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EXPERT SYSTEMS: ARTIFICIAL INTELLIGENCE APPLIED*

William B. Gevarter

Abstract—This article provides an overview of expert systems, the topic of greatest current interest in Artificial Intelligence (AI). The article describes what an expert system is and sketches the mechanisms by which several of the better known systems operate. The prerequisites for constructing an expert system are given and the state of the art of current expert systems is indicated, with an extensive listing of these systems being provided. The article concludes with a forecast of the nature and applications of future expert systems.

1. INTRODUCTION

1984!

The most popular topic in Artificial Intelligence (AI) today is Expert Systems. Prior to the last decade, in trying to find solutions to problems, AI researchers tended to rely on non-knowledge-guided search techniques or computational logic. These techniques were successfully used to solve elementary problems or very well structured problems such as games. However, real complex problems are prone to have the characteristics that their search space tends to expand exponentially with the number of parameters involved. For such problems, these older techniques have generally proved to be too weak and a new approach was needed. This new approach emphasized knowledge rather than search and has led to the field of Knowledge Engineering and Expert Systems. The resultant expert systems technology, limited to academic laboratories in the 70's, is now becoming cost-effective and is beginning to appear in commercial applications.

2. WHAT IS AN EXPERT SYSTEM?

Feigenbaum, a pioneer in expert systems, states:[1]

An "expert system" is an intelligent computer program that uses knowledge and inference procedures to solve problems that are difficult enough to require significant human expertise for their solution. The knowledge necessary to perform at such a level, plus the inference procedures used, can be thought of as a model of the expertise of the best practitioners of the field.

The knowledge of an expert system consists of facts and heuristics. The "facts" constitute a body of information that is widely shared, publicly available, and generally agreed upon by experts in a field. The "heuristics" are mostly private, little-discussed rules of good judgement (rules of plausible reasoning, rules of good guessing) that characterize

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The author is now assigned to NASA Ames Research Center, Space Science Division, Moffett Field, Mt. View, CA 94035, U.S.A.

expert-level decision making in the field. The performance level of an expert system is primarily a function of the size and quality of the knowledge base that it possesses.

These days, it is common to characterize any large, complex AI system that uses large bodies of domain knowledge as an expert system. Thus, nearly all AI applications to real-world problems can be considered in this category, though the designation "knowledge-based systems" is more appropriate.

3. THE BASIC STRUCTURE OF AN EXPERT SYSTEM

An expert system consists of: Hechos Reglas

(1) a knowledge base (or knowledge source) of domain facts and heuristics associated with the problem;
(2) an inference procedure (or control structure) for utilizing the knowledge base in the solution of the problem;
(3) a working memory—"global data base"—for keeping track of the problem status, the input data for the particular problem, and the relevant history of what has thus far been done. ⇒ Explanation module

A human "domain expert" usually collaborates to help develop the knowledge base. Once the system has been developed, in addition to solving problems, it can also be used to help instruct others in developing their own expertise. → Educational usage

It is desirable, though still far from common, to have a user-friendly natural language interface to facilitate the use of the system in all three modes: development, problem solving, instruction. In some sophisticated systems, an explanation module is also included, allowing the user to challenge and examine the reasoning process underlying the system's answers. Figure 1 is a diagram of an idealized expert system. When the domain knowledge is stored as production rules, the knowledge base is often referred to as the "rule base," and the inference engine as the "rule interpreter."

An expert system differs from more conventional computer programs in several important respects. Duda[2] observes that, in an expert system ". . . there is a clear separation of general knowledge about the problem (the rules forming a knowledge base)

