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KNOWLEDGE-BASED TECHNIQUES IN ARTIFICIAL INTELLIGENCE

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Annual Summary Report, Feb 77-Jan 78,

Covering the Period February 1977 through January 1978

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By: Nils J. Nilsson, Staff Scientist  
Artificial Intelligence Center

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Prepared for:

Office of Naval Research  
Information Systems Branch  
800 North Quincy Street  
Arlington, Virginia 22217  
Attn: Mr. Marvin Denicoff

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Approved:

*Peter E. Hart*  
Peter E. Hart, Director  
Artificial Intelligence Center

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333 Ravenswood Ave. • Menlo Park, California 94025  
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## I INTRODUCTION

### A. Task Objective

This report summarizes the research performed during the first year of a project to investigate knowledge-based techniques in Artificial Intelligence (AI). The objective of this research is to expand the technology of incorporating and using knowledge in computer systems. In developing computer systems for applications in software production, information retrieval, file management, signal identification, photointerpretation, and other data processing problems of interest to the U.S. Navy, it is necessary to provide these systems with large amounts of domain-specific knowledge. Artificial Intelligence research has recently been developing various techniques for incorporating knowledge into computer systems, but as yet it lacks any unifying framework that can be used to coalesce these methods into anything like the engineering discipline that is prerequisite to large-scale practical applications. Because such a unifying framework has not yet been synthesized, each new application effort spends excessive time in developing an individual approach to representing and using knowledge-based systems. Success in the present program will greatly increase the efficiency of future application efforts.

### B. Summary of Progress During the Past Year

Our specific goals for the past year were to survey knowledge-based approaches in AI, to fill in gaps by performing new research where necessary, and to begin the development of a unifying framework for the field. A large part of the field of knowledge-based AI systems has been thoroughly surveyed, and an outline of a unifying framework has been proposed. In addition, new research conducted under this project has resulted in the design of a new knowledge-based automatic deduction system with potential applications in intelligent information retrieval and expert systems.

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## II DETAILED DESCRIPTION OF WORK PERFORMED DURING THE PAST YEAR

### A. Development of a Framework for AI Systems

High-performance AI systems generally require such a large amount of knowledge that it has to be obtained gradually during the lifetime of the system. The requirements for dealing with plentiful and accumulating knowledge put special restrictions on acceptable methods for the design of AI systems. Ad hoc programming efforts are likely to be frustrated by the overwhelming complexity of the knowledge required and by the need to make thoroughgoing changes to the system as more knowledge is added. The designer's problem would be made easier if he could select from among certain standard organizations for AI systems, each of which encouraged evolutionary development.

Artificial Intelligence research has produced a large family of useful organizations or structures for problem solving systems. Although many variations exist, most AI systems can be viewed as belonging to (or closely related to) a single family of computational structures. These structures might be called production systems because they bear a close resemblance to computational formalisms that use productions to rewrite strings. The major elements of a production system are a global data base, a set of rules, and a control system.

The production rules operate on the global data base. Each has a precondition which is either satisfied or not by the global data base. If the precondition is satisfied, the rule can be applied. Application of the rule changes the data base. The control system makes the choice of which applicable rule should be applied and decides when computation should terminate.

We have based our framework of AI knowledge-based techniques on the general concept of a production system. We distinguish several varieties of production systems. These differ in the kinds of control systems they use, in properties of their rules, and in the way in which they are applied to specific problems.



One criterion that we use to distinguish different types of production systems is whether they reason forward from initial facts to a goal condition or whether they reason backward from goal to facts. Another distinction concerns the type of control strategy. One type uses simple backtracking; another maintains an explicit tree or graph of alternatives. Yet another distinction is based on whether the set of rules that are applicable to a given global data base can be applied in any order. If any sequence of any subset of the applicable rules can be applied to produce a result that is dependent only on the subset and not on the sequence, then the system is said to be commutative. An important way in which a system can be commutative is if the data base can be decomposed or split into nonoverlapping segments such that the applicability conditions and the effects of the rules are confined to the individual segments. We shall call systems with this property decomposable. Commutative and decomposable systems find application in automatic deduction, information retrieval, and program synthesis; the more general (noncommutative) ones are used in robot planning and automatic problem solving.

These classification ideas can be quite usefully employed to organize and unify much of the work in AI. We have developed a rather extensive outline of the field based on this classification. The outline is included as Appendix A.

