RESEARCH REVIEW

Application of Expert Systems in the Sciences[1]

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ABSTRACT. **Studies from the field of artificial intelligence have given birth to a relatively new but rapidly growing technology known as expert systems. An expert system is a computer program which captures the knowledge of a human expert on a given problem, and uses this knowledge to solve problems in a fashion similar to the expert. The system can assist the expert during problem-solving, or act in the place of the expert in those situations where the expertise is lacking. Expert systems have been developed in such diverse areas as science, engineering, business, and medicine. In these areas, they have increased the quality, efficiency, and competitive leverage of the organizations employing the technology. During the 1980s, scientists and engineers have used this technology to search for oil, diagnose medical problems, and explore space. This paper provides an overview of this technology, highlights the major characteristics of expert systems, and reviews several systems developed for application in the area of science.**

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INTRODUCTION

Expert system technology has captured the interest of professionals in a number of fields in recent years. Systems have been developed in such diverse areas as science, engineering, business, and medicine. Almost every professional and computer society currently has a special interest group for expert systems technology. This widespread interest can be attributed to the ability of the expert system to aid various organizations in solving practical, real-world problems. Currently, over two-thirds of the Fortune 1000 companies have expert system projects under development (Medsker et al. 1987). Organizations are looking toward these systems to aid them in increasing the quality, efficiency, and competitive leverage of their operations.

During the 1980s, expert systems have been used in a wide range of applications in the area of science. Scientific and technology-oriented organizations have applied expert systems underground to find oil or mineral deposits (Duda et al. 1977), in space to help control various spacecrafts (Durkin and Tallo 1989), and on earth to help in diagnosing medical problems (Shortliffe 1976). Expert systems can aid scientists by interpreting data from an experiment, interact with a physician to identify a given disease, or aid an engineer in controlling a particular process.

This paper provides an overview of this technology, highlights the major characteristics of expert systems, and reviews several systems developed for application in the area of science. The paper also includes a short bibliography on expert systems for the interested reader to explore further.

EXPERT SYSTEM DEFINITION

Expert systems are an offspring of the more general area of study known as *artificial intelligence* (AI). In the simplest sense, AI is the study of developing computer programs which exhibit human-like intelligence. Early AI researchers focused on such problems as game theory, robotic control, and vision systems (Nilsson 1980). Common to each of these problems was research into ways of representing and reasoning with knowledge, in a computer, in a fashion similar to humans.

The early studies in AI provided the insight needed to develop expert systems. In particular, these studies showed that reasoning alone is not a sufficient measurement of intelligent behavior, but rather, one had to have a rich set of knowledge with which to reason. It was also determined that the problem needed to be well-focused, using only the knowledge relevant to a specific problem. These two requirements led AI researchers to use human experts for their source of problem-solving knowledge. By virtue of being an expert, the human possesses unique talents, made possible by the human's knowledge and problem-solving skills on a particular subject. Because of the nature of these intelligent computer programs, they were aptly called *expert systems* (Feigenbaum 1977). An expert system is a computer program designed to model the problem-solving ability of a human expert.

The program models the following characteristics of the human expert:

- Knowledge
- Reasoning
- Conclusions
- Explanations

The expert system models the knowledge of the human expert, both in terms of content and structure. Reasoning is modeled by using procedures and control structures which process the knowledge in a manner similar to the expert. Conclusions given by the system must be consistent with the findings of the human expert. The expert system also provides explanations similar to the human expert. The system can explain "why" various questions are being asked, and "how" a given conclusion was obtained.

One of the principal attractions of expert systems is that they enable computers to assist humans in many fields of

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endeavor with the processes of analyzing and solving complex problems. They extend the application of computers beyond the conventional mathematical processes we have customarily assigned computers, to applications where the computer can carry on a somewhat natural conversation with the user to arrive at a conclusion or recommendation that aids the human decision-maker. This is accomplished by encoding in the expert system the knowledge and problem-solving skills of a human expert. This expert computer program can then be used by others to obtain and use this expertise for solving a current problem that would have previously required the expert to be present.

EXPERT SYSTEM STRUCTURE

The structure and operation of an expert system are modeled after the human expert. Experts use their knowledge about a given domain coupled with specific information about the current problem to arrive at a solution. For example, a physician would possess knowledge about a variety of possible diseases and, coupled with specific information about a given patient, would be able to diagnose the patient's problem.

