Expert Systems for Geographic Information Systems

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ABSTRACT: Expert systems (ES) are computer systems that advise on or help solve real-world problems which would normally require a human expert's interpretation. This paper discusses the nature of expert systems with special attention given to the construction process. Four major problem domains of geographic information systems (GIS) where expert system technology has been developing are identified. They include map design, terrain/feature extraction, geographic database management, and geographic decision support systems. Some efforts in each domain are briefly reviewed. Considering the accomplishments and shortcomings of efforts to date, we discuss some prospects for future developments. We suggest that many of the future research needs of geographic information systems will be addressed within the context of expert system development. We identify the formalization of geographic knowledge and the formalization of uncertainty as two of the most fundamental problems facing the development of expert GIS. Finally, development of multiple prototype expert GIS, addressing the same problem but using different methods, is encouraged so that we can begin to conduct comparative analyses.

INTRODUCTION

EXPERT SYSTEMS (ES)are computer systems that advise on or help solve real-world problems which would normally require a human expert's interpretation. Such systems work through problems using a computer model of expert human reasoning. Thus, they are designed to reach the same conclusions that a human expert would be expected to reach if faced with a comparable problem (Weiss and Kulikowski 1984).

There are a number of areas where geographic information systems (GIS are expected to benefit from the application of expert system technology. Geographic data input is one area where expert systems can be used to extract features from imagery, exploit the potential of automatic scanning of manuscript maps, manage the editing of geographic data at the same time data are being captured, and assess the quality of data being entered into the system. Expert systems may be used to exploit knowledge about a user query and the GIS itself in order to speed the search through very large spatial databases. Development of intelligent user interfaces will make GIS responsive to user needs because the user will no longer have to become an expert in the use of GIS in addition to their own field of specialization (e.g., forest management or urban planning). Cartographic expert systems could be used to produce high quality maps which would effectively communicate information derived from a GIS. These are but a few of the areas where expert systems can play a significant role in improving the efficiency and effectiveness of GIS.

In previous papers we introduced expert systems for land information systems (LIS) (Robinson *et al.*, 1986a), critically surveyed efforts related to expert systems for geographic information systems (GIS), and identified several research themes for developing expert system technology for GIS in general (Robinson *et al.*, 1986b,c) and for applications in resource management in particular (Robinson *et al.*, 1987). In this paper we provide a brief introduction to expert systems. We direct more attention to the process of expert system construction. The introductory sections are followed by a brief presentation of some important efforts relevant to the development of expert GIS. In conclusion, we discuss some prospects for linking ES and GIS.

CHARACTERISTICS OF EXPERT SYSTEMS

Expert systems are unique in their ability to "explain" their line of reasoning or justify conclusions reached. Fisher and Mackaness (1987) consider the ability to "explain" to be one of the fundamental criteria for cartographic expert system definition. The ability to explain the reasoning behind a conclusion implies a certain level of self-knowledge. Thus, a cartographic expert system should not only be able to make excellent maps, but also explain why specific decisions were made (e.g., in regard to fonts, line weights).

Expert systems should interact with humans in natural language, function despite some errors in the data and uncertain judgemental rules, contemplate multiple competing hypotheses simultaneously, and explain their reasons for requesting additional information when needed. Generally speaking, contemporary expert systems lack any ability to learn, except in the crudest sense. Development of powerful learning ability and its incorporation into the design of expert systems remains an area of research.

ORGANIZATION OF EXPERT SYSTEMS

Expert systems differ from conventional computer programs in their organization. Ordinary computer programs organize knowledge on two levels: data and program. Most expert systems organize knowledge on three levels: facts, rules, and inference. Many systems having this organization are referred to as knowledge-based systems. In the knowledge base there is declarative knowledge (i.e., facts and rules) about a particular problem being solved. Rules represent knowledge specific to solving a particular problem and are used to reason about the problem, while the "inference engine" controls when and how specific problem-solving knowledge is used.

Expert systems differ markedly from conventional computer programs and database management systems because of the treatment of facts and rules as "data" in the knowledge base. In conventional computer programs rules are embedded in the procedural knowledge coded as the program. Hence, it is difficult to separate the rules from the procedural, or control, mechanism of program execution (i.e., inference). For example, database systems store facts in data files, while domain-specific rules are combined with other considerations into the database programs. A knowledge-based system would separate domain-specific rules from the procedural language used for controlling program execution. This organization makes it much easier to encode and maintain facts and rules. In fact, PROLOG, a commonly used language for building expert systems, has been described as a database programming language (Sterling and Shapiro, 1986).

