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ARTIFICIAL INTELLIGENCE RESEARCH AT THE APL RESEARCH CENTER: AN OVERVIEW

This overview of the artificial intelligence research at APL's Milton S. Eisenhower Research Center introduces the subject by discussing what it is, how it differs from other areas of computer science, and why there is such intense interest in it now. Artificial intelligence projects under development are also summarized.

WHAT IS ARTIFICIAL INTELLIGENCE?

I would answer this question by examining various definitions of artificial intelligence (AI) that have been used over the years. Probably the oldest is that attributed to M. Minsky of MIT:

> Artificial intelligence is the study of how to make computers do things which, if done by a human, would be said to require intelligence.

This definition bypasses the need to define intelligence and assumes we know intelligent activity when we see it. Indeed, if there were universal agreement about what constitutes intelligent activity, Minsky's would be an adequate working definition of AI. But in the absence of such agreement, the definition presents some problems. For example, does performing the arithmetic operations of addition, subtraction, multiplication, and division require intelligence? One would think so, and yet no one would say that a program that numerically integrates complicated differential equations (even one that adaptively changes its mesh size to take into account singularities of the equations) is an AI program. So, although the definition starts us thinking about AI and what it is, it is clear that more should be said.

Another definition, this one by E. Rich in her recent textbook on AI,[1] states that

> Artificial intelligence is the study of techniques for solving exponentially hard problems in polynomial time by exploiting knowledge about the problem domain.

This definition sheds new light on the subject, once we understand some of the terms used. A problem is said to be exponentially hard if all known algorithmic solutions to the problem have operation (and therefore time) requirements that grow faster than powers of the problem size. For example, the number of operations needed to invert an N by N matrix is proportional to N^3, while to solve the N-city traveling salesman problem[2] (and many similar scheduling problems) by algorithmic methods requires operations that are proportional to $(N-1)!$ Thus, to invert a 100 by 100 matrix requires on the order of 100^3 operations, and, assuming that one operation takes a nanosecond, the time required to perform the inversion is on the order of 10^{-3} second. However, for a 100-city traveling salesman problem, the number of operations is proportional to $99! \cong 9.3 \times 10^{155}$. At 10^9 operations per second, solving this problem would require approximately 10^{139} years!

The traveling salesman problem belongs to a class of problems known as NP-complete, that is, those problems for which nondeterministic (i.e., an arbitrary number of paths can be followed at once) polynomial-time algorithms are known but for which all known deterministic algorithms are exponential. If AI is to solve such problems in polynomial time, how is it going to be done? One answer is to use specific knowledge about the problem domain along with heuristics (i.e., plausible procedures, rules of thumb, etc.) to produce acceptable (although possibly suboptimal) solutions in an acceptable amount of time. Therefore, we can summarize by saying that AI is concerned with exponentially hard problems and uses specific domain knowledge and heuristics to solve them. The same definition could be used to define operations research, although the meaning of the word heuristic in the context of operations research would have a slightly different connotation.

Another definition of AI is that given by Kurzweil:[3]

> Artificial intelligence attempts to provide practical demonstrations of the Church-Turing hypothesis.

The Church-Turing hypothesis says that if a problem that can be presented to a Turing machine[4] is not solvable by the machine, then it is also not solvable by human thought. One implication of this hypothesis is that if humans can solve a problem (perform intelligent activities), then ultimately machines can be constructed to do the same thing. Thus, the Church-Turing hypothesis (and its implicit assumption that thought and computation are somehow equivalent) is at the foundation of AI.

Finally, perhaps the best definition of AI is not a definition at all, but a listing of the major areas of AI:

knowledge acquisition and representation, control strategies for reasoning with this knowledge, learning, natural language (written and spoken) processing, computer vision, expert systems, and intelligent robotics.

