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by

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Preface

This collection of reports is divided into two sections. The first contains the research summaries for individual faculty members and research associates in the Computer Science Department. Two professors from Electrical Engineering are included as "Affiliated Faculty" because their interests are closely related to those of the Department, while Professors George Dantzig and Roger Schank do not appear because they were on leave and unavailable when the summaries were prepared.

The second section gives an overview of the activities of research groups in the Department. "Group" here is taken to imply many different things, including people related by various degrees of intellectual interests, physical proximity, or funding considerations. We have tried to describe any group whose scope of interest is greater than that of one person. The list of recent publications for each is not intended to be comprehensive, but rather to give a feeling for the range of topics considered.

This collection of reports has been assembled to provide a reasonably comprehensive review of research activities in the Department. We hope that it will be widely useful -- in particular, students in the Department may find it helpful in discovering interesting projects and possible thesis topics. We expect also that it will be of interest to many other people, both within and outside the Department.

Opinions herein expressed are generally the responsibility of the individual researchers; blatant distortions or inaccuracies may be attributed to the authors, named below.

Randall Davis
Margaret Wright

TABLE OF CONTENTS

Preface	i
 Section I	
Forest Baskett, III	1
Thomas Binford	2
Thomas H. Bredt	3
Bruce Buchanan	4
Vinton Cerf	5
Dr. Kenneth Colby	6
Edward A. Feigenbaum	7
Jerome Feldman	8
Robert W. Floyd	9
John T. Gil II, III	10
Gene H. Golub	11
C. Cordell Green	12
John G. Herriot	14
Donald E. Knuth	15
David C. Luckham	16
John McCarthy	17
Edward J. McCluskey	18
Lynn Quam	19
Arthur Samuel	20
Harold S. Stone	21
Yorick Wilks	22
Terry Winograd	24
 Section 2	
Combinatorics and Analysis of Algorithms	25
Digital Systems Laboratory	26
Heuristic Programming Project (DENDRAL)	27
Higher Mental Functions Project	23
Numerical Analysis Group	30
Stanford Artificial Intelligence Laboratory	31

SECTION 1

Forest **Baskett**, III
Assistant Professor of Computer Science
and Electrical Engineering

*analysis of operating systems
measurement and modeling of
operating systems*

Professor Baskett's interests are in the general area of operating systems. His research has included work on the design of practical operating systems, as well as analysis of specific aspects, including scheduling methods, computing system components, and memory organizations. He has worked on several kinds of modeling, e.g. of computing systems, program behavior, and file systems,

His future research will be directed toward further design and analysis of computing systems and architectures. The general aim is to determine features that are useful and helpful in systems, and to analyze the effects of these features on system performance. Techniques are being developed for analysis and comparison of different architectures, configurations, and components, given varying assumptions about the computing environment. Mathematical models, typically stochastic, are used as the bases for analysis and for defining and evaluating the measures to be used for comparison. The hope is to provide soundly based methods that will allow definition and implementation of "optimized" computing systems. The research in these areas combines theory and practice -- choosing appropriate parameters and measurements for models, and experiments to decide whether the models have validity in representing realized systems.

Professor Baskett sees this research as valuable in the design of newly developing operating systems and in the improvement of existing computing systems. Scientific methods for achieving stated goals under given constraints in the design of computing and operating systems should provide the basics for the quantitative engineering of such systems.

Thomas Binford
Research Associate, AI Lab

*machine vision
perceptiort and automation
representations for use
in perception*

Dr. Binford is involved with several projects related to machine perception and its applications to automation. The segmentation of real-world (outdoor) scenes has been approached using both probabilistic world models and textural values and relationships. The visual interpretation and representation of data from &dimensional depth information, in addition to standard light intensities, have led to work on representing objects as volumes, rather than surfaces, with decomposition into primitive subunits determined by cross-sections normal to axes which are space curves. A particular interest is the representat ion of shape of complex objects. The representation work is also involved in strategy planning for automation: in particular, it would form the basis for mode l -based assemb l y systems. Work on i ndustr i a l automat ion has involved automatic programming aspects as well, and confronts questions of the nature of primitive operations for both vision and manipulation. Dr. Binford would also like to see work done on representations of space aimed at planning efficient and effective trajectories for the Hand-Eye system arm.

His interest in these problems is aroused by their contribution to the question of the general character of intelligence, both in terms of machine intel l igence and suggested mechanisms for biological systems. A central problem in AI, he feels, is working out, careful ly and in detai l, the semantics for particular domains. Vision in particular is convenient, since it is both compact and work may be based on the highly intuitive field of geometry.

Thomas H. Bredt
Assistant Professor of Electrical Engineering

design of operating systems
reliability

The general field of Professor Bredt's work is the design of computer operating systems. He has worked previously in several areas; modeling of parallel systems such as asynchronous hardware systems; computational linguistics; and modeling of thought processes.

He is presently working with implementation methods such as structured programming and system reliability. The study of reliability includes development of methods for proving the correctness of operating systems, and methods for detection and recovery from errors that occur during system operation. Other areas of interest are resource allocation in computer systems, and mathematical models of parallel systems such as hardware and operating systems. His future work will continue along these same directions, with particular emphasis on reliability questions.

