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EXPERT SYSTEMS: Working Systems and the Research Literature

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Abstract:

Many expert systems have moved out of development laboratories into field test and routine use. About sixty such systems are listed. Academic research laboratories are contributing manpower to fuel the commercial development of AI. But the quantity of AI research may decline as a result unless the applied systems are experimented with and analyzed.

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WORKING SYSTEMS AND THE RESEARCH LITERATURE

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1. INTRODUCTION

According to the popular press, expert systems can do everything. But responsible developers know differently. Although the *possibilities* for AI programs arc limitless. and the *actual* working applications arc more and more numerous, we have much work to do in order to learn from the applications of AI already in place, so that more comprehensive applications can be delivered. Unfortunately, very few of the applications will tell us much about AI.

There are now four areas of application of Al that have commercial significance: robotics (i.e., both vision and manipulation), natural language understanding, automatic programming, and expert systems. This paper concentrates on expert systems. although all four areas share characteristics of all symbolic reasoning systems. with similar overall value of applications.

There is no single definition of an expert system. and thus no precisely defined set of programs or set of literature references that represent work on expert systems. Nevertheless, I have attempted to put together such lists in an effort to further research and technology transfer.

The major dimensions along which I have defined expert systems [48] are the following:

1. AI METHODOLOGY -- Expert systems are AI programs. That is. they are programs that reason with symbolic information and use heuristic (non-algorithmic) inference procedures.

2. HIGH PERFORMANCE -- Expert-level performance is what the designers are attempting to achieve, but this, too. is not always well defined. In narrow problem areas, it is possible to construct systems that reason as well as the specialists in those areas. In some areas, it is beneficial to construct systems that solve only a fraction of the problems that an expert can solve -- but solve them correctly -- if, for instance, those systems can free an expert's time for the more difficult problems.

3. FLEXIBILITY -- AI programs, generally, are more flexibly designed than algorithmic programs, partly because they have to be in order to allow modification as problems become better defined. In addition to the flexibility needed at design time. it is desirable for expert systems to exhibit flexibility at run time. In particular, the more tolerant they xc of unanticipated input, new contexts of application, and different kinds of users. the more "expert" they would seem to be.

4. UNDERSTANDABILITY -- Just as an expert can explain his/her reasoning[1], an expert system should be able to explain its line of reasoning and the contents of its knowledge base. This, too. is important both at development time, for debugging, and at run time. for accepting the reasonableness of the system's conclusions.

One of the key elements of an expert system that makes possible this degree of flexibility and understandability is the separation of the knowledge base from the inference engine. This has become the fundamental organizing principle of all successful work on expert systems. McCarthy[2] noted years ago that a straightforward, modular, declarative representation of knowledge was a prerequisite for a system that could be told new facts and relations. Because AI systems are often used to help define ill-structured problems. they arc constructed incrementally. Thus representing the knowledge base in a form outside of the main body of code will make it easier to modifv and explain.

A significant development in research on expert systems was the introduction of framework systems that provide an inference engine and syntax for knowledge but contain no problem-specific knowledge themselves. EMYCIN was designed and written in the mid-1970's by van Melle [341] as a test of our claim at Stanford that MYCIN's inference engine was completely independent of the knowledge base. He developed generalizations of the tools in MYCIN. and developed new tools. that made EMYCIN a useful environment for building and interpreting knowledge bases for new problem areas. It is not a framework for building every kind of expert system. On the contrary, its utility is limited to a class of problems like MYCIN's: selecting plausible answers to a problem from a fixed set of alternatives by gathering and weighing evidence for the alternatives. By fixing the representation of knowledge and the modes of inference. however, framework systems allow builders of expert systems to start from a substantial base of programs and to concentrate on formulating the contents on the knowledge bases without having to design new data structures and programs that manipulate them.