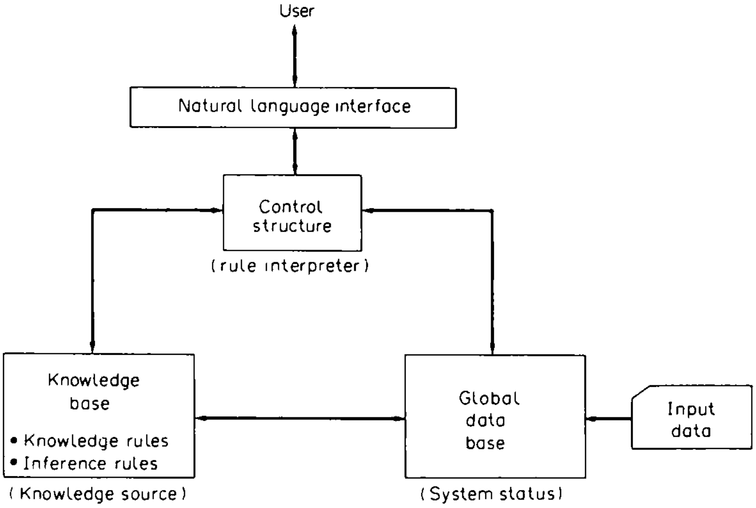

Figure 1. Basic structure of an expert system.

from information about the current problem (the input data) and the methods for applying the general knowledge to the problem (the rule interpreter)." In a conventional computer program, knowledge pertinent to the problem and methods for utilizing this knowledge are all intermixed, so that it is difficult to change the program. In an expert system, "... the program itself is only an interpreter (or general reasoning mechanism) and (ideally) the system can be changed by simply adding or subtracting rules in the knowledge base."

3.1. The knowledge base

The most popular approach to representing the domain knowledge (both facts and heuristics) needed for an expert system is by production rules (also referred to as "SITUATION–ACTION rules" or "IF–THEN rules").* Thus, often a knowledge base is made up mostly of rules which are invoked by pattern matching with features of the task environment as they currently appear in the global data base.

3.2. The control structure

Direction of Inference

In an expert system a problem-solving paradigm must be chosen to organize and control the steps taken to solve the problem. A common, but powerful approach involves the chaining of IF–THEN rules to form a line of reasoning. The rules are actuated by patterns (which, depending on the strategy, match either the IF or the THEN side of the rules) in the global data base. The application of the rule changes the system status and therefore the data base, enabling some rules and disabling others. The rule interpreter uses a control strategy for finding the enabled rules and for deciding which of the enabled rules to apply. The basic control strategies used may be top-down (goal driven), bottom-up (data driven), or a combination of the two using a relaxation-like convergence process to join these opposite lines of reasoning together at some intermediate point to yield a problem solution. However, virtually all the heuristic search and problem solving techniques that the AI community has devised have appeared in the various expert systems.

4. ARCHITECTURE OF EXPERT SYSTEMS

One way to classify expert systems is by function (e.g. diagnosis, planning, etc). However, examination of existing expert systems indicates that there is little commonality in detailed system architecture that can be detected from this classification. A more fruitful approach appears to be to look at problem complexity and problem structure and deduce what data and control structures might be appropriate to handle these factors.

The Knowledge Engineering community has evolved a number of techniques (presented in the excellent tutorial by Stefik *et al.*[3] and summarized in Gevarter[4]) which can be utilized in devising suitable expert system architectures.

The use of these techniques in four existing expert systems is illustrated in Table 1 (a–d). Table 1 (a–d) outlines the basic approach taken by each of these expert systems and shows how the approach translates into key elements of the Knowledge Base, Global Data Base

* Not all expert systems are rule-based. The network-based expert systems MACSYMA, INTERNIST/CADUCEUS, Digitalis Therapy Advisor, HARPY and PROSPECTOR are examples which are not. Buchanan and Duda[8] (1982) state that the basic requirements in the choice of an expert system knowledge representation scheme are extendibility, simplicity and explicitness. Thus, rule-based systems are particularly attractive.

Table 1. Characteristics of example expert systems

Table 1 (a).

Purpose	Approach	Knowledge base	Key elements of Global data base	Control structure
Generate plausible structural representations of organic molecules from mass spectrogram data	1. Derive constraints from the data 2. Generate candidate structures 3. Predict mass spectrographs for candidates 4. Compare with data	Rules for deriving constraints on molecular structure from experimental data Procedure for generating candidate structures to satisfy constraints Rules for predicting spectrographs from structures	Mass spectrogram data Constraints Candidate structures	Forward chaining Plan, generate and test

System: DENDRAL; Institution: Stanford University; Authors: Feigenbaum & Lederberg; Function: Data interpretation.

Table 1 (b).