Expert systems solve problems using a process which is very similar to the methods used by the human expert (see Fig. 1).

Knowledge Base

The *knowledge base* contains specialized knowledge on a given subject that makes the human a true expert on the subject. This knowledge is obtained from the human expert and encoded in the knowledge base using one of several knowledge representation techniques. One of the most common techniques used today for representing the knowledge in an expert system is rules.

A rule is an IF/THEN type structure which relates some known information contained in the IF part to other information. This information can then be concluded to be contained in the THEN part. For example,

RULE 1	RULE 2
IF Battery is dead	IF Battery voltage is below 10 volts
THEN Car will not start	THEN Battery is dead

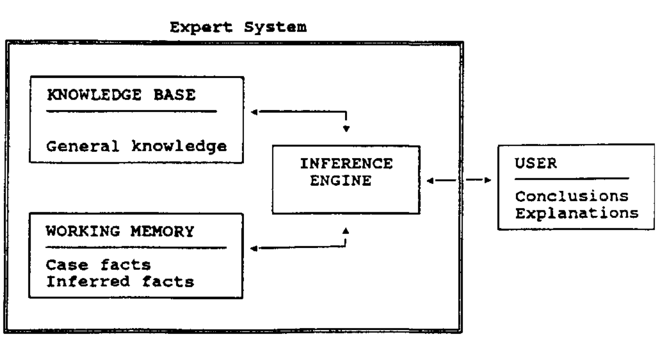

FIGURE 1. Expert system structure.

These two rules capture knowledge which represents natural relationships for automobile diagnostics. The first rule relates the status of the battery to the status of the car. The second rule relates the state of the battery to its status. Using rules like these, one can form a complete knowledge base for diagnosing problems with an automobile.

Representing knowledge in rules has two major advantages. First, each rule is a separate declarative statement about the problem, allowing one to add rules to the system as needed. Secondly, rules appear to match the way many experts formulate their knowledge about a problem in a natural "cause and effect" manner. Other knowledge representation techniques used are frames, semantic networks, and predicate calculus (Barr and Feigenbaum 1981).

Working Memory

Specific information on a current problem is represented as case facts and entered in the expert system's *working memory.* The working memory contains both the facts entered by the user from questions asked by the expert system, and facts inferred by the system. The working memory could also acquire information from databases, spreadsheets, or sensors, and be used by the expert system to conclude additional information about the problem by using the general knowledge contained in the knowledge base.

Inference Engine

The analogy of human reasoning is performed in the expert system with the *inference engine.* The role of the inference engine is to work with the available information contained in the working memory and the general knowledge contained in the knowledge base to derive new information about the problem. This process is similar to the way a human reasons with available information to arrive at a conclusion.

Two principle inference techniques are employed in the design of an expert system. The first technique relies upon first establishing a goal or hypothesis, and then attempting to prove it true. For example, a technician believes a particular fault exists, then collects data to verify this hypothesis. This style of reasoning is known as *backward chaining.*

The second style of inference first collects information about the problem and then attempts to infer other information. For example, a control process engineer gathers data from senors monitoring some process, and then uses this information to conclude the present status of the process. This style of reasoning is known as *forward chaining.*

Backward and forward chaining may be integrated to solve a given problem. For example, a physician may initially gather information about a patient and use this information to form a hypothesis of the possible disease. This hypothesis would then be checked by gathering additional evidence to support the belief. Both techniques may also be challenged by a situation where the information is inexact or unknown. In this situation, the inference technique must have the ability of continuing its reasoning under the constraint of incomplete information. Inexact reasoning techniques for expert systems are discussed further in the reports that are cited.

The inference engine, working either in the backward or forward chaining mode, will attempt to conclude new information about the problem from available information until some goal is reached or the problem is solved.

Explanation Facility

Besides providing final results or conclusions, both human experts and expert systems can explain *how* they arrived at their results. This capability is often important because the types of problems to which expert systems are applied require that a justification of the results be provided to the user. For example, an expert system which recommends some antibiotic treatment for a patient would need to explain to the physician how this recommendation was formulated.