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Knowledge Representation

Knowledge may be represented in at least three ways. Using the formulas of first-order predicate logic is one well-known method that provides the basis for logic programming languages (Mylopoulos, 1980; Gallaire *et al.*, 1984). This method is useful because it can be used to represent both facts and rules. Procedural knowledge can also be represented in first-order predicate logic if the logical formulas are suitably interpreted. The programming language PROLOG is an example of just such an approach (Kowalski, 1979). It is important for the reader to realize that the rules we speak of are not simply branching points in a program, but are nonprocedural statements of fact.

A second common method of representing declarative knowledge is to use semantic nets (or semantic networks). Semantic nets were introduced as a means of modeling human associative memory (Quillian, 1968). In this method, objects are represented by nodes in a graph and the relations among them by labeled arcs. One of the useful aspects of semantic nets is their indexing property. The network can be constructed so objects often associated in computations, or those which are conceptually close to one another, may be represented by nodes in the network that are near one another.

Frames are a third common method of representing declarative knowledge (Minsky, 1975). One can think of frames as data structures in which all knowledge about a particular object or event is stored together. Because the organization of knowledge is more modular, its accessibility is increased.

One of the main advantages of semantic nets and frames over first-order predicate representation is that, for each object or event, all relevant information is collected together. This improves the ease with which information is accessed and manipulated. The selection of one method of representation over another appears to be a matter of suitability for a particular problem. Some systems, such as KBGIS (Glick *et al.*, 1985), discussed later, use a hybrid frame-based, semantic net method of knowledge representation. Because it has been widely acknowleged that first-order predicate logic, semanic nets, and frames are generally equivalent forms of representation (Nau, 1983), the choice of method may influence performance characteristics of a system but not its logical power.

Knowledge Exploitation

Many problems that expert systems are called on to solve are ones where steps necessary for reaching a solution are not precisely known. It is often necessary to search through a "state-space" containing a large number of alternatives where each might lead to a solution. Often the search space is extremely large. The size of the search space makes it impractical to construct all potential paths; rather, a path is constructed only as far as necessary. Most approaches to determining when a solution has been found are grounded in pattern matching. One can think of a pattern being matched when, given a pattern rule and a collection of objects, those objects are found which satisfy the pattern rule. One of the simplest examples is when a wildcard is used in a directory search to find all files whose name begins with the letter S.

There are several general strategies for searching through the state-space. State-spaces can be thought of as being represented by a graph. Walking through the graph is analogous to searching for a path to reach a state that corresponds to a solution. They can also be searched in a backward direction by starting with a goal, or solution, state and then finding a path to the initial state. The appropriateness of the approach depends on the particular problem being addressed and the nature of the state-space. Two fundamental approaches are forward chaining and backward chaining. Forward chaining is a data-driven approach. One of the major problems with implementing this approach is in specifying how to determine whether or not a fact is useful for the problem at hand. Backward chaining is goal-driven. The advantage of this kind of search is that the goal is known from the start and can be used to advantage when searching large state-spaces. On the other hand, this introduces additional complexity into required pattern matching expressions. For more detail, the reader is referred to Nilsson (1971) for general discussion of these and other methods. For those interested in examples, Bratko (1986) provides implementations of these strategies in PROLOG.

Pattern Matching

Pattern matching plays a central role in most methods of state-space search. The selection of the next step in the path is often based on the present state matching a pattern given a rule(s). It is, therefore, not surprising that pattern matching has received considerable attention in the field of artificial intelligence (Jackson, 1985). Early Lisp-based languages such as CONNIVER(Sussman and McDermott, 1972) and PLANNER (Hewitt, 1969) and their descendants, all include methods to invoke rules based on matching patterns.

Pattern-invoked programs are not called by other programs in the usual sense. Their invocation is driven by patterns in the rules being matched by the present state. One of the most fundamental pattern-invoked program is the production rule. It is a degenerate program of the form

IF ⟨condition⟩ THEN ⟨primitive action⟩.