Purpose	Approach	Knowledge base	Key elements of Global data base	Control structure
Discovery of mathematical concepts	Start with elementary ideas in set theory Search a space of possible conjectures that can be generated from these elementary ideas Choose the most interesting conjectures and pursue that line of reasoning	Elementary ideas in finite set theory Heuristics for generating new mathematical concepts by modifying and combining elementary ideas Heuristics of "interestingness" for discarding bad ideas	Plausible candidate concepts	Plan, generate, and test

System: AM; Institution: Stanford University; Author: Lenat; Function: Concept formation.

Table 1 (c).

Purpose	Approach	Knowledge base	Key elements of Global data base	Control structure
Configure VAX computer systems (from a customer's order of components).	Break problem up into the following ordered subtasks: 1. Correct mistakes in order 2. Put components into CPU cabinets 3. Put boxes into unibus cabinets and put components in boxes 4. Put panels in unibus cabinets 5. Lay out system on floor 6. Do the cabling Solve each subtask and move on to the next one in the fixed order	Properties of (roughly 500) VAX components Rules for determining when to move to next subtask based on system state Rules for carrying out subtasks (to extend partial configuration) (Approximately 1200 rules total)	Customer order Current task Partial configuration (System state)	"MATCH" (data driven) (no backtracking)

System: R1; Institution: CMU; Author: McDermott; Function: Design.

Table 1 (d).

Purpose	Approach	Knowledge base	Key elements of Global data base	Control structure
Diagnosis of bacterial infections and recommendations for antibiotic therapy	Represent expert judgmental reasoning as condition-conclusion rules together with the expert's "certainty" estimate for each rule Chain backwards from hypothesized diagnoses to see if the evidence supports it Exhaustively evaluate all hypotheses Match treatments to all diagnoses which have high certainty values	Rules linking patient data to infection hypotheses Rules for combining certainty factors Rules for treatment	Patient history and diagnostic tests Current hypothesis Status Conclusions reached thus far, and rule numbers justifying them	Backward chaining thru the rules Exhaustive search

System: MYCIN; Institution: Stanford University; Author: Shortliffe; Function: Diagnosis.

Table 2. Control structures of some well known expert systems

			Control structure																
			Search direction				Control								Search space transformations				
System	Function	Domain	Forward	Backward	Forward and backward	Event driven	Exhaustive search	Generate and test	Guessing	Relevant backtracking	Least commitment	Multilines of reasoning	Network editor	Beam search	Multiple models	Break into sub-problems	Hierarchical refinement	Hierarchical resolution	Meta rules
MYCIN	Diagnosis	Medicine		x			x												
DENDRAL	Data interpr.	Chemistry	x					x											
EL	Analysis	Elec. circuits	x						x	x									
GUIDON	C.A.I.	Medicine				x													
KAS	Knowl. acquis.	Geology	x										x						
META-DENDRAL	Learning	Chemistry	x					x											
AM	Concept formation	Math	x					x											
VM	Monitoring	Medicine				x	x												
GA1	Data interpr.	Chemistry	x					x											
R1	Design	Computers	x				x									x			
ABSTRIPS	Planning	Robots		x													x		
NOAH	Planning	Robots		x							x					x			
MOLGEN	Design	Genetics			x				x	x	x					x	x		x
SYN	Design	Elec. circuits	x												x				
HEARSAY II	Signal interpr.	Speech unders.			x						x	x						x	
HARPY	Signal interpr.	Speech unders.	x											x					
CRYSALIS	Data interpr.	Crystallography				x		x											x

and Control Structure. An indication of the basic control structures of the systems in Table 1 (a–d) and some of the other well known expert systems, are given in Table 2.

Table 2 represents expert system control structures in terms of the search direction, the control techniques utilized, and the search space transformations employed. The approaches used in the various expert systems are different implementations of two basic ideas for overcoming the combinatorial explosion associated with search in real complex problems. These two ideas are:

(1) Find ways to efficiently search a space.
(2) Find ways to transform a large search space into smaller manageable chunks that can be searched efficiently. ⟶ Main Problem of RETE algorithm.

It will be observed from Table 2 that there is little architectural commonality based either on function or domain of expertise. Instead, expert system design may best be considered as an art form, like custom home architecture, in which the chosen design can be implemented from the collection of available AI techniques in heuristic search and problem solving.

In addition to the techniques indicated in Table 2, also emerging are distributed knowledge and problem solver approaches exemplified by the MDX expert system (Chandrasekaran[5]) and the object-oriented programming language, LOOPS (Stefik *et al.*[6]).