By now, several other framework systems have been built and used in both research and commercial settings [148]. They offer considerable power for experimentation in AI because these systems can be held constant over several problem areas, or most of the system can be held constant while one part varies. The commercially available framework systems (see [141]) are built on the same principles. frequently merging

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[1]Plato, in the *Theaetetus*, distiguished a person's *knowing* something from merely *believing* it by the ability to explain the underlying reasons for a belief. Similarly, it seems odd to say that a person has expertise in a reasoning task if he/she cannot explain the line of reasoning. S. Savory points out [298] that Virgil also refers to understandability in his phrase "Felix qui potuit rerum cognoscere causas." which might be translated as "Happy is he who has been able to learn the causes of things"

[2]"Programs with Common Sense," *Proceedings of the Symposium on the Mechanisation of Thought Processes, 1958*, pp. 77-84. Also reprinted in *Semantic Information Processing*, M. Minsky, Ed., MIT Press. 1968.

ideas from several paradigms in a single hybrid system. The existence of these commercial tools -- and. more importantly, of expert systems using these tools -- marks the transition of AI from a purely academic discipline to a commercially important set of products.

2. EXPERT SYSTEMS IN ROUTINE USE OR FIELD TESTING

Depending on which speakers you believe it has been suggested that only *one* expert system, at most, is "really" working (namely R1) or that there arc *hundreds* of operational systems. Because the instituitions developing systems are slow to publish, and there is so much marketing "hype" surrounding AI, it is difficult to separate fact from fiction. And there is some fiction. However, in many meetings over the last year expert systems were discussed that have been moved out of a laboratory development environment into field test. and some out of field test into routine use. The list below is the result of my having collected the names of several such systems, and having tried to follow up with additional verification of their status.

The list is based on information supplied largely by reliable sources among the developers. A few systems have been included based on strong and unambiguous claims in reputable journals. I have omitted other systems reported in the literature without a clear indication of status, unless I could talk with someone in authority who knew the status. A survey on AI in Engineering [315] resulted in a list of expert systems, most of which are still under development. Several journals, including Expert *Systems*, present reports on systems. but these. too. are largely early prototypes. Classified systems done for the U.S. government have been omitted also, because it is so difficult to determine their status.

This list is almost certainly incomplete. It is regrettable that published accounts of working systems do not always exist. I have attempted to supply as many references as possible or. when not available, the name of the person who furnished information about status. Additional classified and proprietary systems were mentioned by representatives at several companies. There are news stories of working systems in Japan which I was unable to follow up on. For these reasons, and because many systems are under development, the list is only a sample of what exists in late 1985, and presumably is much smaller than one we will be able to compile next year.

My criteria for including a system were that (a) it is based on AI principles. as described above, and (b) it runs. as well as I could determine. in a field-test or run-time environment outside the development laboratory. There may well be some systems on the list whose status I misinterpreted: unfortunately, time did not permit first-hand examination of these systems. Therefore this list is meant as evidence that there arc several expert systems out of the laboratory and in the hands of users.

AGRICULTURE

SITE	EXPERT SYSTEM AND DESCRIPTION	SOURCE
ICI	WHEAT COUNSELLOR Advise on control of disease in winter wheat crops	[96]
Virginia Polytechnic Inst.	POMME Advise farmers on management of apple orchards. including pest management. drought control. pesticide selection. treatment of winter injuries	[289]

CHEMISTRY

SITE	EXPERT SYSTEM AND DESCRIPTION	SOURCE
British Gas	Advise on appropriate herbicide for specific application	Tim Boyd. ICI. (Sydney)
Lawrence Liver-more Natl. Labs	TQMSTUNE Tune triple quadrupole mass spectrometer	Carla Wong. LLNL [94]
Molecular Design Ltd	DENDRAL (parts) Search chemical structure libraries for substructures	James Nourse. Mol. Design [42. 207]
Shell Institute (Kent England)	Screen new chemicals for herbicidal properties based on structure- activity relationships	Donald Michie, Turing Institute (Glasgow)
SUNY-Stonybrook	SYNCHEM Plan chemical synthesis steps	Herb Gelernter, SUNY [122]