The pattern is the "condition" that is usally a conjunction of predicates that test properties of the current state. The "primitive action" is some simple action that changes the current state. For example, it may change the state associated with a particular proposition from "FALSE" to "TRUE."

CONSTRUCTING EXPERT SYSTEMS

Generally speaking, when one builds an expert system one goes through a number of stages that closely resemble classical systems analysis. These include identification, conceptualization, prototyping, creating user interfaces, testing and redefinition, and knowledge-base maintenance (Bobrow *et al.*, 1986).

To identify problems amenable to solution through expert system technology, a critical mass might be one or two knowledge engineers and a group of experts. Several test cases should be collected for later use. With distributed knowledge, the interview process should strive to expose specializations and then determine the degree of consensus in solution methods among the group of experts.

Once the problem domain has been identified, the next step is conceptualization and formalization of knowledge about the problem. Initial knowledge acquisition sessions should start with a single expert who can demonstrate problem-solving by working through several examples. Having developed some sense of the problem, the knowledge engineer can then attempt to articulate what is believed to be occurring in the problem-solving sessions. A useful next step is to simulate the process of solving of one or more test cases.

After several rounds of simulation and critiquing by a single expert, it is useful to bring in other experts to help identify idiosyncracies and determine the multiplicity of problem-solving styles. Very often these sessions result in knowledge design documents that can be of great assistance in later stages (e.g., Mittal *et al.*, 1985). The documents also provide something tangible that can be circulated among experts for comment, correction, and identification of omissions. Thus, it helps make explicit some of the knowledge that had been implicitly applied by experts.

Significant amounts of time and effort may be consumed creating a suitable user interface to an expert system. It is often important to develop an interface that matches what human problem-solvers used prior to the ES. This often demands careful design of man-machine interaction.

Goal browsers are an artifact of the user interface unique to expert systems. Goal browsers can be used to lay out the expert system design process as a network of different goals, and display goal status during the construction stage. They also sometimes allow the user to edit, undo, advise, and reexecute goals.

It becomes important to start testing the system with users when a prototype has reached the stage where it is possible to go through the initial test problems from beginning to end. This usally reveals new problems. It is common for a second or even a third version of a prototype to be developed. Feedback from solving real problems often forces reimplementation. This cycle is characteristic of knowledge programming.

After testing the second or third version of the prototype, a plan for a large software development project should be developed. The plan must provide for testing, development, transfer, and maintenance of the knowledge base. A process should be in place at user locations to help tune the interface, and to extend the knowledge-base as new problems are found and easier ways to interact with the system are suggested.

SOME EFFORTS IN EXPERT SYSTEMS AND GEOGRAPHIC INFORMATION SYSTEMS

There have been a number of expert system efforts reported that are relevant to GIS. We identify four major problem domains in which there have been a number of ES-related efforts for GIS. The problem domains are map design, terrain/feature extraction, geographic database management, and geographic decision support. Table 1 illustrates the relationship between problem domains of geographic information systems and some efforts in areas particularly relevant to the development of expert geographic systems. Not all reported efforts in Table 1 are discussed here, but have been detailed in previous papers e.g., MAP-AID(Robinson and Jackson, 1985), ACES, (Pfefferkorn *et al.*, 1985), CERBERUS (Engle, 1985), MAPS (McKeown, 1984), and ACRONYM (Brooks, 1983). Here we review only a small group of efforts especially selected to illustrate the potential of expert systems technology to improve GIS.

MAP DESIGN

The production of maps is one of the most common uses of GIS, and maps are the distinctive information product of GIS. However, making good maps that communicate effectively is not a trivial task. The design and production of high quality maps is a time-consuming, hence expensive, task requiring the expertise of trained cartographers. The efforts discussed below address the problems of map generalization, name placement, and general map design.