Professor Bredt feels that this work is important because operating systems serve large numbers of people; if the operating systems are incorrect or inefficient, all users of a system are affected. The theories developed help to design reliable operating systems, and hence have a wide influence on computing,

Bruce Buchanan
Research Computer Scientist

artificial intelligence
scientific inference
theory formation
biomedical applications

Dr. Buchanan is interested in artificial intelligence, particularly in the general problems of scientific inference, theory formation, and knowledge acquisition by computer. His work with the DENDRAL project has been aimed at elucidating techniques for generating plausible explanations of empirical data. The model of scientific inference in the DENDRAL program is heuristic search through a space of possible explanations of analytic data in organic chemistry.

Theory formation is carried out in the context of the Meta-DENDRAL program, which finds regularities in large sets of data and general principles which will account for them. A heuristic search model is used for this program also, but the search space is a space of possible general principles. Empirical theory formation is one method of imparting knowledge of a scientific discipline to a performance program. The task domain is a subset of organic chemistry.

His interest in biomedical applications of artificial intelligence has led to involvement with an interdisciplinary project at the Medical School, whose goal is to provide computerized therapy consultation. An interesting aspect of this work is its emphasis on a system with both the capacity to offer competent therapeutic advice and the ability to incorporate into the data base new knowledge learned through interaction with users.

Dr. Buchanan has also done some unusual work on computer-aided legal reasoning which investigated the possibilities of automated case analysis. Rather than simple information retrieval, the work surveyed the problem of providing an analysis of each case according to the legal principles under consideration,

Vinton Cerf
Assistant Professor of Computer Science
and Electrical Engineering

operating systems
computer networks

Professor Cerf's current research is in the general field of computer networks and computer communication systems. He has worked previously on numerous aspects of computing systems: the design and implementation of computer system measurement; a study of parallel computer modeling; analysis of multiprocessor systems; network measurement; and interactive graphics.

He is now working primarily on three problems related to computer communication system protocols. The first problem is to define for interconnected packet switching networks a set of protocols and message formats to permit maximum throughput while preserving sequencing, and allowing duplicate detection, flow control, alternate routing, and status reporting. This research is intended to be applied to new ARPA Network protocols, and the creation of generally accepted packet switching standards. Another problem is the development of a graph-theoretic approach to understanding the effects of topology on throughput, delay, and congestion in networks. Finally, some of his work deals with the economics of networks, involving primarily charging strategies, regulation issues, and interfacing standards.

Professor Cerf believes that computer networks are an area of increasing importance as they become progressively more widespread. The need for computer communication has grown explosively; computer networks offer a new means for improved communication and sharing of results.

Dr. Kenneth Colby
Senior Research Associate, AI Lab

*computer simulation of paranoia
natural language understanding
therapy for autistic children*

Dr. Colby is the director of the Higher Mental Functions project at the AI Lab, which has been working on two major projects -- a computer simulation of paranoia (called PARRY), and development of computer-mediated therapy for non-speaking autistic children. The first of these involves problems as varied as natural language understanding, information processing models of cognition, semantic memory models, and the study of psychiatric judgments. The linguistic aspects of the effort are concerned with a natural language input and output for the program and have been designed primarily as a vehicle for program performance, since, for example, linguistic recognition is based on pattern matching. While this is not claimed to parallel any normal psychological processes, it does function effectively in what is intended to be a potentially wide-ranging discourse. A new semantic memory has been implemented which provides for generation of responses from semantic constructs, rather than using the fixed patterns previously employed. The paranoid behavior of the model is supplied by an information processing model of thought that suggests the disease has its roots in unconventional interpretations of common linguistic constructs.

The second effort of the group on therapy for autistic children has resulted in the development of a 'multi-media' program which uses computer generated sound and graphics, in an attempt to draw the child's attention to language. This work (as well as that on PARRY) has confronted the standard behavioral science problem of establishing objective psychiatric measurements of behavior and its changes from normal to abnormal.

Dr. Colby sees great promise in the use of computer science to provide formalisms and models for psychology and psychiatry and in the practical contribution such formalisms can make to clinical medicine, as models of psychological phenomena.

Edward A. Feigenbaum
Professor of Computer Science

heuristic programming, DENDRAL
information processing psychology

The primary focus of Professor Feigenbaum's work in the past several years has been the Heuristic Programming Project (primarily the DENDRAL program) whose high-level goal is an understanding of the process of scientific theory formation. The vehicle currently used is data from chemical mass spectra, and the work proceeds in two parallel efforts -- first, the development of information-processing models of hypothesis induction from specific, individual spectra, and second, theory induction from large collections of spectra. The first of these is embodied in the perform-ante program called Heuristic DENDRAL. The development of automatic theory formation has seen realization in the Meta-DENDRAL program which attempts to construct sets of rules about molecular fragmentation by generalization from large sets of data.

Professor Feigenbaum describes the long-term goals of the Heuristic Programming project as: the achievement of power in AI problem-solving programs using various types of knowledge obtained from experts: constructing homogeneous heuristic program structures in terms of which this knowledge can function; and constructing programs for extracting such knowledge and embodying it in formalized theories.

Jerome Feldman
Associate Professor of Computer Science

decision theory and AI
automatic programming
robotics

Professor Feldman has previously worked in the areas of programming languages, compilers, computer graphics, and data structures. His more recent interests have been in various aspects of artificial intelligence, including machine perception, memory organization, automatic programming, grammatical inference, and robotics and automation.