Combining the definitions, we can say that artificial intelligence is the subfield of computer science having as its foundation the hypothesis that thought and computation are equivalent; i.e., that computers can eventually be constructed that emulate human thought processes; that emulating human thought processes requires the solving of exponentially hard problems; that major areas of concern to AI are knowledge acquisition, knowledge representation, and how to reason with knowledge once it is acquired; and, finally, that the major subfields of AI are learning, natural language processing, computer vision, expert systems, and intelligent robotics.

HOW DOES AI DIFFER FROM OTHER AREAS OF COMPUTER SCIENCE?

Three answers come readily to mind: (a) AI emphasizes symbolic rather than numerical computations; (b) AI programs are by nature nonalgorithmic rather than algorithmic; and (c) AI is concerned at the top level with learning, the nature of intelligence, knowledge representation, and reasoning.

An example may be useful. Assume that the problem is to evaluate

$$\int_0^1 \frac{dx}{x^3 + 1} \; .$$

The conventional computational approach would use a quadratures formula, such as Simpson's rule, to approximate the integral by

$$\frac{h}{3} \, [f_0 + 4 \, (f_1 + f_3 + \, . \, . \, . \, + f_{2_{n-1}}) + 2 \, (f_2 + f_4 + \, . \, . \, . \, + f_{2_{n-2}}) + f_{2_n}] \; .$$

Here f_1 denotes the value of the integrand at the point x_i, $0 = x_0 < x_1 < \ldots < x_{2n} = 1$, and $h = x_{i+1} - x_i$. This is a purely algorithmic numerical procedure. Furthermore, given a different integral, the algorithm remains the same; only the values of f_i change.

What would an AI approach be? First, the AI program would contain specific knowledge about integration, including such things as factoring polynomials, partial fractions, useful transformations, and a small table of integrals (e.g., $\int x^n dx = x^{n+1}/(n + 1)$), and rules of thumb about ways to convert integrands into easier forms for integration. Thus, in this example, an approach that would be useful would be one that says that when dealing with a cubic expression in the denominator, try to factor it. Applying this, the given integrand becomes

$$\frac{1}{(x + 1) \; (x^2 - x + 1)} \; .$$

Another heuristic would guide the program to try partial fractions. (Other heuristics may suggest other paths from this point, but to avoid unnecessary complication they will not be considered here.) The resultant integrand is

$$\frac{1}{3} \left(\frac{1}{x + 1} + \frac{-x + 2}{x^2 - x + 1} \right) .$$

From here, the problem naturally decomposes into two subproblems. This process is continued until all terms are reduced to ones that are directly integrable via the program's table of integrals. The definite integral is then obtained by evaluating the antiderivative at 0 and 1.

The AI program takes a fundamentally different approach that emphasizes symbolic computation, specific knowledge about the domain in which the program is designed to work, and heuristic information to control the search for a solution. Further, unlike the conventional quadratures approach, the steps the program follows in solving a problem are highly dependent on that problem. For example, given $\int x^4/(1 - x^2)^{5/2} dx$, the program would not try to factor the denominator but would proceed by making the substitution $x = \sin y$ to transform the integral into $\int \tan^4 y \, dy$. Then other transformations and trigonometric identities could be used to simplify the problem further.

WHY THE INTENSE INTEREST IN AI NOW?

This question can be answered at many levels, and different commentators would give different answers. Among them would be the following:

- The diminishing time available in which to make decisions, coupled with the rapid increase in information that the decision maker must consider, necessitates intelligent automated decision aids.
- When adversaries outnumber us in manpower and military hardware, the deficit must be overcome by smarter weapons and, it is hoped, by weapons that replace humans (e.g., automatous vehicles).
- The amount of knowledge in any given field appears to be growing exponentially, and no one can hope to understand, assimilate, and effectively use it all without some help from intelligent automated assistants and/or expert systems.
- Our trading partners are rushing pell-mell to automate their manufacturing processes and, as a matter of survival, so must we.

The list could go on and on, but in all of the answers, either explicitly or implicitly, there is the implication that intelligent machines are becoming more and more necessary in our fast-paced, technologically advancing society.