TABLE 1. SOME EXPERT SYSTEM EFFORTS RELEVANT FOR GEOGRAPHIC INFORMATION SYSTEMS

Problem Domain	Expert System Effort	
Map Design	MAPEX	(Nickerson and Freeman, 1986)
	AUTONAP	(Freeman and Ahn, 1984)
	MAP-AID	(Robinson and Jackson, 1985)
	ACES	(Pfefferkorn *et al.*, 1986)
	CES	(Muller *et al.*, 1986)
Terrain/Feature Extraction	Palmer (1984), Frank *et al.* (1986)	
	ACRONYM	(Brooks, 1983)
	FES	(Goldberg *et al.*, 1984)
	CERBERUS	(Engle, 1985)
	MAPS	(McKeown, 1984)
	SPAM	(McKeown *et al.*, 1985)
Geographic Database Management	ORBI	(Pereira *et al.*, 1982)
	LOBSTER	(Frank, 1984)
	KBGIS	(Glick *et al.*, 1985)
	KBGIS-II	(Smith *et al.*, in press)
	SRAS	(Robinson and Wong, 1987)
	Wu and Franklin (1987)	
Geographic Decision Support	TS-Prolog	(Barath and Futo, 1984)
	URBYS	(Tanic, 1986)
	GEODEX	(Chandra and Goran, 1986)
	ASPENEX	(Morse, 1987)
	AVL 2000	(Karimi *et al.*, 1987)
	DeMers (1986, 1987)	

MAPEX is a rule-based system for automatic generalizaton of cartographic products (Nickerson and Freeman, 1986). This system is designed to work with U.S. Geological Survey (USGS) 1:24,000 scale Digital Line Graph (DLG) data being generalized to 1:250,000 scale. Like other efforts in this field, there was no reported effort to extract expertise from human experts in map generalization. However, significant contributions of this effort include the formalization of the problem of generalization within a rule-based framework and the identification of existing rules and generation of rules-of-thumb.

AUTONAP is perhaps the most successful name placement expert system developed to date (Ahn, 1984; Freeman and Ahn, 1984). This system emulates an expert cartographer in the task of placing feature names on a map. However, like MAPEX there was no reported effort in extracting knowledge from an expert in name placement. AUTONAP utilizes heuristic knowledge about name placement based on established procedures and conventions. The knowledge base consists of a small set of explicit rules (approximately 30) organized as subroutines in a large RATFOR program. The approach taken by AUTONAP is that area features are annotated first, then point features, and finally line features. In this manner the system progresses from the most constrained annotation task to the least constrained feature annotation task. Once the placement of area feature names has been accomplished, a free-space list and possible-positions list are developed and used in subsequent name placement tasks. These two lists essentially form a graph of permissible name placements and locations.

CES is a prototypical cartographic expert system intended for use by Energy, Mines and Resources of Canada as a cartographic advisor (Muller *et al.*, 1986; Muller, personal communication). Using decision tables, it provides a set of mapping specifications that "optimally" fulfill a set of map requirements that are given to the system. It was developed to help cartographers design the Electronic Atlas of Canada. This project experienced some of the same problems as MAP-AID (Robinson and Jackson, 1985). Namely, it was discovered that cartographic knowledge is difficult to formalize and sometimes inconsistent.

TERRAIN/FEATURE EXTRACTION

The extraction of terrain features or land-use/land-cover features from geographic data has, for sometime, been one of the fundamental uses of GIS. For example, given a set of points describing the elevation of an area, a GIS may be asked to identify terrain features which have meaning for solving the problem at hand. Thus, the same data may be used to identify different features, but to do so often requires the expertise of a specialist.

Palmer (1984) illustrated the use of logic programming for analysis of terrain features. Using a triangular tesselation, he represented nodes with their elevation, segments and triangles as first-order predicates. Then using PROLOG to conduct symbolic analyses, he demonstrated how valleys, streams, and ridges could be deduced. This work was subsequently extended by Frank *et al.* (1986), using LOBSTER, to illustrate how definitions in physical geography can be formalized using logic programming.

FES is a Forestry Expert System developed to analyze multitemporal Landsat data for classification of land cover and identification of change for use by forest managers (Goldberg *et al.*, 1984). Using a multitemporal Landsat image database, production rules are used to infer the nature of land-cover changes and determine a measure of reliabilty.

GEOGRAPHIC DATABASE MANAGEMENT

The management and query of geographic databases have attracted much attention because they are fundamental to operation of any GIS. Use of expert systems promises to make GIS more user-friendly and responsive. Making spatial searches more rapid is one of the objectives of KBGIS-II. Other systems such as ORBI and SRAS have focused on making the user interface more natural and meaningful.