One additional area in which he plans future work is decision theory and artificial intelligence, i.e., the question of planning under uncertainty. There is a fairly well-developed field of mathematical decision theory which considers a **class of events** under given assumptions about relevant probability distributions. However, these classes of problems are much simpler than the **corresponding artificial intelligence problems** -- for example, a robot's complex **decisions** about how to build an engine. This work is an attempt to apply techniques of formal analysis to an area where decisions have previously been **guided** primarily by heuristics; hence the results can have wide application in many fields of artificial intelligence.

Professor Feldman will also consider various aspects of automatic programming. One problem is to implement automatic selection of data structures; the aim of this effort would be to allow the user to describe the goals of **his** program in a specified style, whereupon the compiler would choose appropriate data structures. He also plans to work on special-purpose programming languages, or "very high level languages", and to study learning of grammars and programs from examples.

Robert W. Floyd
Professor of Computer Science

complexity theory
analysis of algorithms

Professor Floyd has worked in many areas of computer science: programming language design, sorting algorithms, language and compiler theory, formal linguistics, and mechanical theorem proving. His present research involves primarily the area of analysis of algorithms, in particular the theory of minimal algorithms. Computable problems can often be simply characterized and solved by simple algorithms: but known algorithms may require more time (or **space**, or other scarce resource) than the best possible algorithm to solve the problem. His research, after postulating models of computation which are reasonably accurate descriptions of present and foreseeable computing equipment, attempts (1) to prove absolute lower bounds on the expected time, or the maximum time, required for any algorithm to solve a given problem, and (2) to construct very efficient algorithms for given problems, thereby providing upper bounds on necessary expected or maximum time. The difference between upper and lower bounds can suggest where to look for improvements in one or the other, possibly suggesting revision of the model of computation, followed by renewed attempts on goals (1) and (2). The final result ideally should be the design of an actual computer program which is provably the minimal time program.

Several problems that have been considered from this viewpoint are computing quantiles (elements of a set at a fixed rank: e.g., medians) in minimum expected time and minimum maximum time, sorting with two tapes in minimax time, transposing boolean matrices, and permuting records on disc or drum storage. The ultimate aim of this work is to provide a calculus of optimal algorithms, which would allow one to systematically assemble the best possible algorithm for a broad range of practical problems on a broad range of computing equipment.

Professor Floyd is also working on the design and implementation of a programming language (Chiron) primarily for student use, to be suitable for teaching structured programming systematically to novices, and to be nearly universal in its capabilities. His experience with current languages and methods for teaching introductory programming suggests that technical details tend to overwhelm questions of systematic design. Chiron represents an attempt to provide a programming environment in which, to the largest extent possible, one designs a program by designing the process which the program carries out.

John T. Gill, III

Assistant Professor of Electrical Engineering

Professor Gill's work is in the area of computational complexity and information theory, with emphasis on axiomatic and concrete complexity theory. He has recently worked on three main topics. The first is probabilistic computation (the study of a "coin-tossing computer"); the goal of this work is to decide whether certain kinds of computation can be carried out **faster on a** "coin-tossing" machine than on other kinds of computers.

Another topic is the study of efficient ways of making fair decisions based on the outputs of a biased information source. An example is to **analyze** successive tosses of a biased coin to obtain a "fair guess." The criterion of efficiency means in this example to determine **as** many fair decisions as possible from the smallest number of tosses.

A third research area involves variable-length source codes -- for example, in transmission of messages, where frequently occurring strings of symbols can be transmitted in compressed form. Professor Gill is interested in the mathematical and combinatorial properties of these codes, whose formal structure corresponds to that of binary trees,

His future work will be in the area of probabilistic computation mentioned above, which has many interesting applications. He also plans to consider independence and parallelism in computation. A formal theory is to be developed to define what it means for two processes to be independent, and to analyze the implications of independence in parallel computing. The importance of this work derives from the growing importance of parallelism,

Gene H. Golub
Professor of Computer Science

*matrix computation
structured linear systems
least-squares and eigenvalues*

Professor Golub's work has the unifying theme of matrix computation, with the goals of devising and analyzing algorithms for solving numerical problems that arise in a variety of applications. His research is oriented toward development of methods based on sound mathematical theory, with a heavy emphasis on practical considerations of computing.

He is currently working on several different problems in numerical analysis. One of these is the fast direct solution of systems of linear equations arising from elliptic partial differential equations: these techniques are particularly **useful** for solving Poisson's equation in a rectangle, and are **very widely** used. Once a "black box" is developed to solve this subproblem, similar problems can then be solved by iteration and mathematical manipulation. Another area of active study includes various kinds of least-squares problems, which arise in many contexts of data analysis. He feels that a very interesting approach to the nonlinear **case** is the use of stable linear techniques; a particular application is the analysis of ozone in the Los Angeles air in order to analyze the effect of pollution devices, and seasonal parameters. Calculation of **eigenvalues** is a further area being considered from several new viewpoints, particularly with respect to different matrix structures: some recent uses of this work have been in analysis of ocean tides and nuclear reactor fuel control. Finally, Professor Golub is working on methods for updating stable matrix factorizations, which are increasingly used in mathematical optimization programs and control theory.