5. EXISTING EXPERT SYSTEMS

The uses of expert systems are virtually limitless. They can be used to help: diagnose, repair, monitor, analyze, interpret, consult, plan, design, instruct, explain, learn, and conceptualize.

Table 3 is a list, classified by function and domain of use, of most of the existing major expert systems. It will be observed that there is a predominance of systems in the Medical and Chemistry domains following from the pioneering efforts at Stanford University. From the list, it is also apparent that Stanford University dominates in number of systems, followed by MIT, CMU, BBN and SRI, with several dozen scattered efforts elsewhere.

The list indicates that thus far the major areas of expert systems development have been in diagnosis, data analysis and interpretation, planning, computer-aided instruction, analysis, and automatic programming. However, the list also indicates that a number of pioneering expert systems already exist in quite a number of other functional areas. In addition, a substantial effort is under way to build expert systems as tools for constructing expert systems.

6. CONSTRUCTING AN EXPERT SYSTEM

Duda[2] states that to construct a successful expert system, the following prerequisites must be met:

There must be at least one human expert acknowledged to perform the task well.
The primary source of the expert's exceptional performance must be special knowledge, judgment, and experience.
The expert must be able to explain the special knowledge and experience and the methods used to apply them to particular problems.
The task must have a well-bounded domain of application.

Table 3. Existing expert systems by function

Function	Domain	System*	Institution
Diagnosis	Medicine	PIP	MIT
	Medicine	CASNET	Rutgers U.
	Medicine	INTERNIST/CADUCEUS	U. of Pittsburgh
	Medicine	MYCIN	Stanford U.
	Medicine	PUFF	Stanford U.
	Medicine	MDX	Ohio State U.
	Computer faults	DART	Stanford U./IBM
	Computer faults	IDT	DEC
	Nuclear reactor accidents	REACTOR	E G & C Idaho Inc.
Data analysis and interpretation	Geology	DIPMETER ADVISOR	M.I.T./Schlumberger
	Chemistry	DENDRAL	Stanford U.
	Chemistry	GA1	Stanford U.
	Geology	PROSPECTOR	SRI
	Protein crystallography	CRYSALIS	Stanford U.
	Determination of causal relationships in medicine	RX	Stanford U.
	Determination of causal relationships in medicine	ABEL	MIT
	Oil well logs	ELAS	AMOCO
Analysis	Electrical circuits	EL	MIT
	Symbolic mathematics	MACSYMA	MIT
	Mechanics problems	MECHO	Edinburgh
	Naval task force threat analysis	TECH	Rand/NOSC
	Earthquake damage assessment for structures	SPERIL	Purdue U.
	Digital circuits	CRITTER	Rutgers U.
Design	Computer system configurations	R1/XCON	CMU/DEC
	Circuit synthesis	SYN	MIT
	Chemical synthesis	SYNCHEM	SUNY Stonybrook
Planning	Chemical synthesis	SECHS	U. of Cal. Santa Cruz
	Robotics	NOAH	SRI
	Robotics	ABSTRIPS	SRI
	Planetary flybys	DEVISER	JPL
	Errand planning	OP-PLANNER	Rand
	Molecular genetics	MOLGEN	Stanford U.
	Mission planning	KNOBS	MITRE
	Job shop scheduling	ISIS-II	CMU
	Design of molecular genetics experiments	SPEX	Stanford U.