Expert systems also have the capability of explaining *why* a given question is being asked. When an individual consults with a human expert, the conversation is highly interactive, and on occasion, the individual may ask why a certain line of reasoning is being pursued. The explanation given can make the user feel more comfortable with the line of questioning and also help to clarify what issues the expert believes are important for the problem.

CONVENTIONAL PROGRAMS VERSUS EXPERT SYSTEMS

It is important to understand and appreciate the differences between conventional computer programs and knowledge processing or expert systems. Knowledge processing represents an evolution, rather than a revolution, in the way individuals and computers interact to solve problems.

The most basic difference between the two is that conventional programs process data, while expert systems process knowledge. This basic difference influences both the nature of the processing technique used and the results obtained. The general differences between expert systems and conventional programs are characterized in Table 1.

Conventional programs process data which is usually in numeric form, while an expert system works with symbolic information. Data are isolated bits of information about a problem, whereas symbolic information represents statements or facts concerning the problem which can be used with general knowledge to infer new information.

TABLE 1

Expert system versus conventional programs.

Conventional Programs	Expert Systems
Numeric	Symbolic
Algorithmic	Heuristic
Precise information	Uncertain information
Command interface	Natural dialogue with explanations
Final solution given	Recommendation with explanation
Optimal solution	Acceptable solution

Conventional programs process data by means of algorithms, whereas an expert system will use heuristic reasoning techniques. An algorithm represents a finite set of well-defined steps to be performed. Heuristic reasoning works with the available information to draw conclusions about the problem, but does not follow a prescribed sequence of steps.

A conventional program requires complete and precise information. An expert system can work with the available information whether it is incomplete or uncertain. In this sense, an expert system can provide some results even under the constraints of limited or uncertain information. A conventional program would be severely limited under such constraints.

The interface of an expert system permits questions to be asked and answers given using a natural language style. This interface is more readily accepted by end-users than the command interface found with most conventional programs. Interaction with an expert system also follows more closely the conversation between one human obtaining advice from another human.

During the conversation, explanations are provided by the expert to queries as to "why" a question is being asked, and "how" a given conclusion was reached. This point makes an expert system considerably unlike a conventional program, which simply provides a final answer.

Conventional programs provide a final solution usually in the form of a result from a computation. The computation may have involved a complex series of tasks, but the user will only see the final result and not the intermediate steps that led to the final result. Expert systems provide a result in the form of a recommendation, with a justification in the form of a tracing of its reasoning.

Given the correct information, conventional programs will provide an exact solution to a problem. It is an "all or nothing" situation. Expert systems can make mistakes, just as a human expert might. This point appears to give the conventional program an advantage over the expert system. However, this appearance is only an illusion. Expert systems work on types of problems which are less structured than conventional programs, and the information available may not be sufficient to obtain an exact solution. However, the expert system will still be able to reach some reasonable conclusion, even if it is not optimal, whereas a conventional program will fail if not provided with all of the information it needs. This ability of an expert system to be able to make decisions in the absence of complete or certain information is the result of developments in the area of *inexact reasoning*.

INEXACT REASONING

A number of inexact reasoning techniques have been developed with three principle ones adopted by expert system developers: Bayesian, Certainty Theory, and Fuzzy Logic.

The Bayesian approach is based in classical probability theory where data is gathered about the problem, and can then be used for forming probability statements. This approach offers a sound mathematical basis for drawing inexact inference. However, the approach requires the gathering of data about all possible events of the problem, a situation which may not be possible or practical for all problems. One of the most noted expert systems developed using a Bayesian approach for inexact reasoning is PROSPECTOR (Duda et al. 1977), a system designed for mineral exploration.

Certainty theory is a product of the work performed during the development of MYCIN (Shortliffe 1976). Certainty theory is an ad-hoc approach to inexact reasoning which captures uncertain information and inference in a number called the *certainty factor* (CF). If a statement would be provided such as; "I *may* go to the game today," then this fact would be represented in the system with a CF value of 0.7, which quantifies the qualitative word *may*. This numeric representation of the uncertainty in this fact can be used by the expert system to form uncertain inferences.

Certainty theory does not have the formal mathematical basis such as Bayesian theory, but allows for inexact reasoning for those problems which lack a wealth of prior data. This approach to inexact reasoning is also the most common found in expert systems today.