Professor Golub feels that numerical analysis questions are at the heart of many different kinds of problems in the physical sciences, social sciences and statistics. A strong numerical analysis technology now exists which can satisfactorily help many people, and it is hoped that his future research will **continue to have wide applications.**

C. Corcilell Green
Assistant Professor of Computer Science

*automatic programming
production automation
biomedical applications
Diplomacy*

Professor Green's primary interest has been in automatic programming. His group is studying the problems of finding new methods of specifying programs, codification of programming knowledge, and implementation of working program-writing systems. The types of programs to be written by machines range from simple list manipulation to pattern matching, tree-searching, and sorting. The main emphasis is on codification of the considerable body of list-processing programming knowledge. An interesting feature of the research is some emphasis on 'human' methods of program specification, such as example input-output pairs, generic examples, annotated traces, and possibly natural language descriptions. Prototype systems have been developed that can write short programs (fewer than seven lines), including sort, merge, reverse, list flattening, etc. A tentative one-year goal of the project is the automatic synthesis of a six-page concept formation program that employs simple list-processing techniques,

He is also involved with the production automation project at the AI Lab, where the effort is to design a very specific automatic programmer that writes plans for the assembly of small engines by the Hand-Eye system. The current goal is the generation of a detailed plan for the assembly of a chainsaw, given the kind of high-level task description now used for assembly-line workers.

Professor Green is **also** working with a group attempting to implement a 'natural language understanding system that plays the game of Diplomacy. The game forms an interesting problem because as play develops the players are required to negotiate with one another, and this involves making "deals", and possibly lying and cheating. As presently planned the system is based on Schank's conceptual dependency framework, and includes a strategist program that determines best moves independent of bargains, and a sophisticated bargainer that understands the various aspects of negotiating. The aim is to produce a system with the capacity of a beginning player.

Professor Green is part of a group working on a biomedical application, namely the design and implementation of a program to give antimicrobial therapy consultation in a clinical setting. A prototype system has been developed in the past year, and work has started on the problem of automatic knowledge acquisition from experts. A complete set of therapy rules for a particular class of

infect ions may include several hundred rules. The acquisition, manipulation, and interaction of these rules present interesting challenges in a real-world problem situation.

His interest in automatic programming is sparked by the feeling that it is the "most critical problem in AI," and is a prerequisite to the development of intelligent systems. Such systems require changing representations, changing strategies, and doing concept formation, all of which involve reprogramming. And in order to reprogram very complex systems, humans will require machine assistance. He finds the involvement in the antimicrobial therapy system interesting as a study in knowledge acquisition "where it can be done" -- in a real problem from a real domain: but the production automation project is just for "sheer fun and love of gadgetry".

John CL **Herriot**
Professor of Computer Science

spline functions
partial differential equations

Professor Herriot's interests are in the field of numerical analysis, with **emphasis** on implementation of algorithms for computation. He has previously worked on elliptic partial differential equations, especially on the "method of particular solutions", where a linear combination of particular solutions is computed which satisfies in some sense the given boundary conditions. These methods are useful in fluid flow and other physical problems.

His most recent work has been to study how to compute interpolating natural spline functions most efficiently and accurately. Although the theory has been known for some time, he has dealt with the specific problem of combining efficient coding and maximum numerical accuracy. He has written procedures to solve the general case, as well as procedures for the cubic case and the quintic case which take advantage of simplifications to speed up the calculations tremendously. Various special kinds of splines are also being considered in this same context.

He plans to work in the future on applications of spline functions to partial differential equations, such as the finite element method.

Professor Herriot feels that this work is important because there is often a gap between the mathematical theory of a problem and the actual computation of a numerical solution. Implementation of an algorithm for the computer involves a combination of mathematical and programming knowledge. Since the ultimate goal is to provide a computed solution, the numerical analyst must be concerned with programs as well as theory.

Donald E. Knuth
Professor of Computer Science

*analysis of algorithms
combinatorics and discrete
mathematics*

The broad area of Professor Knuth's work is analysis of algorithms, i.e., making quantitative statements about how good algorithms are. This research has two "flavors". The first is analyzing various aspects of particular algorithms -- for example, determining how fast they are and how much space they require, and comparing several algorithms for solving the same problem to decide which is best in terms of given criteria. The second is developing the tools of discrete and combinatorial mathematics required to answer such questions about computer methods. A more general problem is to prove that a method is optimum in the class of all possible ways to solve a problem. This approach leads to questions about definition and study of the basic complexity of algorithms,

The emphasis is on the computer methods that are the most fundamental and application-independent. The motivation for this research is to obtain more understanding of known methods, and to learn the fine points of their behavior under varying conditions. Such detailed study is at the foundation and center of computer science, not on the periphery; it is like "fertilizing the soil and establishing law and order rather than pushing back the frontiers."

Professor Knuth feels that there is an unlimited set of problems to be solved in this field, with no end in the foreseeable future. His continuing work on his series of books, which summarize and bring together related results, is aimed to provide a thorough foundation in the essentials of computer science.

David C. Luckham
Research Associate, AI Lab

theorem-proving
program verification
automatic program construction

Dr. Luckham has been working for the past few years on theorem-proving, program verification, and automatic program construction; three corresponding systems, intended for on-line interactive use, have been developed.

The theorem-prover has been used in many successful experiments testing its usefulness in proving theorems in different areas of mathematics, mainly algebra and geometry. Some steps have been taken to develop its application to information retrieval; question-answering facilities have been programmed and tested on small data bases, but nothing further has been done yet. The prover is also being used as part of a system for verifying the correctness of programs written in PASCAL. This second system is based on a verification condition generator and incorporates special procedures for simplification and problem reduction. In addition to the theorem prover, a number of programs, including standard algorithms for sorting linear arrays, have been verified. Currently the system is being extended to deal with programs containing parallel processes and data types such as sequences.