ORBI is implemented in PROLOG as an expert system to keep track of environmental resources for the country of Portugal (Pereira *et al.*, 1982). There are aspects of a classification system for environmental data and a decision-support system for resource planning. ORBI provides (1) a natural language parser for Portuguese that supports pronouns, ellipses, and other transformations; (2) a menu handler for fixed-format input; (3) an explanation facility that keeps track of the steps in a deduction and displays them on request; and (4) help facilities that explain what is in the database, the kinds of deductions that are possible, and the kinds of vocabulary and syntax that may be used. It remains one of the most impressive accomplishments to date.

LOBSTER, like ORBI, is based on the logic programming paradigm. It is a new implementation of a task previously solved using a traditional programming approach, namely, a query language for a geographic database (Frank, 1982). It serves as an intelligent user interface to a spatial database management system using the network data model rather than the relational model. The flexibilty in building the interface using a PROLOG-like language was believed significant (Frank, 1984).

KBGIS is a comprehensive knowledge-based GIS using hybrid knowledge representation (Glick *et al.*, 1985). That is to say, it uses methods of knowledge representation that are combinations of the "pure" forms we discussed earlier. KBGIS uses frame-based semantic nets to represent the "meaning" of geographical objects and their interrelationships. This provides the ability to incorporate new entities, attributes, and relationships. These new entities can also inherit characteristics from their object-types or similar entities. Incorporation of geographical entities is eased through the use of an expert system shell that is part of the KBGIS. Most importantly, this KBGIS has recently become operational and is used on a daily basis for trafficability studies and geopolitical trend analysis.

KBGIS-II is a knowledge-based GIS that is designed to speed the search of very large geographic databases (Smith and Pazner, 1984). It uses a spatial object language similar to others based on predicatecalculus. Because it is a pixel-oriented system, its search procedures exploit the use of a constraint-satisfaction procedure acting on a database represented in quad-tree form. It also uses some primitive learning procedures to make spatial searches more efficient. Using the spatial object language, a user can edit the knowledge base or perform a query operation. However, hardware deficiencies do not permit this system to be truly interactive (Smith *et al.*, in press).

SRAS is a spatial relations acquisition station (Robinson and Wong, 1987). It is concerned with acquiring representations of natural language concepts to be used in subsequent queries of a geographic database. This is a mixed-initiative, question-and-answer system that chooses questions based on anticipated user response and its effect on the representation of the natural language concept. It is one of the very few efforts in acquiring representations from "experts" rather than developing rule bases. Another unique feature of this effort is its recent concern with the composition of multiperson concepts for subsequent use in expert systems.

Geographic Decision Support

To the resource manager, urban planner, or transportation manager the major reason for developing ES for GIS is to help them in their day-to-day decision-making processes. Each of the systems—ASPENEX, URBYS, AVL 2000, and GEODEX—is developed to help support geographic decision making. In order to develop an ES that supports decision-making functions, one must first formalize the knowledge and processes used in those decision-making functions (see DeMers, 1984).

ASPENEX is an expert system for aiding in the management of aspen in the Nicolet National Forest (Morse, 1987). It is described as a system that interfaces an expert system with a GIS. The GIS component of ASPENEX is MOSS (Map Overlay and Statistical System), a public domain GIS. The EXSYS (1985) shell environment is employed to develop the user interface, rule base, and interprogram communication on a microcomputer. the microcomputer-resident expert system provides rules required in aspen management and MOSS provides spatial information on characteristics of aspen stands. This prototype system is operating in Nicolet National Forest. It is significant that the project has recently assigned a person specifically to maintain the knowledge base and user interface.

URBYS is an expert system designed to aid in territorial planning and analysis of urban areas (Tanic, 1986). Although there is recognition of the need for formalizing planning knowledge, it is unclear whether the rigors of expert system construction will be followed in the elaboration of URBYS. Its organization is characteristic of the hybrid systems. Rather significantly, there is no formal provision for knowledge acquisition. It is left to the "expert" to change the rules and/or facts.

AVL 2000 is an automatic vehicle location and navigation system currently under development (Karimi *et al.*, 1987). It is based on a 68000 microprocessor with high resolution graphics, and real-time utilization of GPS data. Utilizing a database containing a representation of the transportation network, it determines an optimal path using an "expert route consultant" and displays a map upon which is superimposed the location of the vehicle as it is tracked. The dynamic map is supplemented by directions, from an expert navigator, which are currently displayed as text.