Fuzzy logic (Zadeh 1964) provides an approach to inexact reasoning for subjective or vague terms used in our natural language such as: *little; hot;* or *heavy*. In many problems, an expert will use these vague terms to describe some issue; fuzzy logic then provides the methods for both capturing and reasoning with them numerically. Like certainty theory, fuzzy logic lacks the formal basis of Bayesian theory; but, expert system developers have found this inexact reasoning approach to be valuable in a number of applications. Giarratano and Riley (1989) provides a detailed discussion of these three and other approaches to inexact reasoning.

INTEGRATING EXPERT SYSTEMS WITH CONVENTIONAL PROGRAMS

In an earlier section, the major differences between conventional programs and expert systems was discussed. However, though the two play different roles, in many applications the two are combined to effectively solve a problem. This section discusses some of the major areas where expert systems are integrated with conventional programs.

Intelligent Database Management Systems

In database systems, records of information are maintained which are accessed by the user through the use of a menu or query interface. To effectively use the system, the user must have a clear understanding of *what* information is needed, *how* to obtain it, and *what* decisions can be made from the information obtained. These tasks require the user to make intelligent decisions and to understand the operation of the database interface.

An expert system acting as an intelligent interface, can accommodate the user by assuming the responsibility of accessing the information and forming decisions. The expert system can interact with the user to determine the information which would be of most value, access the information, analyze it in the context of the problem, and present its findings to the user. This capability provides ease of use of existing database systems, makes the information available to a larger number of people due to its ease of use, and improves the decision-making process in using the available information.

One system which integrated these two technologies successfully is called EP-X (Smith et al. 1985). This system was designed to aid a user in accessing information in the *Chemical Abstracts* database. Like most information retrieval systems, this database contains thousands of references, and the user needs to carefully filter through the vast amount of records to find relevant information. EP-X was found to be an effective interface in that it decreased the time to acquire the information and provided information which best met the needs of the user.

Intelligent database management systems provide the capability to access and use information for analysis and decision-making. This capability is not only accommodating to the user, but also allows the expert system to be embedded into existing database management systems.

Real-Time Control and Monitoring

Another area where the two programming techniques merge is in real-time control and monitoring applications. Any control or monitoring system requires the acquisition of data. This data may be coming in quickly from a number of sources, and the responsibility of the human or computer system is to form some understanding of the information and take the appropriate action. At Three Mile Island, for example, decisions needed to be made immediately to isolate the leak and on whether to evacuate the area. The problems associated with the large amount of information, and the time constraints to decide on the appropriate action, are taxing for not only humans but conventional computer programs.

Real-time expert system design offers an approach which can assimilate the information quickly and make human-like decisions. Several expert system development packages have been built which incorporate an expert system module with an interface to external conventional programs. Together they offer the capability of operating in real-time. ART by Inference Corp., and G2 by Gensym Corp., are the two packages which expert system designers have often turned to for real-time system development. For example, when NASA wanted a computer system which would integrate the vast amount of information they had gathered on the operation of the space shuttle in order to make navigational decisions, they turned to Inference Corp. Inference developed NAVEX (Marsh 1984), a real-time expert system which recommends control actions.

Intelligent Statistical Analysis

A number of statistical analysis programs exist with a wide range of applications; but, when inexperienced individuals use them, they often provide poor results.

Expert system interfaces to these programs can offer the user advice on how to best use them. The expert system can suggest what analysis should be done and how to interpret the results. Consequently, the intelligent interface can ease the use of the statistical package, enable the package to be used by a wider audience, and avoid most of the more common errors in their use.

One system which integrated an expert system interface with a standard statistical package was REX, developed at AT&T Bell Laboratories. REX aids in the use of a commercial regression analysis package called S. The purpose in developing REX was to increase the productivity in the use of S and increase the number of people who could effectively use the package. REX interacts with the user to obtain the data, interfaces with the regression program, checks all of the assumptions needed for regression analysis, and analyzes the results. If it finds something wrong, it determines how to correct the problem and produce a quality regression. AT&T found that REX eases the use of S and made it available to individuals who could not previously use the package.