	Medical diagnosis	HODGKINS	MIT
	Naval aircraft ops	AIRPLAN	CMU
	Tactical targeting	TATR	RAND
Learning from experience	Chemistry	METADENDRAL	Stanford U.
	Heuristics	EURISKO	Stanford U.
Concept formation	Mathematics	AM	CMU
Signal interpretation	Speech understanding	HEARSAY II	CMU
	Speech understanding	HARPY	CMU
	Machine acoustics	SU/X	Stanford U.
	Ocean surveillance	HASP	System Controls Inc.
	Sensors on board naval vessels	STAMMER-2	NOSC, San Diego/SDC
	Medicine—Left ventrical performance	ALVEN	U. of Toronto
	Military situation determination	ANALYST	MITRE
Monitoring	Patient respiration	VM	Stanford U.
Use advisor	Structural analysis computer program	SACON	Stanford U.
Computer aided instruction	Electronic troubleshooting	SOPHIE	BBN
	Medical diagnosis	GUIDON	Stanford U.
	Mathematics	EXCHECK	Stanford U.
	Steam propulsion plant operation	STEAMER	BBN
	Diagnostic skills	BUGGY	BBN
	Causes of rainfall	WHY	BBN
	Coaching of a game	WEST	BBN
	Coaching of a game	WUMPUS	MIT
		SCHOLAR	BBN
Knowledge acquisition	Medical diagnosis	TEIRESIAS	Stanford U.
	Medical consultation	EXPERT	Rutgers
	Geology	KAS	SRI
Expert system construction		ROSIE	Rand
		AGE	Stanford U.
		HEARSAY III	USC/ISI
		EMYCIN	Stanford U.
		OPS 5	CMU
		RAINBOW	IBM
	Medical diagnosis	KMS	U. of MD
	Medical consultation	EXPERT	Rutgers
	Electronic systems diagnosis	ARBY	Smart Sys. Tech.
	Medical consultation using time-oriented data	MECS-AI	Tokyo U.

Table 3. (continued)

Function	Domain	System*	Institution
Consultation/intelligent assistant	Battlefield weapons assignments	BATTLE	NRL AI Lab
	Medicine	Digitalis Therapy Advisor	MIT
	Radiology	RAYDEX	Rutgers U.
	Computer sales	XCEL	CMU/DEC
	Medical treatment	ONCOCIN	Stanford U.
	Nuclear power plants	CSA Model-Based Nuclear Power Plant Consultant	GA Tech
	Diagnostic prompting in Medicine	RECONSIDER	U. of CA, S.F.
	Estate planning	TAX ADVISOR	U. of IL
Management	Automated factory	IMS	CMU
	Project management	CALLISTO	DEC
Automatic programming	Modelling of oil well logs	ΦNIX	Schlumberger-Doll Res.
		CHI	Kestrel Inst.
		PECOS	Stanford U.
		LIBRA	Stanford U.
		SAFE	USC/ISI
		DEDALUS	SRI
		Programmer's apprentice	MIT
Image understanding		VISIONS	U. of Mass.
		ACRONYM	Stanford U.

* References to these systems can be found in Duda,[2] Stefik *et al.*,[3] Buchanan,[7] Buchanan and Duda,[8] Barr and Feigenbaum,[9] IJCAI-81,[10] and AAAI-82.[11]

Using present techniques and programming tools, the effort required to develop an expert system appears to be converging towards five man-years, with most endeavors employing two to five people in the construction.

7. SUMMARY OF THE STATE-OF-THE-ART

Buchanan[7] indicates that the current state of the art in expert systems is characterized by:

Narrow domain of expertise Spatial complexity.
Because of the difficulty in building and maintaining a large knowledge base, the typical domain of expertise is narrow. The principal exception is INTERNIST, for which the knowledge base covers 500 disease diagnoses. However, this broad coverage is achieved by using a relatively shallow set of relationships between diseases and associated symptoms. (INTERNIST is now being replaced by CADUCEUS, which uses causal relationships to help diagnose simultaneous unrelated diseases.)

Limited knowledge representation languages for facts and relations

Relatively inflexible and stylized input-output languages

Stylized and limited explanations by the systems

Laborious construction
At present, it requires a knowledge engineer to work with a human expert to laboriously extract and structure the information to build the knowledge base. However, once the basic system has been built, in a few cases it has been possible to write knowledge acquisition systems to help extend the knowledge base by direct interaction with a human expert, without the aid of a knowledge engineer.

Single expert as a "knowledge czar"
We are currently limited in our ability to maintain consistency among overlapping items in the knowledge base. Therefore, though it is desirable for several experts to contribute, one expert must maintain control to insure the quality of the data base.

Fragile behavior
In addition, most systems exhibit fragile behavior at the boundaries of their capabilities. Thus, even some of the best systems come up with wrong answers for problems just outside their domain of coverage. Even within their domain, systems can be misled by complex or unusual cases, or for cases for which they do not yet have the needed knowledge or for which even the human experts have difficulty.

Requires knowledge engineer to operate
Another limitation is that for most current systems only their builders or other knowledge engineers can successfully operate them—a friendly interface not having yet been constructed.

