From Conventional to Knowledge Based Geographical Information Systems

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ABSTRACT

Artificial intelligence (AI) has received an explosion of interest during the last five years in various fields. There is no longer any question that expert systems and neural networks will be of central importance for developing the next generation of more intelligent geographic information systems. Such knowledge based geographic information systems will especially play a key role in spatial decision and policy analysis related to issues such as environmental monitoring and management, land use planning, motor vehicle navigation and distribution logistics. This paper sketches briefly the major characteristics of conventional geographic information systems, and then looks at some of the potentials of AI principles and techniques in a GIS environment where emphasis is laid on expert systems and artificial neural networks technologies and techniques.

1. INTRODUCTION

Geographic information systems (GISs) have been around for almost thirty years. It is the development of universally available computers and new types of software which has made these systems so popular and wide-spread at the present time. GISs have moved from a concern with geo-processing in the 1960s, to management of geographic information in the 1970s and to first steps of spatial decision support systems in the 1980s. Gradually, but at an increasing pace, spatially indexed data, both from a large variety of sources and concerning a large number of diverse areas are becoming available in computer databases for display, manipulation, decision support, and analysis. This is happening at all spatial scales, from local to regional, national and increasingly global. The demand for geographical information systems to handle such volumes of data in a large variety of decision-making situations is increasingly dramatically.

Knowledge based GISs will play an important role in spatial decision and policy analysis (environmental monitoring and management, land use planning, motor vehicle navigation, distribution logistics etc.). Geographic information systems without intelligence have only little chances to provide effective and efficient solutions to spatial decision making problems in a highly complex and imprecise decision making environment. The application of artificial intelligence (AI) principles and techniques provides a great potential to meet the challenges encountered in developing the next generation of intelligent GISs. Expert Systems (ESs) and artificial neural networks (ANNs) may be considered to be essential ingredients for intelligent geographic information systems (see Fischer 1993).

This paper sketches briefly the structure and functions of conventional geographic information systems, and then looks at some of the actual and potential applications of AI techniques in a GIS environment where emphasis is laid on ES- and ANN-technologies and techniques.

2. CONVENTIONAL GEOGRAPHIC INFORMATION SYSTEMS: SOME ESSENTIAL CHARACTERISTICS

GISs are currently being used for a wide range of government, business and private activities including real time navigation of planes, automobiles and ships, the registration and organisation of pipeline networks and other services such as electricity and telephones, cadastral registration, city and regional planning. They are also being used for inventory, analysis and decision making in all kinds of natural resources studies, agriculture and forestry.

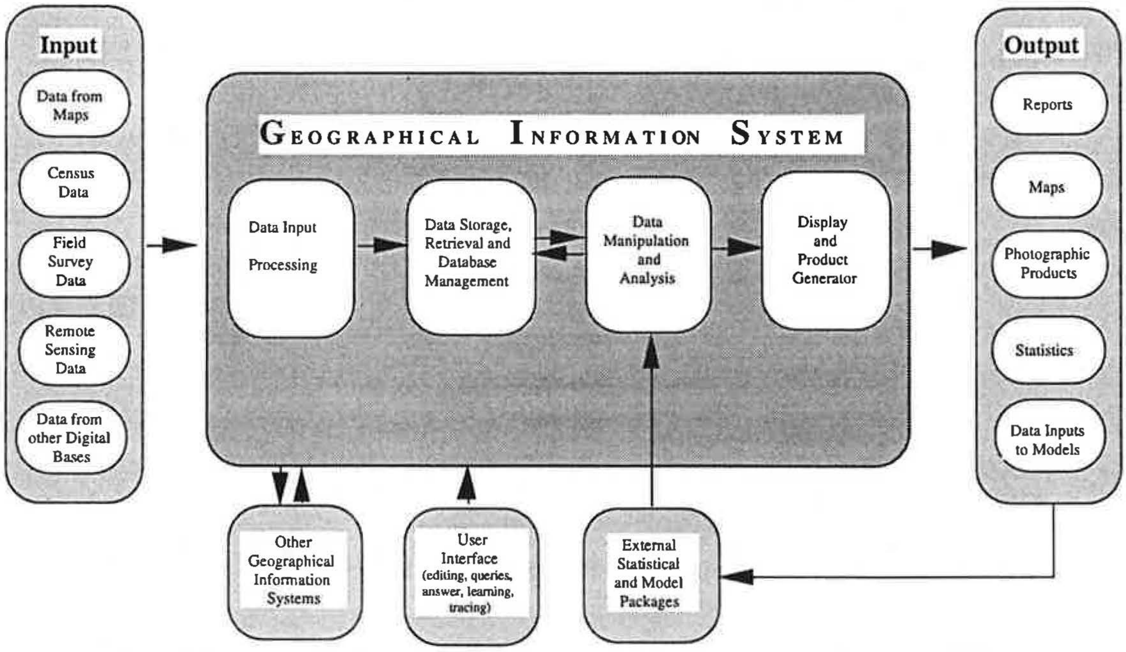
A geographical information system (GIS) may be viewed as a special case of general database systems and may be defined as a computer based information system which attempts to capture, store, manipulate and display spatially referenced data (in different points in time), for solving complex research, planning and management problems. Geographic information systems have five major components:

- a d*atabase of spatially referenced data* consisting of locational and associated attribute data, (large-scale) data sets where the data included usually have special characteristics such as spatial (space-time) dependencies, non-stationarity, varying degrees of reliability, multivariate non-normality, non-linearities, sensitivity to scale and aggregation effects, noise because of error propagation or due to the nature of data sources (see Openshaw 1990),
- appropriate *software components* encompassing procedures for the interrelated transactions from input via storage and retrieval, and the adhering manipulation and spatial analysis facilities to output,
- associated *hardware components* including high-resolution graphic display, large-capacity electronic storage devices and processing units,
- skilled personnel, and
- a proper organisational context.

These components have to be in balance if the systems are to function satisfactorily. There are many different software packages for GISs but they can all be represented by the model outlined in fig.1 (see Burrough 1991, Smith et al. 1987a, Star and Estes 1990). These basic modules are subsystems for

- data input processing,
- data storage, retrieval and database management,
- data manipulation and analysis,
- display and product generation, and
- a user interface.

Fig. 1: Subsystem of a Geographic Information System (see Fischer and Nijkamp 1992b)



Query input is the link between the user and the GIS. Spatial query possibilities distinguish GIS from other modern information systems.

GIS data concern location, relations and attributes. It is not simple to design appropriate data structures which can handle large multiscale data sets. In principle, two classes of conventional GIS may be distinguished. The first class models the location and spatial relations exactly by vector structures which represent points, lines, polygones etc. in terms of sets of exact coordinates and topological linkages. The attributes of these objects are then stored in records in relational databases leading to a hybrid structure. The second class models the location of points, lines, areas etc. by raster data structures in which the objects are expressed by sets of grid cells (pixels). These raster based GISs which, for example, find applications in remote sensing systems can only supply data about implicit spatial relations (Burrough 1991).

Today, geographic information systems incorporate many state-of-the-art principles such as relational database management, powerful graphics algorithms, elementary spatial operations such as calculating the accessibility or nearness of geographical objects to one another, buffering in vector maps, polygon overlay with logical operations, interpolation, zoning and simplified network analysis, as well as a certain degree of user friendliness through windows, icons, menus and pointers interfaces. However, the lack of analytical modelling functionality and the low level of intelligence in terms of knowledge representation and processing are widely recognised as major deficiencies of current systems (see Fischer and Nijkamp 1992a, Goodchild 1991, Openshaw 1990). The GIS industry has largely failed up to now to take on board the facilities offered by the modelling and the AI communities.