This section discussed some of the more common applications where expert systems can be integrated with conventional programs. It provided insight into how an effective marriage can be formed between two technologies where each perform a function best-suited for their design. It also highlighted the fact that expert systems can be embedded into an existing environment to improve present productivity. Besides the applications discussed in this section, expert systems have also been successfully integrated with spreadsheets, hypertext, and CD-ROMS.

TYPES OF PROBLEMS SOLVED BY EXPERT SYSTEMS

There are several reasoning strategies used by humans during problem-solving. However, cognitive studies of human problem-solving has shown that humans will use different strategies for different types of problems (Hayes-Roth et al. 1983). For example, the diagnostic reasoning used when solving a problem with a carburetor is unlike the reasoning used for financial planning. Cognitive studies have also shown that reasoning strategies can be categorized to reflect common methods used by humans. The grouping of these common reasoning methods is referred to as *problem-solving paradigms*. That is, diagnostics is a problem-solving paradigm, and represents a style of reasoning which would be similar whether diagnosing a problem with an automobile or a television. Expert system designers characterize the different styles of reasoning into various paradigms (Table 2; adapted from Hayes-Roth et al. 1983).

Each paradigm represents a different style of reasoning about a given problem. For each paradigm, humans will collect information about the problem differently and will process this knowledge with the domain knowledge, using different methods. The results of a survey of a number of companies employing expert systems illustrate the percentage of applications of expert systems for each of these paradigms (Fig. 2), (SanGiovanni and Romans 1987).

The predominant type of problem addressed by expert systems is one of diagnostics. There are two major reasons for this, one based on the nature of the problem and the other based on the solution.

The majority of problems involving a human expert are diagnostic in nature. Experts diagnose problems with machines, manufacturing processes, or living systems. These and other types of diagnostic problems can be found in most organizations. The diagnostic knowledge needed to solve these problems can generally be captured in an expert system.

The second reason for the large percentage of total expert systems which are diagnostic can be traced to their relative ease of development. Most diagnostic problems have a finite list of possible solutions, and a limited

TABLE 2

Types of problems solved by expert systems.

Paradigm	Description
Control	Interpreting, prediction, repairing, and monitoring system behaviors
Design	Configuring objects under constraint
Diagnosis	Inferring system malfunctions from observables
Instruction	Diagnosing, debugging, and repairing student behavior
Interpretation	Inferring situation description from data
Monitoring	Comparing observations to plan vulnerabilities
Planning	Designing actions
Prediction	Inferring likely consequences of given situations
Prescription	Recommending solution to system malfunction
Selection	Identifying best choice from a list of possibilities

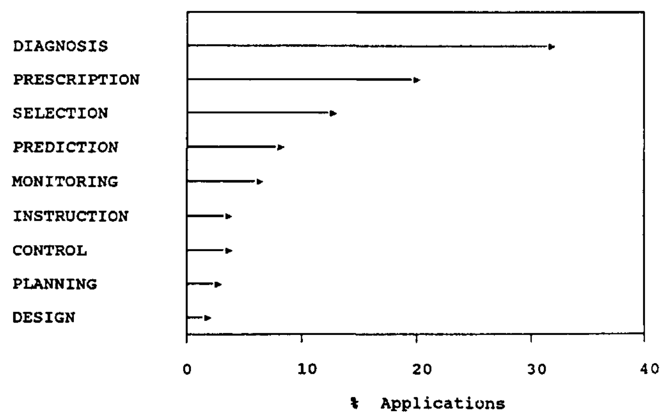

FIGURE 2. Expert system applications.

amount of information is needed to reach a solution. These bounds provide an environment which is conducive to effective system design.

Another explanation for the large percentage of diagnostic expert systems can be traced to the practical considerations of introducing a new technology into an organization. Most organizations prefer to take a low-risk position when considering new technology. As such, projects which require minimum resources and have maximum likelihood of success, are preferred. A well-focused diagnostic problem within an organization will usually meet these practical requirements.

There are far fewer applications in other areas such as planning or design (Fig. 2). The major reason for the relative absence of expert system applications in these areas can be traced to the nature of the problem. These areas are difficult to implement in an expert system because the knowledge and problem-solving approach used by the human expert are often difficult to capture.