However, I believe that the explanations given above put the cart before the horse. The current interest in AI stems from the very real successes produced by the expert system paradigm introduced in the late 1960s and highly publicized in the late 1970s and early 1980s. The realization that expert systems could solve important, difficult, real-world problems signaled that AI had finally arrived as a useful scientific discipline. As this realization became more and more pervasive, everyone started creating their own lists of what AI could do. Many people are making overly optimistic forecasts about the capabilities of AI (at least in the short run), with the result that some disappointments are certain. But equally certain are some startlingly brilliant successes. Therefore, I believe that, disappointments notwithstanding, the future belongs to AI. After all, everyone wants programs that are smarter, not dumber!

ARTIFICIAL INTELLIGENCE RESEARCH IN APL'S MILTON S. EISENHOWER RESEARCH CENTER

The four research projects in AI being conducted in the Research Center are described briefly below. More detailed accounts of three of them appear in subsequent articles in this issue.

Machine Vision

The long-range goal of the vision project is to configure a general vision system with a performance that is commensurate with current hardware constraints (i.e., memory size and processing speed). Initially, because of the relatively limited memory capacity and the serial operation of current computers, performance would not be expected to be high compared to human vision capabilities. As larger memories and parallel machines become widely available, performance would be expected to improve dramatically. A guiding principle for such a system is that performance would improve automatically as a direct function of the increase in the scale of the hardware available, without the need to formulate additional or different concepts in the architectures of the vision module. Thus, generality is the initial primary goal and performance is secondary. Of course, long-range goals are achieved through a collection of shorter-term goals that will change with time as some goals are satisfied and new ones are targeted. However, all goals will have one feature in common—the development of vision modules that will serve as building blocks from which the general system can be assembled. An initial short-term goal is to complete a system for recognizing simple objects. A necessary attribute of the module is that once an object has been recognized, it should continue to be recognized after undergoing rotations, translations, and dilations. A description of the recognition system is given in the article on computer vision by Kim et al. elsewhere in this issue.

Intelligence Aids for Designing Interactive Information Systems

The long-range goal of this project is to develop a computer environment for automating software development, with particular emphasis on developing information systems. The short-range goal is to produce an expert system that will transform application-specific requirements (residing in an application database) into an executable specification. An environment called TEDIUM* already exists and will be used to transform the specifications produced by the expert system into an executable system. An extensive description of the project is given in an article by Blum and Sigillito elsewhere in this issue.

Acquisition and Representation of Knowledge for Distributed Command Decision Aiding

The technology for knowledge-based expert systems technology has advanced rapidly in the past few years. It is one area of AI that appears to have come into its own and seems to be ready for application to the development of operational systems. Among potential applications are planning and decision aiding, both of which are important to the solution of distributed tactical decision-making problems. Research is being conducted on fundamental issues that underlie the design and development of reconfigurable knowledge-based systems. Such systems support decision aiding for multiple tactical commanders who use a common decision-aiding system in which their own tactical knowledge is represented in separate instantiations of a knowledge base. Issues considered include acquisition of relevant knowledge from subject-matter experts, representation of such knowledge in structural formalisms in order to transfer it to a knowledge base in computer memory, and the use of stored knowledge in problem solving and decision-making tasks in support of tactical decision makers who are separated spatially, electronically, and organizationally.

Knowledge acquisition is being investigated by developing and refining techniques to elicit context-sensitive responses to structured tactical situations from acknowledged domain experts. Their responses are analyzed to determine the essential nature and extent of the knowledge they contain or imply. Knowledge representation is being investigated within a human information-processing model by determining either analytically or empirically what structural formalisms are needed to represent the tactical knowledge of two or more coordinated but possibly separated decision makers in knowledge bases in computer memory. Knowledge utilization is being investigated by exercising knowledge bases developed in the course of research on knowledge acquisition and knowledge representation; efforts to identify measures of decision-making performance for system evaluation will be included. For details, refer to the article by Hamill and Stewart in this issue.