COMPUTERS AND ELECTRONICS

SITE	EXPERT SYSTEM AND DESCRIPTION	SOURCE
DFC	XCON,XSEL,XSITE Configure VAX orders, Check orders for accuracy, Plan site layout	[214, 215] [251]
DEC	AI-SPEAR Diagnose failures in tape drives and suggest preventive actions	Neil Pundit, DEC (Hudson) [30]
DEC	CALLISTO Help manage resources for chip designers	Mark Fox, Carnegie Mellon
DEC	CDx Analyze VMS dump files after system crashes	Neil Pundit, DEC (Hudson)
DEC	DAS-LOGIC Assist circuit designers with logic design	John McDermott, Carnegie Group
DEC	NTC Troubleshoot problems related to Ethernet & DECnet networks	Neil Pundit, DEC (Hudson) [264]
Fairchild	PIES Diagnose problems on circuit fabrication line	Marty Tenenbaum, Schlumberger (Palo Alto)
GTE	COMPASS Analyze maintenance records for telephone switching system and suggest maintenance actions	Chuck Rich, MIT [134]
Hewlett-Packard	PHOTOLITHOGRAPHY ADVISOR Troubleshoot photolithography steps in circuit fabrication	[185, 66]
Hughes Electra-Optical & Data Systems	HI CLASS Sequence steps in pc board assembly	[344]
IBM	CSS Aid in planning relocation reinstallation & rearrangement of IBM mainframes	A. Way ne Elwood, IBM (San Jose)
IBM	PINE Guide people writing reports on analysis of software problems	A. Wayne Elwood, IBM (San Jose)
IBM	YES/MVS Monitor MVS operating system	Peter Hirsch, IBM (Palo Alto) [135, 142, 241]
I.C.L.	Configure Series 39 computers	Tim Boyd, ICL (Sydney)

COMPI JTERS AND ELECTRONICS. cont.

SITE	EXPERT SYSTEM AND DESCRIPTION	SOURCE
ITT (Germany)	Diagnose faults on printed circuit boards	Donald Michie, Turing Institute (Glasgow)
Lockheed	BDS Troubleshoot baseband distribution subsystem of communications hardware	Wait Perkins. Lockheed (Palo Alto)
Lockheed	DIG VOLTAGE TESTER Aid troubleshooting digital voltage sources in testing lab	Tom Laffey, Lockheed (Palo Alto)
NCR	OCEAN Check orders for computer systems, configure orders	Barry Plotkin, Teknowledge
Nixdorf	FAULTFINDER Diagnose failures in disk drives	[297]
N ixdorf	CONAD Check order entry and configure computer systems	[297]
S.W. Bell	ACE Troubleshoot telephone lines	[343, 229, 358]
Travelers Insurance	DIAG8100 Diagnose failures in DP equipment	Luther Weeks Travelers [336]

CONSUMER SERVICES

SITE	EXPERT SYSTEM AND DESCRIPTION	SOURCE
Infomart, Dallas	INFOMART ADVISOR Advise shoppers on computer purchases	John Alden, TI (Dallas)

EDUCATION

SITE	EXPERT SYSTEM AND DESCRIPTION	SOURCE
DEC	TVX Tutor users of VMS operating system	Neil Pundit DEC (Hudson) [31]
Lockheed (Sunnyvale)	DECGUIDE Tutor designers in design checking	Walt Perkins. Lockheed (Palo Alto)
XEROX, PARC	BUGGY Debug students* subtraction errors [field tested. now dormant]	Kurt Van Lehn. CMU [36, 49]

FINANCIAL

SITE	EXPERT SYSTEM AND DESCRIPTION	SOURCE
AIG [American International Group]	Advise & support commercial insurance underwriters (e.g. on risks)	Peter Hart. Syntelligence
First Financial Planning Systems [Travelers Ins.]	APEX System Aid professional financial planners manage clients' accounts	Randall Davis, MIT
St. Paul Insurance Co.	Assess a variety of commercial insurance risks	Peter Hart. Syntelligence

GEOLOGY

SITE	EXPERT SYSTEM AND DESCRIPTION	SOURCE
Elf-Aquitaine	SECOFOR Advise on drill-bit sticking problems in oil wells [training tool]	Barry Plotkin, Teknowledge [69]
NASA	GEOX Identify earth surface minerals from remotely sensed hyperspectral image data	Wun Chiou. Lockheed (Palo Alto) [58]
NL Indus.	MUDMAN Diagnose problems in composition of drilling mud during oil well drilling	John McDermott. CMU [169)
Schlumberger	DIPMETER ADVISOR Analyze oil well logging data	[311]

INFORMATION MANAGEMENT

SITE	EXPERT SYSTEM AND DESCRIPTION	SOURCE
EPA	EDDAS Advise on disclosure of confidential business information	[99]