Although various problem-solving paradigms can be shown as individual tasks (Fig. 2), for many real-world problems, a combination of paradigms is used. For example, a problem on control may involve the task of data *interpretation* and *diagnostic* reasoning, followed by *control* of the process.

WHY USE AN EXPERT SYSTEM?

Like any project venture, developing an expert system must have some justification. Insight for justifying an expert system can be gained when one compares an expert system with a human expert. From the comparison (Table 3), one can formulate several general reasons for employing an expert system such as:

- Replacement of human expert
- Assistant to human expert
- Transfer of expertise to novice

Using an expert system to replace a human expert is done primarily to use the system when the expert is not available. For example, through time constraints, the human expert may not be available, while an expert system designed to control some manufacturing process would be available 24 hours a day. Another expert system, containing the expertise of a unique expert within a company, could be made available to company sites located in other geographic areas. If the expert should leave or retire from the company, the expertise captured in the expert system could serve as a replacement for the expert. Human experts may be scarce, hence expensive. Expert systems, by contrast, may be inexpensive. Developing an expert system can be a costly venture, but the finished product would have low operating costs. The finished system can also be duplicated at low cost and distributed widely.

In the area of science, justifying an expert system for replacing a human can be found in such applications as space exploration (Durkin and Tallo 1989), or providing the expertise of a geophysicist to some remote oil exploration site (Elf-Aquitaine and Teknowledge 1983). Another example would be to replace the human operator of a control process.

Assisting a human expert is one of the most commonly found applications of expert systems. In this application, the expert system attempts to aid the human expert in a routine or mundane task. For example, a physician may have general knowledge of most diseases, but could use some additional support in diagnosing a given problem with a patient. In another example, a bank manager may be responsible for processing numerous loan applications, but could use help with some of the routine decisions made. In both applications, the human expert is fully capable of performing the task, but obtains additional support from the expert system. In this type of expert system application, the objective is to improve the overall productivity of the current practice.

TABLE 3

Comparison between a human expert and an expert system.

Factor	Human Expert	Expert System
Time availability	Workday	Always
Geographic availability	Local	Anywhere
Perishable	Yes	No
Consistent results	No	Yes
Cost	High	Affordable
Productivity	Variable	Consistent

One specialized application of an expert system which can be used to assist the expert is the ability of the expert system to learn about a specific problem. The most common learning method used in expert systems today is a technique known as induction (Quinlan 1979). The induction technique works with information contained in a set of examples to induce a set of rules which capture the knowledge about the problem. This approach has particular value for those problems where the expert lacks the knowledge to form decisions, but has a history of data on the problem. The induction technique can uncover classifications in the data which can be used for guiding the decision process.

The expertise held by a human expert is a valuable resource. Knowledge is gained by the expert through years of experience from working on the problem. In many organizations, it is important that this expertise not be lost, but transferred to others through training. An expert system can be developed to accomplish this training task.

EXPERT SYSTEM APPLICATION AREAS

The application of expert systems has been found to be of value in many disciplines. Applications of expert systems vary from aiding a laboratory technician in interpreting data, to providing guidance in establishing marketing direction to an executive of an organization.

This section will review the application of expert systems in various areas of science. Several applications in each area will be highlighted and a number of references of expert system applications for each area will be given.

Agriculture

In the area of agriculture, expert systems have been applied to such problems as crop management, insect control, and productivity considerations for raising a given crop. Farmers and agents from the Department of Agriculture Research Services must make decisions concerning the effective and profitable production of various crops. Expertise for making these decisions exists, but the major problem is making this talent available to the large number of farmers.

PLANT (Boulanger 1983) predicts the damage to corn caused by the invasion of black cutworms. The system first obtains information on the current field situation, including such information as the concentration of weeds, soil condition, and corn variety being grown. This information, coupled with black worm simulation programs, is used to predict the expected level of damage from this pest.

COMAX (Baker and Lemmon 1985) incorporates the knowledge of a model of cotton production to provide advice on the growing and management of this crop. The expert system uses the cotton model to predict crop growth and yield in response to weather conditions, soil variables, and pest damage. COMAX is capable of providing recommendations for management decisions on a daily basis to maximize cotton yields.