GEODEX was built to assist planners in evaluating site suitability for land-use activities (Chandra and Goran, 1986). Its rules are drawn informally from a land-use planner. Using rules in its knowledge-base, GEODEX operates in a forward-chaining fashion, applying site constraints drawn from the knowledge base. There is mention of a capability of backtracking should the constraints prove so restrictive over the geographic database that no sites satisfy the constraints.

DeMers (1986) reports an effort to develop a strategy for acquiring knowledge from land-use experts for use in the USDA/Soil Conservation Land Evaluation and Site Assessment system. DeMers (1986) did not link knowledge acquisition to a formal method of knowledge representation. Recently, he has extended his ideas to incorporate man-machine interaction (DeMers, 1987).

PROSPECTS FOR LINKING EXPERT SYSTEMS AND GEOGRAPHIC INFORMATION SYSTEMS

We suggest that many of the areas of past efforts will continue to be areas of research (Robinson *et al.*, 1986b,c). A clear trend is towards the use of more established artificial intelligence tools such as PROLOG, Lisp, and expert system shells such as EXSYS. However, some characteristics of these tools limit their usefulness for building large-scale expert systems for geographic applications. Storage issues and inferencing speeds are particular problem areas (Robinson *et al.*, 1986b). This is borne out by the inadequate performance of many of the Lisp and Prolog-based systems (e.g., Chandra and Goran, 1986; Frank 1984; Smith *et al.*, in press).

LOBSTER (Frank, 1984) and ORBI (Periera *et al.*, 1983) have demonstrated the ability of logic programming to serve as an intelligent user interface. Use of logic programming in this capacity is likely to increase as its capabilities are demonstrated in a practical context to a broad audience of users. In fact, Prolog has been credited with playing a major role in the blossoming of artificial intelligence research in Portugal (Damas and Filgueiras, 1986). Perhaps most significant, in relation to development of expert systems, was their observation that the difficult problem of implementing required pattern matching and search procedures is obviated by use of PROLOG.

The map design problem will continue to be a focus of expert system application (Fisher and Mackaness, 1987). It is an important, difficult, high-value problem. The success of AUTONAP has raised the level of research in automated name placement (e.g., Cromley, 1986; Langran and Poiker, 1986; Mower, 1986); map generalization is fast becoming a focus of developmental activity (Nickerson and Freeman, 1986). Government agencies such as the Alberta Bureau of Surveying and Mapping are beginning to investigate automated generalization as a means of reducing costs and improving throughput of map production systems.

Work on the problems of land-use/land-cover classification and monitoring, like FES (Goldberg *et al.*, 1984), will continue. However, another area that is beginning to develop is in the automated extraction of geomorphological features. For example, Band (1986) has recently shown how stream networks and basin structure can be automatically extracted from a digital elevation model.

The importance of managing uncertainty in expert systems will almost certainly increase. Its importance has been recognized in, for example, FES (Goldberg *et al.*, 1984), which included a reliability measure. Shine (1985) reviewed the utility of Bayesian, Fuzzy, and Belief logics in feature extraction systems. It is clear that many future concerns in ES will be directed at the resolution of contradictory information resulting from the use of several types of remote sensors.

Geographic decision support is an area receiving increasing attention from resource managers as they begin to appreciate the value of having expert systems to support the decision-making process (e.g., Morse, 1987). The work being done by Densham and Rushton (1986) on decision support systems (DSS) for locational planning and that of Armstrong (1987) on a DSS for water resources planning highlight two very important trends. Their efforts rely on sophisticated geographic database designs with implementations being directed towards the microcomputer environment. In fact, Robinson (1987a) argued that as microcomputing technology matures it will become more integrated into the decision-making process. He views this process being dominated by development of interactive intelligent systems acting as decision support workstations.

Development of spatially distributed GIS can only encourage development of expert systems that navigate through distributed systems, combine contents of spatially distributed databases while maintaining database integrity, and determine the reliability of information provided the user. Expert systems will become the automated managers of the information resources contained in a large-scale geographically distributed GIS.