The automatic programming system is an interactive system that writes programs to satisfy given input-output specifications. The system requires as input a programming environment consisting, roughly speaking, of primitive functions and procedures, rules of composition and logical facts. It will take account of certain kinds of advice from the user in solving a problem. If successful, the system will output the solution in the form of a program in a language somewhat similar to a subset of Algol containing assignments, function calls, conditional branches, while loops, and non-recursive procedure calls. This system has been used to generate programs for robot control and automation problems, for *every-day* planning, and for computing arithmetical functions.

Projected research projects include: (1) Developing a HUNCH language for expressing intuitions about how proofs of conjectures (i.e., expected theorems) are likely to be found (a very primitive HUNCH language already exists); (2) programming new deduction rules and special strategies for particular problem areas such as the verification of programs containing parallel processes; and (3) extending the automatic programming system and its applications,

John McCarthy
Professor of Computer Science

artificial intelligence
mathematical theory of computation
timesharing

Professor McCarthy has devoted most of his recent research efforts to representation theory **and** the mathematical theory of computation. His work in representation theory -- how facts about a particular situation are represented in the computer -- is oriented toward formalisms from mathematical logic, in particular predicate calculus and set theory. Research in this area includes the development of an interactive proof-checking and theorem-proving system (FOL, First Order Logic) by Richard Weyrauch. The mathematical theory of computation is concerned with proving correctness and assertions about programs, and operates by taking a statement in a formal language about a program's purpose as a theorem to **be proved**.

Current time-sharing projects include the development of services for home terminals (the news service based on the Associated Press editor is a start) and a system for a uniform access to data bases stored in many different computers.

The common problem of the non-exportability of programs has led him to consider the need for a standardized programming language with standardized facilities for interaction with people, files, computer networks, etc. While this work has not yet reached the status of a full-fledged research project, it would involve discovering a framework for and then implementing the primitive operations **performed** by programs so that they were possible on any major operating system.

Professor McCarthy sees the problem of artificial intelligence as the "grand-daddy of all science problems", in the sense that if a good solution can be found, the possibility exists for programs capable of bootstrapping themselves to high levels of intelligence. The work is still in an exploratory stage,

He has also supervised Ph.D. theses in chess programs, speech recognition, proving compilers correct, and other areas of artificial intelligence, mathematical theory of computation, and time sharing.

Edward J. McCluskey
Professor of Computer Science
and Electrical Engineering

*digital systems
reliability*

Professor McCluskey's current work is in the general area of computer reliability, or fault-tolerant computing, which involves the study of methods to detect, analyze, and correct the errors that may occur in a computing system. The field of reliability includes a broad spectrum of topics and applications, ranging from specific and practical to general and theoretical. Professor McCluskey is working with several different projects, all investigating varying aspects of computer reliability. One particular effort is a study with NASA of a computer system to be placed in an airplane within a year. This kind of implementation provides a chance to try out theoretical results in a practical environment.

A major emphasis of research in reliability is the design of general techniques for improving reliability, as well as methods for evaluating and comparing the resulting techniques. For example, an early model for reliability was Von Neumann's proposal of triplicated systems, where the non-matching value of the three is considered to be at fault. This model has been generalized to that of triplicated systems with spares, and to more complex configurations; several new techniques for improving reliability are being studied in these more general settings. Another project along these lines involves the actual design of a self-diagnosing mini-computer with the capability of detecting internal errors and reporting their presence and location to the outside world. The general problem of fault testing and diagnosis in arbitrary logic networks is also being studied; methods of network testing include manipulation of gate-equivalent algebraic expressions and probabilistic test generation.

Professor McCluskey believes that reliability is an important research area because most topics have aspects that involve reliability in one form or another, so that many different problems can be studied with respect to a unified approach. Furthermore, reliability in computing is becoming more and more significant for several reasons: computer systems are being used in an increasing number of places where their reliability is vital; computer systems continue to become bigger, and hence require more safeguards; and with electronic components becoming cheaper, the user can afford and ask for increasingly sophisticated reliability equipment and mechanisms.

Lynn Quam
Research Associate, AI Lab

*computer vision
contour mapping
hardware for vision*

For several years the AI Lab has had a four-wheeled cart containing a TV camera and transmitter for sending pictures to the PDP-10, and a radio receiver for receiving commands from the computer. One of the problems Dr. Quam has been working on is the development of a system which will enable the computer to make the cart do some interesting or useful task, such as driving on the road. In order to accomplish this, many vision problems must be solved. To move the car reliably from one position to another the TV images must be analyzed in real time to make sure that the cart is on the proper course, and to find features such as the road center line, road edges, and obstacles in the cart's path.

Unlike the the hand-eye domain, where it is possible to exercise control over the lighting, the background and virtually every property of the environment, the nature of the road problem requires the development of techniques which operate in a visually hostile environment. An important application of the computer-controlled cart is the unmanned exploration of space, in particular the planets, where the round trip radio transmission time to Earth is too long to control every movement of the vehicle from Earth.

Dr. Quam has also been working on producing elevation contours from stereo image pairs, where the problem is the production of accurate and efficient methods for the matching of small areas in pairs of images. The 1976 NASA Mars Viking lander mission would like to generate contour maps for all potential landing sites, in order to pick one which is both interesting and safe. Use of traditional analog photogrammetric techniques would introduce a delay of perhaps several days, while computer processing of the images might reduce the delay to several hours.