CROPPRO (Durkin and Godine 1989) was developed to aid farmers in four major areas of crop production such as: crop management problems, pest control, financial considerations, and tutoring on various crop topics. The system is structured to be applicable for most crops by addressing common problem areas. Hypertext and interactive graphics are used extensively, which serve to enhance the system's interface and effectiveness. The Shiitake mushroom was chosen as a test case for this expert system.

Chemistry

The majority of expert systems developed in the area of chemistry have been applied in a laboratory environment. The major advantage of these systems is the assistance they provide to the laboratory technician throughout a given experiment. They can assist in the planning and monitoring of the experiment, and in interpreting test data.

One of the first expert systems was developed by Stanford University upon request by NASA. NASA was planning to send an unmanned spacecraft to Mars, and wanted a computer program developed which would implement chemical analysis of the Martian soil. NASA would provide information on the soil in the form of mass spectrograms; and, from this information, the program would have to determine its molecular structure. To develop this program, the Stanford team had to encode in the program the expertise of a chemist with specialized skills in this area. The resulting program from this effort became known as DENDRAL (Buchanan and Feigenbaum 1978). DENDRAL is capable of inferring the molecular structure of an unknown compound from the mass spectrogram data.

SPEX (Iwasaki 1982) assists scientists in planning laboratory experiments in the area of molecular biology. The scientist defines and describes the various objects to be used in an experiment, such as the physical environment and the structure of the experiment. The system assists in developing a plan for achieving the goal of the experiment.

GA1 (Stefik 1978) determines possible DNA structures from restriction enzyme segmentation data. The system uses a model of enzyme digestion analysis of DNA structures, coupled with knowledge of possible errors in laboratory test environments, to formulate its result.

Computer Science

Expert system applications in the computer science area have been concerned with designing or diagnosing various computer systems. Configuring computer systems which meet customer defined specifications, or diagnosing faults in a given system, can be a difficult and time-consuming task.

XCON (McDermott 1980) was developed to configure VAX computer systems for Digital Equipment Corp. (DEC). Each of DEC's customers requires computer systems with certain characteristics and features, and has certain constraints associated with resources and available space. To accommodate these various characteristics and to make the configuration recommendation problem more efficient, DEC attempted to develop a conventional computer program to help with the configuration task. Unable to find a satisfactory solution, XCON (originally called R1) was, therefore, developed and presently saves DEC a reported $20 million a year.

DART (Bennett and Hollander 1981) diagnoses faults in the hardware of computer systems. The system incorporates knowledge of the structure and expected behavior of a system in order to find design flaws in new computer systems.

YES (Griesmer et al. 1984) assists computer operators in controlling the MVS operating system used in large mainframe IBM computers. This expert system monitors the operating system, interprets MVS messages, and makes recommendations to the console operator for system control. The major tasks of YES are: maintaining adequate queue space, handling network communications, scheduling batch jobs, responding to system errors, and responding to system hardware errors.

Engineering

Expert systems have been used in a wide range of applications in the area of engineering. Design, diagnostics, and control appear to dominate these applications. Expert system applications in this area can either assist an engineer in a task or replace the human operator of a control process.

PEACE (Dincbas 1980) is an expert system developed to assist engineers in the design of electronic circuits. The system is a CAD tool which performs both synthesis and analysis of passive and digital circuits. The system uses knowledge on the functional description of the basic circuit components, coupled with topological structural constraints. The system can synthesize the circuit in defined steps which fulfills the design specification under the problem constraints.

DELTA (Marcus and Steven 1983) aids maintenance personnel in the identification and correction of faults in diesel electric locomotives. The system interacts with the user during the diagnosis process while presenting computer-aided drawings of parts, subsystems, and repair sequences, using videodisc movies. Through this interaction, a final recommendation is made in the form of a sequence of repair steps.

The Smidth Cement Kiln Controller (Zadeh 1984) uses "fuzzy logic" to control the production of cement. The system determines the needed adjustments in air flow, gas fuel, raw materials, and rotation speed of the kiln, to achieve an economical operation of the process. The fuzzy logic approach allows the system to work with uncertain control knowledge, which models the approach taken by the human operator.

Geology

The dominant use of expert systems in the area of geology has been applied to the problem of exploration. Expert systems can aid a geophysicist in the interpretation of survey data or act in their place for those situations where one is not available.