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Knowledge Representation and Languages

The long-range goal is to develop an environment for the design, implementation, and evaluation of languages for knowledge representation and acquisition. The short-range goal is to develop particular techniques and software tools that permit experimenting in the areas of language design, special-purpose operating systems, and control strategies.

The knowledge-representation language and its realization will be enough to provide expression of rules in the context of procedure-oriented, object-oriented, and data-oriented rules. The objective is to demonstrate that these paradigms can be captured through the knowledge-representation language. Although each view can be implemented by standard programming languages, the features occur frequently enough to be identified separately. The paradigms represent techniques to partition large sets of rules and data into structured, manageable objects. It is expected that other paradigms or specialized contexts of these paradigms will evolve from the experience in constructing systems.

Another objective of the work is to develop a knowledge-representation kernel to manage certain aspects of process control from within the knowledge-representation language. The specialized kernel will control process invocations, monitor some resource-consumption patterns, handle interrupts associated with the processes, and terminate processes when required. The kernel will demonstrate a management policy for mutually constrained cooperating processes. These design criteria are based on the view that a knowledge-representation system will manage other systems and may require the monitoring and interpreting of state changes, delayed processing, coordinating of processes, and operation in a distributed environment. Currently, few systems provide process control.

A final objective is to extend and develop a family of control strategies that can be used within the knowledge-based systems for inferencing and to demonstrate the effective use of linguistic variables and null variables in knowledge-representation systems for inferencing under conditions of incomplete and uncertain knowledge, forward and backward chaining, and temporal logics.

This project is not discussed in greater detail elsewhere in this issue. However, an expert system that resulted from early work in the project is discussed in Refs. 5 to 7.

REFERENCES and NOTES

[1] E. Rich, *Artificial Intelligence,* McGraw-Hill, New York (1983).

[2] A salesman has a list of cities, each of which he must visit exactly once. There are direct roads between each pair of cities. Find the route the salesman should follow so that he travels the shortest possible distance on a round trip, starting at any one of the cities and then returning there.

[3] R. Kurzweil, "What is Artificial Intelligence Anyway?" *Am. Sci.* **73**, 258-264 (1985).

[4] A Turing machine consists of two memories: an unbounded type that holds data and instructions, and a finite state control. The set of instructions on the tape is very small and consists of read, write, and scan operations. The read operation is not a data operation but provides conditional branching to a control state as a function of the data under the read head. The Turing machine is the primary theoretical model of computation because of its combination of simplicity and power. It has been proven that a Turing machine can compute anything that any machine (no matter how complex) can compute.

[5] V. G. Sigillito and R. F. Wachter, "An Expert System for Correction of Oceanographic Reports," in *Proc. Intelligent Systems: Their Development and Application,* Association for Computing Machinery, p. 139 (1985).

[6] V. G. Sigillito, R. F. Wachter, and R. E. Hart, "XCOR-A Knowledge-Based System for Correction of Oceanographic Reports," in *Expert Systems in Government Symp.,* IEEE Computer Society, pp. 190-195 (1985).

[7] R. F. Wachter and V. G. Sigillito, "A Man-Machine Interface to a Knowledge-Based System for Validating Oceanographic Reports," in *Proc. 2nd International Conf. on Artificial Intelligence Applications* (in press).

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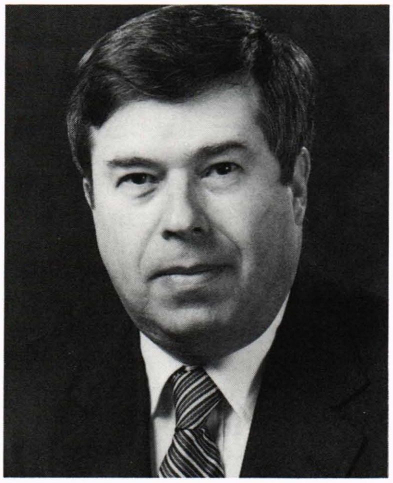

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