It is surprising that more advisory ES for GIS have not been developed. CES (Muller *et al.*, 1986) serves mostly as an advisor on map deign, but there are many other areas where advisory ES can be extremely useful in GIS-related activities. The simple rule-based system described by Karimi and Lodwick (1987) is suggestive of an ES that would advise on the choice of data capture techniques in a GIS project. Spatial analysis is an extremely complicated field where expertise in spatial statistics, data quality, data structure, and interpretation interact to help determine the correct combination of techniques to apply to a particular problem. The development of such advisors would bring about practical improvements in geographic decision making and formalize geographic knowledge in a manner that makes it accessible to nonspecialists.

CONCLUSION

Many of the future research needs of geographic and/or land information systems will likely be resolved within the context of expert systems (see Onsrud, 1986). For example, much discussion over explicit modeling of land data could be productively pursued as a knowledge representation problem. Similarly, incorporating temporal information into the operations of a land information system will likely prove nearly impossible without also incorporating knowledge in the form of temporal logic.

In a recent comparative study of expert systems, Ramsey *et al.* (1986) make an observation that is particularly relevant to building expert geographic information systems. They contend that all three approaches—statistical pattern classification, rule based deduction, and frame-based abduction—are limited in their ability to conveniently represent spatial and temporal knowledge. This would seem to indicate that many research problems associated with constructing expert GIS are fundamental research problems, such as development of improved spatial data models (Ripple and Ulshoefer, 1987).

One of the most generally observed shortcomings of efforts to date has been the lack of concern shown for the process of knowledge acquisition. Many systems appear to have relied on the cartographic and geographic knowledge resident in journals and textbooks, thus avoiding the time, effort, and expense of extracting knowledge from human cartographers, survey engineers, geographers, or regional scientists. Some systems have begun to develop a capacity for primitive learning. Examples are the learning procedures found in KBGIS-II (Smith *et al.*, in press), KBGIS (Glick *et al.*, 1985), and the man-machine interactions of SRAS (Robinson and Wong, 1987). We suggest that further improvement in systems is dependent upon a more systematic, rigorous treatment of the process of acquiring spatial knowledge.

As the issue of knowledge acquisition is looked at more closely, the idea of a community of experts, as suggested by Bobrow *et al.* (1986), will gain acceptance. Only recently, in the work of Robinson and Wong (1987), has the issue of multiperson concept formation been approached explicitly within the context of automated knowledge acquisition. Thus, distributed knowledge and multiperson knowledge must become part of tomorrow's expert GIS if they are to function within a multiperson, organizational context.

Our review of ES efforts related to GIS indicates that there is an implicit assumption that geographic knowledge is static. Not only are geographic facts dynamic, but the rules can change as well, especially those that may be organization-dependent. It is, therefore, significant that Morse (1987) reports the assignment of a person to maintain the knowledge-base of the ASPENEX system. As expert systems become more common in operational settings, questions of knowledge maintenance and temporal logic will increase substantially. Methods will need to be developed to maintain logical consistency in an expert system dealing with a combination of spatial and nonspatial knowledge having differing types and degrees of uncertainty.

Fisher and Mackaness (1987) place great emphasis on the self-knowledge aspect of cartographic expert systems. They rightly note that methods of assessing decisions regarding competing cartographic designs have yet to be formalized. Although Fisher and Mackaness (1987) restrict their discussion to cartographic expert systems, we feel the same concern for formalizing knowledge needs to receive substantial emphasis in geographic information systems.

One of the byproducts of research on knowledge formalization is a concern with the formalization of uncertainty (Lesmo *et al.*, 1985). It is clear that, as progress is made in expert system development, the importance of managing uncertainty will increase (see Robinson, 1987b).

Smaller prototypes that are based on a proper method of expert system development using formal semantics will not only bring practical results but, more importantly, will explore geographical knowledge. Lessons learned in building these smaller systems will, in turn, be transportable to later more advanced systems. We suggest that expert systems for geographic information system applications might presently be built, but that it is advisable to build prototype expert systems. We encourage development of several prototypes addressing the same problem domains, but using different methods, so that we can begin to conduct comparative analyses.

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Today, Terra-Mar is an aggressive, rapidly expanding high-technology computer hardware and software company headquartered in the heart of Silicon Valley. This location provides Terra-Mar's staff instant access to other organizations who are also at the leading edge of technology development and particularly to those technologies upon which Terra-Mar's computer products and related consulting services are based.

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