During the past year we have thoroughly explored the subject matter of PARTS ONE, THREE, FOUR, and FIVE of the outline. Previous research in the field has already produced a coherent understanding of the subject matter of PART TWO.

In addition to this work of organizing the field, our framework has inspired further research in the area of PART FOUR of the outline, which we shall describe next.

## B. Research in Automatic Deduction

One of the most important applications of commutative and decomposable systems is in automatic deduction. Automatic deduction systems, in turn, are used in intelligent information retrieval, program verification, automatic theorem proving, and expert systems. During the past year, we have developed a design for a new automatic deduction system based on production rules. The system combines several developments in Artificial Intelligence and Automatic Theorem Proving research, including the use of domain-specific inference rules and separate mechanisms for forward and backward reasoning. It has a clean separation between the data base, the production rules, and the control system. Goals and subgoals are maintained in an AND/OR tree structure. Another structure (a dual of the AND/OR tree) is introduced to represent assertions. The production rules modify these structures until they "connect" in a fashion that proves the goal theorem. Unlike some previous systems that used production rules, ours is not limited to rules in Horn Clause form. Unlike previous PLANNER-like systems, ours can handle the full range of predicate calculus expressions including those with quantified variables, disjunctions, and negations. This system is described in a paper written during the past year.\*

## III PLANS FOR THE NEXT YEAR

### A. Framework for AI

Work on a framework for AI during the next year will concentrate on PART TWO (Heuristic Search Methods), PART FOUR (Section V, Inexact Reasoning), and PART SIX (Structured Objects) of the outline. Several systems have been developed that are able to reason with inexact knowledge. Two prominent examples are MYCIN, a medical diagnosis system

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\* Nilsson, N. J., "A Production System for Automatic Deduction," Technical Note 148, Artificial Intelligence Center, SRI International (July 1977). [To appear in Machine Intelligence 9, D. Michie (ed.), 1978]

developed at Stanford University, and PROSPECTOR, a mineral exploration consultant being developed at SRI. This topic is important because much reasoning that uses "common sense" and "skilled judgment" is inexact. Many of the techniques used in deduction systems can be extended to deal with inexact knowledge. This topic will be thoroughly surveyed and outlined during the next year.

Additional representational power can be given to predicate-calculus-type representations by including facilities for better indexing, sorting of arguments by type, and handling set-subset information. Many of these more complex representational structures are called Structured Objects. Semantic networks and frames are examples. Because this area is on the frontier of automatic problem-solving research, it is still rather disorganized, and the relations between different approaches are poorly understood. Preparing a unifying framework will constitute a worthwhile challenge.

#### B. Additional Research on Selected Topics

The process of organizing the knowledge about a field usually reveals gaps in that knowledge. These gaps suggest further research. We expect to be confronted by such opportunities for new research during the coming year, and we will selectively undertake some of the more important problems as time and resources permit.

### IV PERSONNEL MATTERS

During the first half of the year (until mid-July of 1977), Dr. Nils Nilsson was associated with the Computer Science Department of Stanford University on a half-time basis. During that time he taught courses and seminars on Artificial Intelligence and advised graduate students. From September through December, inclusive, 1977, Dr. Nilsson was associated with the Computer and Information Sciences Dept., University of Massachusetts, Amherst, Mass. on a half-time basis.



These associations have greatly augmented the present work by providing opportunities for critical examination and discussion of key ideas.

## V MEETINGS AND TALKS

Dr. Nilsson attended the following meetings during the year:

Workshop on Pattern-Directed Inference Systems, May 23-27, 1977. Honolulu, Hawaii. (Joint author of a paper presented by R.O. Duda entitled "Semantic Network Representations in Rule-Based Inference Systems".)

Ninth Machine Intelligence Workshop, April 18-23, 1977. Repino, USSR (Presented a paper entitled "A Production System for Automatic Deduction".)

Workshop on Automatic Deduction, August 17-19, 1977. Cambridge, Mass.

International Joint Conference on AI, August 22-25, 1977. Cambridge, Mass.

Research Directions in Software Technology, Oct. 10-12, 1977. Providence, RI. (Presented paper entitled: "Research on Artificial Intelligence," with R. O. Duda and B. Raphael.)