3. EXPERT SYSTEMS AND GIS

The introduction of knowledge based techniques into database systems has typically taken the form of expert systems (ESs) shells and AI languages. Use of AI languages like PROLOG and LISP was quite popular not too long ago when expert system technology was still in its infancy. Since then, they have fallen out of favour due to two major reasons. First, integrating systems developed in these languages with the mainstream database systems is not easy. Second, there is a shortage of skilled personnel trained in the use of these languages. Most of the commercially available ES shells use standard forward chaining, backward chaining or a combination of both strategies and have an upper limit on the number of rules which they can process.

Expert systems have evolved as a major branch of artificial intelligence and have been successfully introduced in various fields such as, for example, medicine, chemistry, engineering, and the military. Expert systems may be viewed as systems which achieve expert-level performance in a speciality domain utilising symbolic representation of knowledge, inference and heuristic search. They are designed to provide acceptable solutions using knowledge from experts and emphasize domain specific knowledge rather than more general problem solving strategies. The generic components of expert systems include (a) a knowledge base, which contains the knowledge obtained from a domain expert including facts, rules of thumb, and other judgmental factors of the human expert; (b) an inference engine which solves problems at hand using input data from the user and knowledge from the knowledge base; and (c) an user interface which allows the user to communicate with the system providing necessary data to the system. Most ESs use rule-based reasoning. But this kind of reasoning limits a system's ability to acquire knowledge from domain experts. One of the solutions to the knowledge-acquisition problem is to reduce dependency on domain experts as much as possible. Several alternatives, such as model-based reasoning, case-based reasoning, and exploration-based learning have been exploited.

Research in expert system application has lagged in GIS research, while other disciplines have produced significant work with ES application. There are several reasons for the slow pace of adaptation and development of expert systems in the GIS world. First, GIS technology is less mature up to now in both conceptional and implementation terms than non-spatial database system technologies. Second, geographic information systems typically model more complex domains than standard database systems. Third, spatial problems are highly complex, generally ill-structured in nature where the objectives of the problem itself and of the decision maker cannot be fully or precisely defined, and where there is no public domain knowledge (for example, textbooks) and no agreement among experts.

The idea of combining ES- and GIS-technologies has received a great deal of attention, recently. The marriage of ES and GIS may take various forms. From a technical point of view, there are at least four ways to link ES-technology and GIS (see Smith and Yiang 1991, Han and Kim 1990):

First, the strategy to develop generic (spatial) expert system tools to be integrated into appropriate geographic information systems as standard GIS operators ***(full integration*** of expert system tools into GIS technology like true deductive database systems),

Second, the strategy to develop an interface which enables the two systems, the expert system and GIS, to operate simultaneously and to communicate with each other ***(loose coupling)***,

Third, the strategy to employ ***tight coupling*** to facilitate communication between the rule-based system (ES) and the data base management system (GIS). Thus, either the expert system works as a shell around the GIS of the GIS can work as a shell around the rule-based system,

Fourth, the strategy of ***system enhancement***, i.e. to enhance either a rule-based system with limited database management capabilities, such as data access, concurrency control or security (an ES with spatial data handling capabilities), or to enhance a GIS with rule-based system capabilities, such as knowledge-acquisition and representation techniques and reasoning (a GIS with rule-based capabilities).

In contrast to non-spatial database systems, the introduction of knowledge-based techniques in general and ES-technology in particular is at a less advanced stage up to now and mostly refers to system enhancement, in terms of GIS with rule-based capabilities or ES with spatial data handling capabilities, as well as to loose coupling of ES and GIS.