Nevertheless, Randy Davis[12] observes that there have been notable successes. A methodology has been developed for explicating informal knowledge. Representing and using empirical associations, five systems have been routinely solving difficult problems—DENDRAL, MACSYMA, MOLGEN, R1 and PUFF—and are in regular use. The first three all have serious users who are only loosely coupled to the system designers.

DENDRAL, which analyzes chemical instrument data to determine the underlying molecular structure, has been the most widely used program (see Lindsay *et al.*[13]). R1, which is used to configure VAX computer systems, has been reported to be saving DEC twenty million dollars per year, and is now being followed up with XCON. In addition, as indicated in Table 3, hundreds of systems have been constructed and are being experimented with.

8. FUTURE TRENDS

Figure 2 lists some of the expert systems applications currently under development.

It will be observed that there appear to be few domain or functional limitations in the ultimate use of expert systems. However, the nature of expert systems is changing. The limitations of rule-based systems are becoming apparent. Not all knowledge can be readily structured in the form of empirical associations. Empirical associations tend to hide causal relations (present only implicitly in such associations). Empirical associations are also inappropriate for highlighting structure and function.

Thus, the newer expert systems are adding deep knowledge having to do with causality and structure. These systems will be less fragile, thereby holding the promise of yielding correct answers often enough to be considered for use in autonomous systems, not just as intelligent assistants.

The other change is a trend towards an increasing number of non-rule based systems. These systems, utilizing semantic networks, frames and other knowledge representations, are often better suited for causal modeling and representing structure. They also tend to simplify the reasoning required by providing knowledge representations more appropriate for the specific problem domain.

Figure 3 (based largely on Hayes-Roth IJCAI-81 Expert system tutorial[10] and on Feigenbaum[1]) indicates some of the future opportunities for expert systems. Again no limitation is apparent.

It thus appears that expert systems will eventually find use in most endeavors which require symbolic reasoning with detailed professional knowledge—which includes much of the world's work. In the process, there will be exposure and refinement of the previously private knowledge in the various fields of applications.

On a more near-term scale, in the next few years we can expect to see expert systems with thousands of rules. In addition to the increasing number of rule-based systems we can also expect to see an increasing number of non-rule based systems. Also anticipated are much improved explanation systems that can explain (make "transparent") why an expert system did what it did and what things are of importance.

Medical diagnosis and prescription
Medical knowledge automation
Chemical data interpretation
Chemical and biological synthesis
Mineral and oil exploration
Planning/scheduling
Signal interpretation
Signal fusion—situation interpretation from multiple sensors
Military threat assessment
Tactical targeting
Space defense
Air traffic control
Circuit diagnosis
VLSI design
Equipment fault diagnosis
Computer configuration selection
Speech understanding
Intelligent computer-aided instruction
Automatic programming
Intelligent knowledge base access and management
System management
Tools for building expert systems

Figure 2. Expert system applications now under development.

Building and construction
Design, planning, scheduling, control
Equipment
Design, monitoring, control, diagnosis, maintenance, repair, instruction
Command and control
Intelligence analysis, planning, targeting, communication
Weapon systems
Target identification, adaptive control, electronic warfare
Professions
(Medicine, law, accounting, management, real estate, financial, engineering) Consulting, instruction, analysis
Education
Instruction, testing, diagnosis, concept formation and new knowledge development from experience.
Imagery
Photo interpretation, mapping, geographic problem-solving.
Software
Instruction, specification, design, production, verification, maintenance
Home entertainment and advice-giving
Intelligent games, investment and finances, purchasing, shopping, intelligent information retrieval
Intelligent agents
To assist in the use of computer-based systems
Office automation
Intelligent systems
Process control
Factory and plant automation
Exploration
Space, prospecting, etc.

Figure 3. Future opportunities for expert systems.

Rules Induction & Text mining

By the late 80's, we can expect to see intelligent, friendly and robust human interfaces and much better system building tools (currently a major need).

Somewhere around the year 2000, we can expect to see the beginnings of systems which semiautonomously develop knowledge bases from text. The result of these developments may very well herald a maturing information society where expert systems put experts at everyone's disposal. In the process, production and information costs should greatly diminish, opening up major new opportunities for societal betterment.

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