes of citizens and politicians towards the adoption of GIA/GIS must be determined, especially in regard to control of information, pricing policy and equity and fairness of data distribution.

6.6. *Privacy and confidentiality*

The confidentiality of GIS information is a concern in some cases.

Privacy and protection from misuse of information in public files is a litigious issue in part because of the ability to collect, process and integrate such information automatically. Physical security and protection against accidental or unauthorized access is a concern. The pace and extent of the adoption of GIS will depend on public perceptions, as well as on the outcome of litigation. Key research problems include the influence of litigation, public perceptions and concern about government record systems on the development of GIS, protection of hardware and software from unauthorized access, and the role of governments and professions in the protection of privacy.

6.7. *Technology assessment*

We know little about the factors affecting the transfer and adoption of GIS technology.

Knowledge of the process whereby new technologies replace older ones is limited, although theories of technology transfer have evolved in several areas. Past studies of technology transfer have been limited by the need to apply a retrospective methodology. At its current stage, GIS and the transfer process can be analysed in a real-time mode. Use of a case study approach in a real-time setting would generate valuable insights into the process of technology transfer. Such insights can serve to guide the process by which GIS becomes available to, and useful for, the ultimate user.

7. Implementation

The preceding sections have described the Center's overall research plan, which will be implemented in specific areas as research initiatives. Each of these initiatives is intended to last between one and two years, with a structure which follows a common model. An initiative begins with a specialist meeting, at which perspectives on the topic are presented by specialists drawn from the Center, researchers from outside the Center and other representatives of government and industry.These meetings will promote cross-disciplinary exchanges, work out the agenda for the initiative and assign responsibilities to working groups.

Specific commitments of time and resources are made for working groups which will conduct research for periods of six months to two years following the specialist meeting. In many cases research will be conducted jointly with other institutions, agencies and firms. In-progress seminars will form part of the working structure.

The final component of the initiative model is a national or international conference at which substantive findings are presented to a larger audience. We expect that many of these will be held in conjuction with other national and international meetings, and that these will be a prominent feature of the Center.

Twelve initiatives are planned during the first three years of the Center's operation, on the following topics:

- Accuracy of spatial databases
- Languages of spatial relations
- Multiple representations
- Use and value of geographical information in decision making
- Architecture of very large GIS databases
- Spatial decision support systems
- Visualization of the quality of spatial information
- Expert systems for cartographic design
- Institutions sharing spatial information
- Temporal relations in GIS
- Space-time statistical models in GIS
- Remote sensing and GIS

Starting dates will be staggered so that the results of early initiatives can influence later ones.

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Towards a typology of geographical information systems

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Abstract. Attempts at classifying geographical information systems (GIS) have typically focused on the task-orientation of particular systems. With the application domain now becoming increasingly ephemeral, there is a need to take a more systematic view of the differences between systems. It is suggested here that a useful perspective to take is one that emphasizes system architecture. Using concepts well established in the wider field of information systems science, we suggest a framework that characterizes a GIS on the three-fold basis of the problem-processor model, database model and interface model adopted.

1. Introduction

A typical state-of-the-art geographical information system (GIS) will include such functions as data acquisition, data structuring and manipulation, spatial analysis including overlay techniques, display and cartographic techniques and data communication that allows information to be imported to, and exported from, the system. Each of these functions has its own history. Some are extensive, for example, computer-assisted cartography (Taylor 1980, Boyle 1980), with well-developed computing algorithms (Monmonier 1982, Yoeli 1982) mainly concerned with putting traditional techniques into computerized form. Others, such as the organization of geographical data into efficient structures, have a shorter history (Peucker and Chrisman 1975, Rosenfeld 1980, Samet *et al.* 1984, Wang 1986) although they now represent an important branch of geographical theory. As such functions have been refined and brought together in various configurations, the range of GIS has expanded.

Attempts to classify GIS have typically focused on the task-orientation of a system. By focusing on the application domain, for example, Dangermond (1983) has suggested that GIS can be classified under six broad headings, distinguished by the type of information flow:

(i) engineering systems typically associated with public facility management and utilities;
(ii) property-based information systems to handle cadastral data relating to land parcels;
(iii) generalized, thematic and statistical mapping systems as used for natural resource management, census mapping and environmental planning;
(iv) bibliographic systems which catalogue information about data sets and geographical documents;
(v) geographical base file systems relating to functional and administrative boundaries, and
(vi) image-processing systems associated with Landsat and other remotely-sensed data.