Finally, he has been working on the design of hardware to support research in real-time vision and manipulation. It will consist of a DEC PDP-11/45 as the general purpose processor, an SPS-41 for signal processing operations, a TV image input and output facility, and a large, high-bandwidth Intel memory system which will connect to all components of the system, all of which will be under overall control of the PDP-10. This new hardware will give factors of thirty in the performance of various image processing programs, but more important, it will permit experiments which would have been too time-consuming before.

Arthur Samuel
Senior Research Associate, AI Lab

speech recognition

Dr. Samuel, who spent a number of years working on one of the earliest and most successful AI game playing programs, **has** recently turned his attention to the machine recognition of human speech. Working in coordination with a large ARPA-supported project centered at several other institutions, his group at Stanford has concentrated on the problem from the standpoint of acoustics. Their **approach has** been based on adaptive learning techniques implemented with a signature table method similar to the one used successfully in the checker playing program. The tables are built from statistics of the parameters of Fourier transforms of speech segments, and then assembled into hierarchies intended to handle different aspects of the segmentation and recognition problem. Some tables will deal primarily with acoustic parameters expected to be independent of individual speakers, while other tables will attempt to account for parameters specific to, at **best** regional accents, and at worst, individual speakers.

The problem will apparently not soon be solved, however. Dr. Samuel anticipates that it will be almost ten years before large scale **success** is achieved.

Harold S. Stone
Associate Professor of Computer Science
and Electrical Engineering

*parallel computer organization
algorithms for parallel computers*

The general direction of Professor Stone's research is the study of parallel computers and techniques for their efficient programming. He works in computer organization and the development of new algorithms for solving problems. Many algorithms that are not optimal on a sequential machine can be re-considered when multiple processors are available, and new studies can be made of long-standing methods to analyze their behavior in a parallel computing environment. Two particular topics that have been considered are: various ways of interconnecting processors and memories in a highly parallel computer such as the ILLIAC IV, leading to intensive study of applications of a permutation **called the** perfect shuffle and its variants; and algorithms based on the use of recurrence relations for the solution of tridiagonal linear systems on computers with vector instructions. Professor Stone is now working on a study of message routing in computer networks, where the control is done locally at the nodes without global control. The routing and control mechanisms developed thus far have wide theoretical interest and practical application (for **example, in the ARPA** network).

Future research will continue to **explore** innovative directions in computer architecture, especially distributed computing, microprocessors, and memory systems.

Professor Stone sees this research as valuable because the progress of computer technology has created many questions that have not been fully answered by present research. Today there are increasing capabilities in design, and greater freedom in constructing large digital systems. Appropriate **research can thus** guide the implementation of computer systems for applications that were previously impossible,

Yorick Wilks
Research Associate, AI Lab

*natural language
machine translation*

Dr. Wilks has been working for the past few years on machine translation and understanding of natural language. His current project takes short paragraphs of English text and translates them into good French. Its ultimate aim is both to provide a tool for a finite and useful task, and to advance the notion of a semantics-based system for understanding the content of a text. 'Machine translation was written off prematurely because there seemed to be no clear way ahead for the representation of semantic, or conceptual, content on the one hand, and for the representation and manipulation of knowledge of the real world, on the other.

It is a premise of his work that the basic problems of natural language semantics have simply not been solved, either by the linguists or the AI people in the field, and that insights about the structure of **language are still needed**. To this end he avoids the grammatical and semantic systems of the linguists, and the deductive systems of logicians. The essential part of the system that aims to offer a little of the missing content is what he calls "Preference Semantics".

The present system operates with complex trees of semantic markers expressing the meaning structure of English words. It also has access to a system of context dependent semantic patterns called templates that pick out structures of trees to represent possible meaning structures for English clauses, **phrases** and sentences. There is no conventional linguistic syntax used, or needed -- at all operations are specified as manipulations of the patterns of semantic trees,

The key point is that word sense and structural ambiguity will always give rise to alternative competing structures. "Preference" here means procedures at every level of the system for preferring certain derived structures to others on the basis of their "semantic density".

He postulates that humans always interpret language so as to reduce the conceptual density [amount of new information required] to a minimum; without this faculty a language understanding system cannot function. The point about preference is that it prefers the normal, but accepts the unusual. Dr. Wilks believes that conventional linguistic rules, with fixed word classes, operating with (unintelligent) derivational systems cannot do this very simple thing. These preference computations can become quite complex at higher levels when "common

sense inference" rules are used to make inferences from partial information about the real world, such as solving problems like the reference of ambiguous pronouns.

An interesting aspect of the system is that it has' a uniform system of representation and inference, not a series of conventionally distinguished "packets" like syntax, semantics, and deduction. In addition, it works on quite complex material, and in a psychologically satisfying way.