MANUFACTURING & ENGINEERING

SITE	EXPERT SYSTEM AND DESCRIPTION	SOURCE
British Steel Corp. (Scunthorpe rod mill)	ICLX Aid technicians diagnose faults in rod milling process	[138]
Campbell Soups	Troubleshoot problems in soup cookers. anticipate failures	John Alden. TI (Dallas) [308]
Delco Products	ENGINE COOLING ADVISOR Diagnose causes of noise in automobile engine cooling system	Steve Dourson, Delco [86]
Delco Products	MOTOR BRUSH DESIGNER Construct design of brushes & springs for small elec. motors	Steve Dour-son. Delco [277]
DEC	ISA Schedule orders for manufacturing and delivery	Neil Pundit. DEC (Hudson) [254]
DEC	DISPATCHER Schedule dispatching of parts for robots	John McDermott. Carnegie Group
G E	CATS Diagnose problems in diesel-electric locomotive	Piero Bonissone, GE [326]
Hitachi	Control railroad train braking for accuracy and comfort	Edward Feigenbaum, Stanford
Kawasaki Steel (Mizushina Works)	Detect cracks in billets & direct grinding	Akira Miyajima, Kawasaki (Chiba, Japan)
Kawasaki S reel	STOWAGE PLANNER Develop cargo storage plans for warehouse	Akira Miyajima. Kawasaki (Chiba. Japan)
Westinghouse	VT Configure orders for new elevator systems	John McDermott, Sandra Marcus. CMU
Westinghouse	Nuclear fuel enhancement	Donald Michie. Turing Institute (Glasgow) [13]
Westinghouse	ISIS Schedule manufacturing steps in job shop	Mark Fox. CMU [108]
Xerox. Reprographics Business Group	PRIDE Create and analyze new designs for copiers	Sanjay Mittal. Xerox (PARC) [235]

MEDICINE

SITE	EXPERT SYSTEM AND DESCRIPTION	SOURCE
Helena Labs	Serum protein analysis	[354]
Pacific Medical Center	PUFF Interpret pulmonary function tests	[196]
St. Vincent's Hospital (Sydney)	Interpret thyroid hormone assays	[155]
Stanford Oncology Clinic	ONCOCIN Management of therapy for patients with cancer	E.H. Shortliffe [152, 180]

MILITARY[3]

SITE	EXPERT SYSTEM AND DESCRIPTION	SOURCE
U.S. Army	AALPS Plan optimal loading of equipment & cargo on aircraft	Chuck Rich, MIT [10]

SOFTWARE

SITE	EXPERT SYSTEM AND DESCRIPTION	SOURCE
Shell Petroleum	Intelligent front-end for complex software	Donald Michie, Turing Institute (Glasgow)

[3] Classified systems are not included here.

3. THE INTERDEPENDENCY OF AI APPLICATIONS & AI RESEARCH

The commercial goals of companies applying AI to their problems are decreasing cost and increasing quality of goods and services. However. the longer-range *scientific* goal of AI research is to understand how to build intelligent systems better and faster in the future. In a well-established discipline like physics or chemistry. it is possible to separate the applications from the research. A chemical engineering company applies known methods: a research laboratory looks for new ones. In AI and other young disciplines, on the other hand. there are mitigating circumstances that make progress dependent on closer collaboration between applications and research.

First, in AI there is still a small *supply* of experienced researchers in AI. Thirty years ago there were a dozen or so persons working in AI and defining the field. Ten years ago there were a couple of hundred. mostly clustered in three university research labs: CMU. MIT, and Stanford. In the first year after the AAAI was formed in 1979 -- six years ago -- the membership in AAAI was about 400. That is. the supply of persons with 5-10 years of experience in AI is very small. The annual rate of new PhD's in Computer Science has changed little over the last few years -- about 250 per year. Of these, perhaps 60-80 (roughly 1/4 to 1/3) are specialized to AI. So the annual increase in the supply of PhD-level researchers is also small.[4]

Second, as everyone in the AAAI knows, the ***demand*** for trained workers far outstrips the supply. There is intense competition for people who understand the principles of AI and can apply them in practice. That demand comes from three sources: universities, industrial and non-profit research labs. and the new applications industry.