There are several problems with the loose coupling approach (see Smith and Yiang 1991). First, the design of a loosely coupled system can be limited by shortcomings at the front end or back end. For example, if the back end cannot handle recursive spatial queries, the front end is limited. Second, the rule base is main-memory resident, thus, for example, the rule base can be lost if the address space of the shell goes away, while rules cannot easily be solved. Third, there is a semantic mismatch between the language at the front end (typically procedural) and the back end (typically declarative). This might lead to efficiency problems. Fourth, there is also a mismatch in the granularity of the data objects between the front end and the back end. The front end typically deals with a single tuple while the back end with a set of tuples. Thightly coupled as well as full integrated systems are being designed to overcome these and other problems. These strategies, however, have not yet been exploited in a GIS world (Smith and Yiang 1991).

In principle, ES-technology may be applied in all components of GIS to facilitate the construction of GIS applications and use. Prominent application domains in which production rule systems can be applied include:

- **Automated Map Generation**:

  Suitable procedures for automated map generation are needed in GIS for two major reasons: first, to guarantee optimal readability of GIS display products, and, second, to enable mapping from and transformation between high-resolution multi-purpose spatial data base (cost reduction of data capture, increase of data consistency, enabling cross-database analysis) (Weibel 1991). Up to now most of the research has been devoted to narrow aspects of the overall problem of automated map generalisation, such as line simplification and name placement. The relatively large number of theoretical and conceptual papers addressing aspects of building a knowledge base for automated map generalisation contrasts by a relatively limited number of actual implementations of expert sysems in this field (see, for example, Nickerson 1988, Robinson and Zaltash 1989, Laurema et al. 1991). Up to now, the application of ES-technology to the overall problem of automated map generalisation has not yet been very successful because map generalisation is a highly complex process partly encompassing intuitive and even artistic aspects.

- **Automated Device Routines** for extracting, sorting, describing data and object structure:

  There is great interest in the use of metadata as knowledge which can be used in facilitating content-based search. AI languages are increasingly being used to represent metadata. The use of high-level declarative query languages generally requires the use of optimisation procedures to enhance system efficiency. A major approach to query optimisation involves the application of knowledge, characteristically in the form of rules of integrity constraints, relating to equivalence relations, containment relationships, expected value ranges, sorting orders, functional dependencies (Smith and Yiang 1991). Such knowledge is used to transform a query for more efficient processing. Dynamic optimisation, for example, has been employed in KBGIS II (Smith et al. 1987b) to retrieve complex spatial objects. Forward checking is used dynamically to enforce domain constraints. During the search process, the values for any variable are examined sequentially and constraints are explicitly computed to check whether the value selected from the domain satisfies the constraints on the variable. Spatial constraint propagation is used to replace the explicit checking of constraints during backtracking by geometrical search within constrained areas of the database. Frames, semantic networks and rules are the structures used here to represent knowledge (Smith and Yiang 1991).

- **Analysis and Processing**:

  Robinson et al. (1987) provide a survey of 20 systems which involve various ES built in order to assist various GIS operations in the area of resource management. Many of these systems are loosely linked to the data handling capabilities of some GIS and many employ ES shells. For example, there are applications of ES technology for automated interpretation of aerial photography (Brooks 1983), change-detection in LANDSAT images (Goldberg et al. 1984), landslide hazard assessment (Pearson et al. 1992), decision making in urban systems (Tanic 1986). Some ES modules have been developed using logic programming techniques. Franklin and Wu (1987) have expressed polygon overlay in PROLOG, while Webster (1989) has shown how point-in-polygon queries may be formulated in the predicate calculus and answered by resolution theorem proving a PROLOG environment. Pearson et al. (1992) have developed a prototype landslide hazard assessment tool permitting ARC/INFO and Nexpert Object (a commercially available expert system development shell from Neuron Data) to be linked in the Unix environment where they run as two separate processes on a single platform. Loose coupling is achieved via ASCII files and usually only one program is active at one time. Nexpert is controlling ARC/INFO in order to hide GIS functionality from the user.

Relatively little is known about modelling and spatial analysis in a GIS world. But what is known suggests that GIS inspired spatial modelling and analysis tasks are neither well defined nor easily represented in a rules database. Moreover, most of the existing methods and models might be considered as inappropriate for the GIS era so that the ES-technology may be not relevant in this context (Openshaw 1992a).