Terry Winograd
Visiting Assistant Professor
of Computer Science

*natural language
representation of knowledge*

Professor Winograd's recent work has been in computer understanding of natural language, which he sees as a key to understanding the much broader problem of human cognition. "I'm interested in how people think, and natural language is a good way to get at that," He sees representation of knowledge as a critical subproblem, and is investigating the correspondence between a set of pieces of knowledge and its incarnation in a program for natural language. One approach to this adopts an automatic programming-like view of the human knowledge assimilation process, in suggesting the presence of an internal parser and compiler which transform bits of knowledge into internal subroutines available for use. His approach includes the belief that such automatic programming should be based on a strong foundation of knowledge about programming rather than on transformations suggested by input/output pairs. He also feels that learning by example is useful for knowledge acquisition, and that much may be gained by investigating the structures necessary for its implementation,

His interest in AI is aroused by its implications about the character of human intelligence, and he believes that the computational metaphor will make an important difference in many fields. It is, he feels, a new and exciting way of looking at many classic problems in varied fields.

SECTION 2

Research in Combinatorics and Analysis of Algorithms

Professors Knuth, Chvatal, and Dantzig, together with graduate students and mathematicians who are invited to visit Stanford for extended periods, are actively pursuing research in combinatorial mathematics. This subject, which links mathematics with operations research, artificial intelligence, electrical engineering, and computer science, is presently flourishing in many parts of the world, and the group at Stanford has been holding productive seminars. Problems relevant to the analysis of algorithms are given special consideration.

Present plans are to have an especially large group of visitors during the 1974-75 academic year. A small sample of people who spoke at the 1972-73 seminars includes: Prof. Marshall Hall, Jr., California Institute of Technology; Prof. D.R. Fulkerson, Cornell University; Prof. Paul Erdos, Hungarian Academy of Sciences; Prof. J. Edmonds, University of Waterloo; Prof. Robert Floyd, Stanford University; and Prof. N.G. de Bruijn, Technological University, The Netherlands,

Recent publications include:

Dantzig, G. On the Relation of Operations Research to Mathematics, **Stanford O.R. Report**, September 1972.

Klarner, D. and R. Rivest, Asymptotic Bounds for the Number of Convex n-ominoes, **Stanford Computer Science Report CS 327**, Dec. 1972.

Klarner, D., A Finite Basis Theorem Revisited, **Stanford Computer Science Report CS 338**, Feb. 1973.

Klarner, D., The Number of SDR's in Certain Regular Systems, **Stanford Computer Science Report CS 354**, April 1973.

Knuth, D., and F. Stevenson, Optimum Measurement Points for Program Frequency Counts, to appear in *BIT*, **13**(1973), 313-322.

Knuth, D., The Asymptotic Number of Geometries, to appear in *Journal of Combinatorial Theory*, 1974.

Knuth, D., Wheels within Wheels, to appear in *Discrete Mathematics*, 1974.

Knuth, D., Permutations with Nonnegative Partial Sums, *Discrete Mathematics*, **5**: 367-71, 1973.

Knuth, D. and O. Amble, Ordered Hash Tables, to appear in *The Computer Journal*, 1974.

Knuth, D., The Triel: A New Solution, *Journal of Recreational Mathematics* **6**: 1-7, 1973.

Knuth, D., **Matroid partitioning**, **Stanford Computer Science Report CS 342**, May 1973,

Digital Systems Laboratory

The Digital Systems Laboratory (DSL) is a collection of faculty and graduate students from Computer Science and Electrical Engineering who are interested in digital systems and computer organization; it is part of the Stanford Electronics Laboratories. Faculty members include Professors Edward J. McCluskey (Director), Forest Baskett, Thomas Bredt, Vinton Cerf, and Harold Stone. Among the areas of active research at DSL are reliability, analysis and measurement of operating systems, computer networks, and parallel computation.

There are several special-interest groups which meet regularly at seminars devoted to particular areas. These include PIGS (parallel information group), RATS (reliability and testing), PETS (performance and evaluation techniques), and AARDVARKS (architecture).

Recent publications include:

- Baskett, F., K.M. Chandy, R.R. Muntz, and F.G. Palacios, "Open, Closed, and Mixed Networks of Queues with Different Classes of Customers", to appear, *Journal of the ACM*, already published as Tech. Report No. 33, Digital Systems Laboratory, Stanford University, Stanford, California, August 1972.
- Bredt, T.H., "Syntax-Directed Operating Systems Design," Tech. Note 29, Digital Systems Laboratory, Stanford University, Stanford, Calif., Dec. 1972.
- Bredt, T.H., "Analysis of Parallel Systems", *IEEE Trans. on Computers*, C-20, No. 11, 1403-1406, Nov. 1971.
- Carr, C.S., S. Crocker, and V. Cerf, "HOST-HOST Communication Protocol in the ARPA Network", *AFIPS Proceedings of the 1970 SJCC*, pp. 589-597.
- Cerf, V., E. Harslem, J. Heafner, R. Metcalfe, and J. White, "An Experimental Service for Adaptable Data Reconfiguration", *IEEE Trans. on Communications*, COM-20, No. 3, pp. 557-564, June 1972.
- Fuller, S. and F. Baskett, "An Analysis of Drum Storage Units", to appear, *Journal of the ACM*, already published as Tech. Report No. 26, Digital Systems Laboratory, Stanford University, Stanford, Calif., August 1972.
- Kogge, P.M., and H.S. Stone, "Efficient Parallel Solution of Linear Recurrences", *IEEE Trans. on Computers*, Aug. 1973.
- McCluskey, E.J., and F.W. Clegg, "Fault Equivalence in Combinational Logic Networks", *IEEE Trans. on Computers*, C-20: 1286-1293, 1971.
- McCluskey, E.J., and D.P. Siewiorek, "An Iterative Cell Switch Design for Hybrid Redundancy", *IEEE Trans. on Computers*, C-22: 290-297, 1973.
- Stone, H.S., "Dynamic Memories with Enhanced Data Access", *IEEE Trans. on Computers*, C-21:359-366, No. 4.