Universities are starting new Computer Science departments with unfilled slots for AI faculty. And established CS departments are expanding their course offerings in AI. This is healthy, of course. because some of these faculty will start new research projects and will have a fraction of their time for research. It is necessary to increase the number of teachers if we expect an increase in the number of students (although some university administrators seem to believe otherwise). The disappointing part of the university picture, however. is that the faculty slots are unfilled. What is more. because of salaries. work loads, and the absence of a larger AI community around many schools, these schools will continue to have difficulty hiring AI faculty in the next several years.

Non-profit research laboratories have a distinguished history of producing good AI research. Places like RAND, Lincoln Labs. BBN, and SRI-International have fostered much of the work that is now being

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[4] If the growth of the AAAI is any indication, however, the situation should improve considerably within five years. In 1984 the total membership was 7200, including 1400 student memberships. In 1985 it was 9,935 members, including 743 student members.

developed commercially. Industrial research labs, like XEROX-PARC and (more recently) Schlumberger, are also places where the research spirit fosters excellent AI research. In the last few years, more and more positions have opened up in these laboratories. About 25 large (Fortune-500) companies posted recruiting notices at the 1984 AAAI meeting, for example. The only disappointing aspect of this is that the research positions have largely been filled by AI researchers from universities. As a result. there is nearly a steady state in the number of persons doing Al rcscarch, and a net loss in the number who are teaching.

By far, though, the largest demand for AI workers comes from the new industry growing up to develop and market AI software. This is as true in robotics and natural language applications as in expert systems. Overall, this is a healthy development for AI because it is creating many more jobs than the universities and research labs could offer. And the availability of employment certainly encourages bright. young people to enter the field in the first place.

But there is a possibility of killing the goose that lays the golden egg. as many have pointed out. The AI research community has effectively lost a number of good people as they are attracted to the commercial side of AI. This may slow down the research necessary to sustain the industry in its second 5-10-year period. Staffing for AI research is now in a period of instability.

This, then, is a fundamental problem in carrying out AI research. The applications community, however, can help alleviate it. The action item I am proposing to remedy this situation is to ***experiment with applications and publish the results.*** That is, use the applications already being built to make incremental progress in the research.

4. AI AS AN EXPERIMENTAL SCIENCE

The paradigm of successful, experimental research has six steps. Too many of us try to take shortcuts since all six are difficult and time-consuming. But if we're going to advance the state of the art by experimenting with applications programs, then we have to consider each application as applied research. That means following all six steps -- with many iterations and loops among them.

The six are:

1. ***Define the Task.*** Experimental research at its best is hypothesis testing. Given a well-framed hypothesis, determine the extent to which it is credible. This implies that the experimenter starts with a question and knows how to recognize an answer.

In AI, unfortunately, we see too many papers whose strongest claim is that the author set out to "investigate" some issue. These papers do not contain results because nothing was analyzed, no comparisons made, no measurements were taken. In short, this is useless research if future workers cannot determine what problem the investigator was trying to solve.

2. Implement and refine and prototype. The most credible demonstration that ideas in AI have power is with a running program. We have all seen numerous "proofs" of the right ways to empower computers with intelligence. But they lack the convincingness of a program that runs.

Unfortunately, an implementation of an idea provides only a demonstration that a new method is *sufficient* for solving a problem. We cannot show, through the implementation alone, that the method is *necessary* for the solution. Subsequent experimentation and analysis are necessary to make the demonstration of sufficiency more interesting.

3. Experiment with the system. There is not enough well-planned, controlled experimentation in AI. Yet experimentation is important to establish the robustness of a new method, its scope of applicability, its weaknesses as well as its strengths. For example, an empirical sensitivity analysis revealed the extent to which MYCIN's rules and reasoning methods did not depend on precise values of certainty factors [47]. Other studies have tested AI programs against new problems to determine where and why they fail. Others have systematically varied methods used in a program to compare relative performance.

4. Analyze the issues -- what are the design and implementation features that contribute to success? Which are redundant? Where are improvements needed? With a complex system like an AI program, data collection is easier than data analysis. It took a Kepler, if you recall, to interpret the data painstakingly collected by his professor, Tycho Brahe (a warning to the next generation of students). With an artificially constructed system, the designer is often in a much better position to analyze the results of experiments because the points of brittleness in the design are more easily known to the designer. It is undesirable and unscientific for us to accept the words of the designer uncritically: independent verification is important. As a practical matter, however, few large programs are ever examined or tested by others because of their complexity. This has to change.