PROSPECTOR was an expert system developed at the Stanford Research Institute to aid geologists in the exploration of ore deposits (Duda et al. 1977). PROSPECTOR uses knowledge based on five different models which describe various mineral deposits. The system initially obtains information which characterizes a particular deposit of interest, including information on the geological environment, structural controls, and the types of minerals and rocks present or suspected at the site. This information is then compared with the models and the system notes any similarities, differences, and missing information. Then it assesses the potential presence of a given mineral deposit. In 1980, PROSPECTOR was field tested at a site near Mount Tolman, WA. The test resulted in the discovery of a $100 million molybdenum deposit. The dramatic success of PROSPECTOR inspired a number of other commercial expert systems which rely on some of the features used in PROSPECTOR.

DIPMETER (Davis et al. 1981) determines the subsurface geological structure of a given site by interpreting dipmeter logs. The system uses knowledge about dipmeter data and basic geology to uncover features in the data that aid in the identification of geological structures. This capability is of particular importance in oil or mineral exploration.

The French oil exploration company, Elf Aquitaine, maintains a number of oil wells and, like many oil companies, often experiences problems with the drill bits becoming stuck. It is not unusual for drilling-related expenses to exceed $100,000 per day, and shutdowns caused by drilling problems to last for several weeks, until an expert can be brought to the site. Because of the scarcity of experts in this field, Elf Aquitaine contracted with the California-based company, Teknowledge, to develop an expert system which would serve in the place of the human expert. This system was aptly called the DRILLING ADVISOR (Elf Aquitaine 1983). The system uses information about the geological formations at the site, conditions of the current problem, and historical information about other problems experienced in the past. The expert system then performs a diagnosis of the problem, produces a recommendation to correct the problem, and further provides advice for changes to current practices to avoid the problem in the future.

Medicine

The most prolific application of expert systems to date has been in the area of medicine. A possible reason for the extensive application in this area is that most medical applications have been diagnostic in nature, an area where expert systems are very effective. The expert system can assist a physician in diagnosing medical problems of a patient or help in the interpretation of medical test results.

MYCIN was developed to capture the knowledge of an expert on infectious blood diseases (Shortliffe 1976). This expert system captured the expertise of individuals on blood diseases to provide accurate and quick diagnosis of the present disease and the proper therapeutic recommendation. The system could also work with unknown or uncertain information which might be all that is available in an emergency, life-threatening situation. MYCIN was valuable not only for its ability to diagnose infectious blood diseases, but for the contributions it made to our understanding of introducing an expert system into the workplace. Much of the current usage of rule-based expert systems is based on the work of MYCIN.

VM (Fagan 1978) monitors a patient in an intensive care unit and controls the patient's treatments. The system characterizes the patient's state from sensory data, identifies any alarms, and suggests useful therapies. The system measures the patient's heart rate, blood pressure, and the status of operation of a mechanical ventilator that assists the patient's breathing. Working with this information, and coupled with information on the medical history of the patient, the system can then make the needed adjustments to the ventilator.

Space Technology

One of the most recent applications of expert systems has been in the area of space technology. Systems are now being built for diagnosing system problems, planning mission objectives, or controlling spacecraft functions.

ECESIS (Dickey and Toussaint 1984) controls the life support systems aboard a manned space station. After interpreting data from sensors, the system decides how to adjust the life support systems during the transition from shadow to sun.

NAVEX (Marsh 1984) monitors radar data that estimates the velocity and position of the space shuttle. The system detects any errors or predicts if a problem may occur. If an error is located, the system further recommends the appropriate actions.

SATPRO (Durkin 1989) is an expert system for autonomous diagnostics and reconfiguration of a communications satellite. The system models the normal operation of the satellite system and can detect deviations from normal behavior and respond by recommending the proper reconfiguration which will eliminate the fault and maintain proper operation.

SUMMARY

Expert systems technology is an emerging area of computer science which is finding applications in a number of diverse areas. Organizations are employing expert systems to capture the problem-solving skills of human experts to either assist the expert or use them in those situations where the expert is not available. This paper has provided a brief overview of this technology and has discussed its application in the area of science. Applications of expert systems in the sciences are expected to increase in the near future. The review of past systems developed in the various science disciplines should provide insight into the types of applications which can be expected.

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