4. ARTIFICIAL NEURAL NETWORKS AND GIS

Neurocomputing dates back to 1943, but very few scholars were involved until 1983 when the US Defense Advanced Research Projects Agency began funding neural network research, followed soon by other organisations and countries (see Hecht-Nielsen 1990). The effect of this initiative and of significant major breakthroughs in the design and application of artificial neural networks (ANNs) in the 1980s was an explosion of interest.

Neurocomputing - concerned with non-programmed adaptive information systems called Artificial Neural Networks (ANNs) - provides the potential for an alternative information processing pradigm that involves large interconnected networks of relatively simple and typically non-linear processing elements. Several features distinguish this paradigm from conventional computing and traditional AI-approaches. First, information processing is inherently parallel. Large-scale parallelism provides a way to significantly increase the speed of information processing (**inherent parallelism**), second, knowledge within an ANN is not stored in specific memory locations, as it is in conventional computing and expert systems. Knowledge is distributed throughout the system; it is the dynamic response to the inputs and the network architecture (**connectionist type of knowledge representation**). Third, ANNs are extremely fault tolerant. They can learn from and make decisions based upon incomplete, noisy and fuzzy information (**fault tolerance**). Finally, mathematically considered, they adaptively estimate continuous functions from data without specifying mathematically how outputs depend on inputs (**adaptive model free function estimation, non-algorithmic strategy**) (Fischer and Gopal 1993).

One of the most important features in neurocomputing is the learning ability of ANNs which makes it in general suitable for computational applications whose structures are relatively unknown. The dynamic modification of the variable connection weights is the essence of learning. ANNs which use learning are usually subjected to training. There are two general categories of training which are commonly used to adjust an ANN's pattern of interconnectivity. Supervised training implies a situation in which the network is supplied with a sequence of both input data and target output data and the network is thus told precisely what should be emitted as output. Self-organisation or unsupervised training is a biologically more plausible model of learning. It is a training scheme in which the network is given only input data, and it is expected to modify itself in response to it. ANNs are designed to perform a task by specifying the architecture: the number of processing elements, the network topology (feedforward versus feedback), the type of transfer function inherent in the processing elements, the type of training required (supervised versus unsupervised) and the learning rules.

Even if neurocomputing is a subject still in its infancy and the techniques currently available are limited in their capabilities, ANNs have a far-reaching potential as modules in tomorrow's computational world in general and in the GIS world in particular. Useful applications have been already designed and built in various fields (see Fischer 1993), such as

- **image analysis**, i.e. pattern classification and pattern completion problems, in various domain areas (for example, automated medical image analysis, industrial visual inspection of a product or component under manufacture),
- **automated diagnosis** ranging from machine diagnosis and failure analysis to identify and evaluate fault types (for example, jet engine and automobile engine diagnosis) to automated control covering a wide range of complexity of control problems, from simple systems such as balancing a broom to complex systems such as autonomous control of a moving car and robotic control problems,
- **speech analysis and generation**, including text-to-speech translation and automated speed (syllable) recognition where current applications, however, are limited to the recognition of phenomes or simple words and a limited vocabulary.