5. Generalize. Some speculation about the generality of methods is desirable, especially if it is backed up by evidence. This becomes, in effect, a testable hypothesis that others can follow up on. In every science, progress results from advancing hypotheses and testing them. AI should be no different.

Early in the implementation of MYCIN, for example, we claimed that the inference method was sufficiently general to use with other medical or non-medical knowledge bases. Van Melle tested this hypothesis and, -after considerable work, made it true.

6. Publish -- what is the good idea? How can others use it*?.** The quality of publications in AI does not often reflect the high quality of the researchers. Communicating the results of an analysis is an essential part of science, yet far too many of our conference and journal papers seem to be ***descriptions of programs with no ***analysis*** and no results. McCarthy has described these publications as being of the form "LOOK MA, NO HANDS!" because they announce only that a program works. In order to contribute to AI research. a publication must be clear and must identify the reasons why an application is presumed to work well. or the reasons why it does not work better.

Out of the theoretical work in Al has grown a body of knowledge about such issues as rhc formal properties of search algorithms and extensions needed to our logical apparatus to deal with truth maintenance and non-monotonic reasoning. In our own terminology. this research falls under a model-driven or top-down research strategy. Some of the less charitable call it "development of solutions in search of problems," which is always a charge leveled at "pure" research.

The experimentalists in AI are looking at the same issues and have the same ultimate goals as the theoreticians: to understand the nature of intelligence well enough to build intelligent machines. The experimentalists' style is data-driven, or bottom-up, based on observed instances of problems and their solutions as coded in running programs. Whereas the theoreticians start with an issue that needs to be resolved -- like common sense reasoning -- the experimentalists start with a task whose solution requires some intelligence. There is naturally some hope that these will meet somewhere in the middle.

Applications have focused attention on some specific issues and have advanced methods to deal with them. For example, applications have contributed to research on reasoning strategies. explanation. knowledge acquisition, inexact reasoning, meta-level knowledge, causal reasoning, models of interaction, and validation. The primary reason for this is that an application is generally unforgiving of shortcuts and simplifying assumptions. Designing software for persons outside the research laboratory imposes a discipline on AI that it had not had to face in its early, formative years. And. in the process. it forces attention to some of the issues outside the traditional spheres of AI research: methods for symbolic inference and techniques for rtprcscnting symbolic knowledge.

The experiments in AI are often not well designed. however. and the results of the experiments are not easy to state crisply. But we are still able to learn from the applications we build. At the least. it should not require much effort to record ideas that failed and decisions to reimplement parts of an emerging system. Sensitivity analyzes can illuminate the sources of power in a system. Comparative studies can help us understand the relative strengths of different architectural choices. An example of this sort of analysis is the one of R1 [217] or of the Schlumberger Dipmeter Advisor [312]. In every case there is some extra effort required to perform experiments, analyze results, and publish. This cost, if shared among all developers, however, will help insure against the risk of depleting the pool of AI research talent.

5. ARE THESE SYSTEMS "REALLY" EXPERT?

It has been popular to arguc against thc very idca of artificial intelligence by claiming that even though AI programs appcar at timcs to bchave intclligcntly they arc not "really" intclligcnt. A variant of this argumcnt has surfaced with respcct to cxpcrt systems: that they only *appear* to behave cxpcrtly but arc not "rcally" expert. Use of thc tcrm "really" is slippcry, however. and hides the shifting critcria that arc cmploycd cvcry timc thc bchavior of thc programs improves. Thcrc is no rcason to take this criticism seriously.

Howcvcr, thrcc substantial criticisms of cxpcrt systems warrant brief discussion hcrc. Thcy arc that cxpcrt systems arc not going to pay off in the long run bccausc they lack three kinds of knowlcdgc:

1. successively deeper layers of knowledge of their task areas to use when thc shallow, compiled knowledge fails to reach a satisfactory answer,
2. common sense to avoid errors due to reading the expressions of knowledge too literally or due to incomplete coverage of possibilities within the explicitly stated knowledge base, and
3. knowledge about how to learn from experience.