Dr. Nilsson gave the following seminars during the year:

Univ. of Maryland  
"A Production System for Automatic Deduction"  
August 29, 1977

MIT  
"A Framework for AI"  
November 16, 1977

Brown Univ.  
"A Framework for AI"  
November 17, 1977

Medical and Scientific Univ. of Grenoble  
"A Framework for AI"  
November 25, 1977

Cornell Univ.  
"Problem Solving Systems for Robots"  
December 14, 1977

Carnegie Mellon Univ.  
"A Framework for AI" (three lectures)  
January 24-26, 1978



Appendix A  
OUTLINE

ARTIFICIAL INTELLIGENCE

A Framework

Nils J. Nilsson  
SRI International

March 23, 1978

## ONE: INTRODUCTION

### I. General Description of AI

#### A. Scope

#### B. Example Problems for Intelligent Machines

1. Intelligent Information Retrieval
2. Diagnosis of Disease
3. Finding Proofs for Theorems
4. Controlling a Robot
5. Automatic Programming
6. Combinatorial and Scheduling Problems
7. Perception Problems

### II. Structures for AI Systems

#### A. Production Systems

1. Data, Operations and Control
2. The Eight-Puzzle
3. State Descriptions
4. Rules
5. Termination
6. The Basic Procedure
7. Control
8. Examples of Control Regimes
  - a. Irrevocable
  - b. Backtracking
  - c. Tree Search
9. Problems of Representation
10. Some Example Problem Representations
  - a. A Traveling Salesman Problem
  - b. A Syntax Analysis Problem
  - c. A Distribution Problem
11. Backward and Bidirectional Production Systems

#### B. Specialized Production Systems

1. Commutative Production Systems
2. Decomposable Production Systems
  - a. The Basic Procedure
  - b. Control
  - c. Backtracking Control
  - d. Tree Search Control
  - e. Chemical Structure Generation

f. Symbolic Integration

C. Comments on the Different Types of Production Systems

TWO: HEURISTIC SEARCH METHODS  
(To be articulated during the second year)

THREE: PREDICATE LOGIC AND ITS ROLE IN AI

I. The Predicate Calculus

A. Informal Introduction to the Predicate Calculus

1. Predicates and Atomic Formulas
2. Connectives
3. Quantification
4. Rules of Inference, Theorems, and Proofs

B. First-Order Predicate Calculus

C. The Use of the Predicate Calculus in AI

1. State Descriptions and Goals
2. Types of F-Rules
3. Commutative F-Rules
4. Noncommutative F-Rules

II. Resolution-Based Systems

A. Introduction

B. Control Strategies for Resolution Methods

C. Examples of Resolution Control Strategies

1. Breadth-First
2. Set-of-Support
3. Linear Input Form
4. Ancestry-Filtered Form
5. Combinations

D. Extracting Answers from Resolution Refutations

E. The Problem of Inefficiency in Resolution Refutations

1. Redundancy
2. Clause-Form
3. Uniformity



#### FOUR: DECOMPOSABLE SYSTEMS

- I. Motivation
- II. Rule-Based Deduction Systems
  - A. A Simple Rule-Based System for a Subset of Propositional Calculus
  - B. Extending the Production System to Deal with Variables
  - C. Example Rule-Based Deduction Systems
    - 1. An Information Retrieval System
    - 2. A System for Reasoning About Inequalities
- III. Embedding Control Knowledge in Rules
  - A. Importance of Control Knowledge
  - B. F-Rule and B-Rule Programs
    - 1. Control Issues
    - 2. Syntax
    - 3. Procedural Attachment
  - C. Some Example Applications Using Rule Programs
- IV. A More General Rule-Based Deduction System
- V. Systems for Dealing with Uncertain Information

#### FIVE: NONDECOMPOSABLE SYSTEMS

- I. Introduction
  - A. Robot Problem Solving
  - B. Modeling Robot Actions
  - C. The Frame Problem
  - D. A Forward Production System
- II. A Representation for Plans
- III. A Backward Production System

- A. Development of the B-Rules
- B. Regression
- C. B-Rules
- D. An Example Solution
- IV. Systems that Split Compound Goals
  - A. Interacting Goals
  - B. STRIPS
  - C. Control Strategies for STRIPS
  - D. Means-Ends Analysis and GPS
  - E. Example Using GPS
  - F. A Problem that STRIPS Cannot Solve
  - G. Waldinger's Method
  - H. Sacerdoti's Method
  - I. Amending Plans
- V. Hierarchical Planning
  - A. Motivation
  - B. Postponing Preconditions
- VI. Execution of Robot Plans
- VII. Commutative Formulations for Robot Problem Solving
  - A. Background
  - B. Green's Formulation
  - C. Kowalski's Formulation

SIX: STRUCTURED OBJECTS  
(To be articulated during the second year)