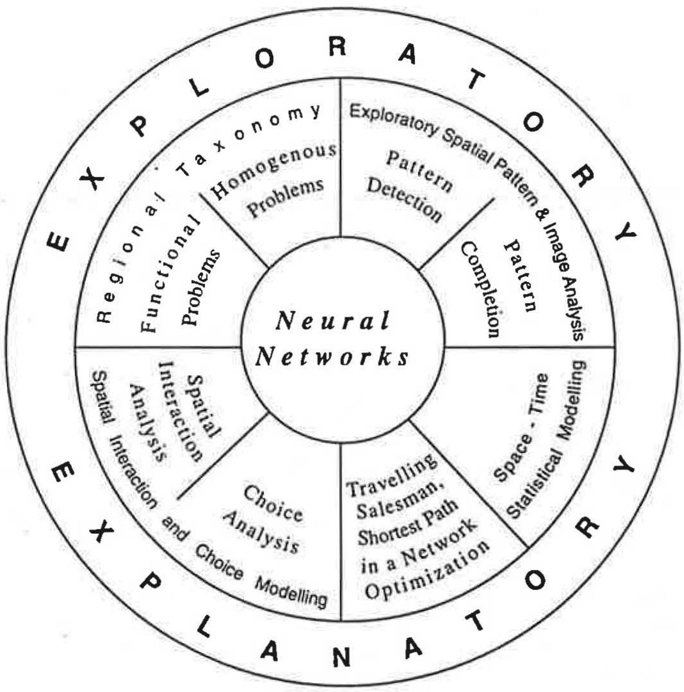
Up to now, geographers and GIS experts have been rather slow in realising the great potential of the revolutionary new technology of neural networks, with the exception of very few scholars like Fischer and Gopal (1992, 1993), Gopal and Fischer (1993) and Openshaw (1992a, b).

In principle, the ANN-technology may be applied in all components of GIS. Especially, it offers an important data driven methodology to develop new modelling and analysis tools needed to cope with the data rich but theory poor GIS world, and thus has the potential to increase the modelling and analysis functionality of geographic information systems. The range of potential applications in th area of GIS and spatial analysis is impressive. Key candidate application areas summarized in fig. 2 include

- **exploratory spatial pattern and image analysis** via (un)supervised neural network architectures, especially in the field of environmental monitoring and management in data rich GIS environments,
- **homogeneous and functional regional taxonomic problems,** especially in the case of very large data sets for example for geomarketing purposes,

- **spatial interaction and choice modelling** via supervised neural network architectures (see Fischer and Gopal 1992 for the application of multi-layered feedback forward networks with a back-propagation learning algorithm to model telephone traffic in Austria),
- **optimization problems such as the classical travelling salesman problem and shortest-path-problems in networks** via supervised neural network architectures (see Wilson and Pawley 1988 for a Hopfield network application to the travelling salesman problem), and
- **space-time statistical modelling** (via supervised or unsupervised neural networks, depending upon the problem under study).

Fig. 2: Some Key Candidate Application Areas of Neural Networks in the Field of Geographic Information Processing (Fischer 1993)



This list of problems addressable by the neural network approach is by no means exhaustive, but certainly reflects priorities for neural network applications in GIS environments. In principle, neural networks may be developed to replicate the descriptive and predictive functions of current statistical and mathematical procedures of any complexity, often with an improved level of performance and accuracy. They can cope with fuzzy and qualitative reasoning and they are particularly effective when the data do not satisfy the rigid assumptions of conventional statistical analysis (Openshaw 1992a). Their major drawback is that serious neural net applications may be not easily built. Training by backpropagation, for example, is often time consuming and sometimes impossible. Another serious issue is the problem of overfitting. However, there are recent signs of practical success in various fields.

5. CONCLUSIONS

Geographic information systems without intelligence have only little chances to provide effective and efficient solutions to spatial decision making problems in the highly complex and imprecise decision making environment in a GIS world. The application of AI principles and techniques provides a great potential to meet the challenges encountered in developing the next generation of intelligent GIS. ES- and ANN-techniques may be considered to be essential ingredients of such systems. They fundamentally differ in their knowledge representation techniques from each other. Expert systems use the way of symbolic encoding of knowledge in form of production rules (forward/backward chaining systems), while artificial neural networks represent knowledge implicitly rather than explicitly. Neurocomputing shows greater flexibility than expert systems to deal with situations characteristic for the GIS world, in which the data at hand are poor (incomplete, noisy, imprecise, etc.) from an analytical point of view, the spot of patterns and relationships in data-rich environments is important, but relevant theories and hypotheses for data analysis are missing.

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