Expert systems of the current generation do lack these three kinds of knowledge. but that is not to say that future systems will. Nor does that lead directly to the conclusion that today's systems arc not able to perform at the level of experts and contribute positively in well-defined contexts. Let us look at them separately.

1. Deeper Layers of Knowledge

Rule-based systems encourage encoding judgmental expertise. in the form of cmpirical associations, in the knowledge base to help expert systems reason about plausible solutions to problems. This is true also of frame-based systems, and it can be true of the associations in logic-based systems. In MYCIN, many of the rulcs are empirical associations that lack a sound theoretical justification, often because medical scientists have not yet discovered the thcory. Other rulcs are definitional. and thus encodc a part of the existing theory of medicine. Still other rules are theoretically based associations bctwccn causcs and effects, which skip thc underlying, "deeper" layers of knowledge that explain and justify the associations [61]. In this sense, a rulc may be "compiled" knowledge in that it accurately allows a system to rcason from A to B but has skipped over the intermediate steps that persons sometimes go through, or appeal to, to justify B in the context of A.

One serious manifestation of this problem appears in the explanations that expert systems currently give of their line of reasoning. While a person can explain a phenomenon at successively deeper layers of detail, current systems show the individual elements of the knowledge base used to draw a conclusion without showing the "decompiled" forms that would justify those elements. Another related manifestation appears in the context of tutoring. A student trying to learn the contents of an expert system's knowledge base needs deeper layers of structure to help tie the elements of the knowledge base together [47].

MYCIN's rules, as with most current rule-based systems, were written and refined with a specific task in mind -- diagnosis and therapy in MYCIN's case. The knowledge base is not generally useful for other tasks but is engineered tightly for a single purpose. This is another sense in which a set of rules constitutes compiled knowledge and is a strong argument for a more declarative representation of knowledge than a set of rules provides.

MYCIN would be admittedly more knowledgeable if it had more knowledge, in particular, knowledge of the physiological and biochemical processes that justify many of its rules. Its explanations and tutorial dialogues could be smarter, and the deeper layers could make it easier to build and maintain the knowledge base. But it would not necessarily perform its tasks of diagnosis and therapy better in the kind of constrained context in which systems are now being designed.

2. Common Sense

McCarthy [212] has argued that MYCIN, and other expert systems, are bound to behave poorly at times because they lack common sense. He describes an interchange in which MYCIN looks stupid to him because it fails to object to the possibility of amniocentesis for a male patient. Obviously, this could be remedied with the same kind of rule that prevents MYCIN from accepting the possibility of pregnancy for males. But McCarthy is pointing to a general fault that without common sense, there will always be failures of this simple kind. (People sometimes are misled when they fail to use their common sense -- so just ***having*** it is not enough.)

McCarthy's point is well taken: if expert systems know more, particularly if they have more relevant common sense, they will probably perform better. Current systems often exhibit the kind of brittleness that McCarthy points out because they make strong assumptions about the context in which they will be used, the types of users, the vocabulary, the "reasonableness" of other lines of reasoning, and so forth. They also tend to have rather sharp fall-off in performance at the boundaries of their knowledge. In common parlance, they "fall off knowledge cliffs" when we would expect an expert's performance to degrade gracefully at the boundaries of his or her knowledge.

But on the positive side. the context for which an expert system is designed to be used can limit the amount of common sense that is necessary in practice. For MYCIN, physicians using the system were assumed to have common sense enough not to tell MYCIN that a male patient has had amniocentesis -- or thousands of other things that would make MYCIN appear to be stupid. The users were assumed to want help enough to supply sensible information to MYCIN. Establishing a common framework between the system and its users is the responsibility of the design team, mostly of the expert. Without a shared vocabulary and shared assumptions, a system's recommendations may easily be misunderstood.

3. Learning From Experience

Expert systems currently do not improve their own behavior based on experience: does that mean they are not "really" expert? This is a definitional question on which one may take a dogmatic stand[5]. However, if we use a performance-based definition of expertise and not a dispositional one. then we may be less dogmatic and say that a person. or a program, is an expert by virtue of excellent performance, regardless of how he, she or it gained his/her/its knowledge in the first place (and kept it current). For example, some of us. anyway, would prefer to have a medical problem diagnosed by a physician with 20 years' experience who knows most of what is relevant for our problem -- even if he or she has stopped learning -- instead of having the problem diagnosed by a recent medical school graduate who knows only little of what is relevant but who is learning rapidly. When the knowledge curves of the two cross, if we could measure them, then we might change physicians.

6. CONCLUSIONS

Every limitation of an expert system presents opportunities for research. including the three areas of criticism listed above. One of the major benefits of focusing sharply on an application is that the limitations are difficult to ignore and proposed improvements have to pass the operational test of improving the performance of the expert system. Current AI research in many different areas can mean increased capabilities for expert systems. For example, research on qualitative reasoning could enhance the reasoning power of systems over their present capabilities. Also, current work on meta-level reasoning can give programs a better sense of knowing their own limitations -- a form of common sense knowledge.

As a result of research in the last decade, simple. rule-based systems are now straightforward to build. They can be important for helping people solve problems for which expertise is in short supply, or is not well distributed. or is not available around the clock. More complex problems will require more complex

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[5] As Schank did in the McNeil-Leherer TV interview and in [299].

knowledge structures and reasoning methods, and may require knowledge of a qualitatively different kind. The next decade should prove to be a time of trying and testing many new ideas for extending the capabilities of expert systems.

There is a shortage of research people, however, whose *charter* is to understand the hows and whys of successful (and unsuccessful) applications. That is why it is necessary for people who are building new applications to aid in the analysis and to publish the results.

We are in many ways in a position similar to that of business data processing 30 years ago. In the proceedings of a conference held at Harvard in 1955. there was a report on the first successful application of computers to a payroll system [303]. It was begun at General Electric in October. 1953 and by the time of the conference two years later was paying approximately 5.500 hourly employees working under many combinations of special-case conditions. The parallels with applications of expert systems are striking. I close with an extended quotation from that report:

> "Developing such a program for computer processing involves a tremendous amount of meticulous work -- far more than we realized in the beginning. What have been the results?
>
> 1. We proved that the job could be done.
>
> 2. We quickly found out that a number of revisions could and should be made to obtain greater efficiency and lower costs.
>
> 3. Cost savings, based on initial performances, would only approximate half of what our original studies predicted. Displacement of clerical personnel. however, appears to be reasonably close to original estimates.
>
> "If we had this to do over, I think we would again start with the same project. Despite the fact that it is probably one of the most complicated projects. payroll does permit displacement of the greatest number of clerical personnel and thus helps to defray expensive starting costs. Further, it has provided an excellent basis for accumulating a lot of good experience on how to use computers. ...
>
> What Have We Learned in This One Year
> of Practical Computer Experience?
>
> "1. The initial overenthusiasm. which inevitably accompanies a project of this scope. can and does make the job harder. Too many people had the impression that this was the answer to all problems. Perhaps it is. but we haven't been smart enough to develop all of them....
>
> "2. Some of our original thinking has been partly confirmed in that the greatest benefits to be derived from a computer will probably consist of information impossible to obtain previously....

"3. Our experience has shown that the computer is more adaptable to some projects than others....

"4. Programmers should be recruited within your own company.... It is easier to teach men the required computer and program techniques than to acquaint them properly with the complex procedures and routines of modern-day industry....

"5. I doubt if it is possible to overemphasize the desirability of providing for convenient corrections or deletion of errors in data....

"6. The maximum justifiable amount of flexibility for extending or integrating applications must be included in the initial programming.

"Albert Einstein once said, 'Concepts can only acquire content when they are connected, however indirectly, with sensible experience. But no logical investigation can reveal this connection, it can only be experienced.' Similarly, we feel that our down-to-earth operating experience has given form to our original concepts. Our experience has verified many of our original concepts of computer application....

"In conclusion, it is my humble opinion that computers are here to stay. We have got to increase our efforts toward understanding them and knowing how best to use [them]. Further, we have to do more experimenting with new fields that ultimately should utilize the equipment to a greater degree and thus return greater dividends."

Expert systems are also here to stay. They have their weaknesses, but careful problem selection and design, explicit definition of context, and additional research will alleviate them. Even with their limitations, they can be applied successfully. Finally, the successes will be all the stronger when the limitations are explicitly noted as opportunities for experimentation and greater understanding.

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8. AN EXTENDED BIBLIOGRAPHY OF EXPERT SYSTEMS

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