Heuristic Programming Project (DENDRAL)

Principal Investigators: Edward Feigenbaum, Joshua Lederberg, Carl Djerassi

Associate Investigator: Bruce Buchanan

Research Associates: Robert Englemore, Dennis Smith, N. Sridharan

Post-Doctoral Fellows: Ray Cathart, Geoff Dromey

The Heuristic Programming Project is an interdisciplinary group working on information processing models of scientific reasoning. A performance program, termed Heuristic DENDRAL, reasons from empirical data, to explanatory hypotheses. Its task domain is mass spectrometry, one discipline within analytic chemistry, in which the empirical data are analytic data from a mass spectrometer, and the explanatory hypotheses are the graph structures of organic molecules. The program is written as a heuristic search program through the space of molecular graphs. Knowledge of chemistry in general, and mass spectrometry in particular, is used to constrain the search.

Recent advances in the project include the enhancement of the capabilities of the performance program to analyze estrogens and estrogen mixtures, as well as the development and proof of correctness of an algorithm for generating cyclic graph structures. Work is also currently going on in the application of the program to biomedical problems. In particular, it is hoped that the mass spectra analysis can be coupled to information available from gas chromatography, and this powerful combination used in such problems as analysis of the chemical components of urine in premature infants.

A theory-formatting program, termed Meta-DENDRAL, reasons from collections of empirical observations to general rules (a theory), also in the domain of mass spectrometry. Theory formatting of this sort is seen as one important way for large knowledge-based systems to acquire the expertise that they need for high performance. In this case, the rules that are inferred are used by the analysis program described above.

Robert Englemore, in collaboration with chemists at UCSD, is investigating new ways to elucidate the three-dimensional structure of protein molecules, relying primarily on inferential reasoning rather than extensive empirical data. Working with 3-D intensity data produced by X-ray diffraction, they hypothesize partial structures and use Patterson functions for verification. The approach is still being tested in molecules of known structure, but will soon be tried on those whose structure is as yet unknown.

Recent publications include:

B.G. Buchanan, E.A. Feigenbaum, and J. Lederberg, A Heuristic Programming Study of Theory Formatting in Science, in *Proceedings of the Second International Joint Conference on Artificial Intelligence*, Imperial College, London (September 1971).

B.G. Buchanan, A.M. Duffield, and A.V. Robertson, An Application of Artificial Intelligence to the Interpretation of Mass Spectra, *Mass Spectrometry Techniques and Applications*, (edited by George W.A. Milne), John Wiley and Sons, Inc., 121-177 (1971).

D.H. Smith, B.G. Buchanan, R.S. Englemore, A.M. Duffield, A. Yeo, E.A. Feigenbaum, J. Lederberg, and C. Djerassi, Applications of Artificial Intelligence for Chemical Inference VIII. An Approach to the Computer Interpretation of the High Resolution Mass Spectra of Complex Molecules. Structure Elucidation of Estrogenic Steroids, *Journal of the American Chemical Society*, 94: 5362-5371 (1972).

6. G. Buchanan, E.A. Feigenbaum, and N.S. Sridharan, Heuristic Theory Formation: Data Interpretation and Rule Formation, in *Machine Intelligence 7*, Edinburgh University Press (1972).

H. Brown, L. Masinter, and L. Hjelmeland, Constructive Graph Labeling Using Double Cosets, to appear in *Discrete Mathematics*.

D.H. Smith, B.G. Buchanan, R.S. Engelmores, H. Aldercreutz and C.Djerassi, Applications of Artificial Intelligence for Chemical Inference IX. Analysis of Mixtures Without Prior Separation as Illustrated for Estrogens, to appear in *Journal of the American Chemical Society*.

D.H. Smith, B.G. Buchanan, W.C. White, E.A. Feigenbaum, C.Djerassi, and J.Lederberg, Applications of Artificial Intelligence for Chemical Inference X. Intsum. A Data Interpretation Program as Applied to the Collected Mass Spectra of Estrogenic Steroids, to appear, in *Tetrahedron*.

B.G. Buchanan and N. S. Sridharan, Rule Formation on Non-Homogeneous Classes of Objects, in *Proceedings of the Third International Joint Conference on Artificial Intelligence*, Stanford, California, August 1973.

D. Michie and B.G. Buchanan, Current Status of the Heuristic DENDRAL Program for Applying Artificial Intelligence to the Interpretation of Mass Spectra, August 1973.

Higher Mental Functions Project

The Higher Mental Functions Project, funded by the National Institute of Mental Health, is doing research in four areas: (1) machine understanding of natural language, (2) computer simulation of paranoia, (3) psychiatric interviewing by computer, and (4) computer-aided treatment of nonspeaking autistic children. Currently a large portion of the effort is devoted to the natural language problem since areas (2) and (3) are heavily dependent on its solution.

Recent publications:

K.M. Colby, F.D. Hilf, S. Weber, and H. Kraemer, H. Turing-like Indistinguishability Tests for the Validation of a Computer Simulation of Paranoid Processes, *Artificial Intelligence*, 3: 199-221, (1972).

_____ and F.D. Hilf, Can Expert Judges, Using Transcripts of Teletyped Psychiatric Interviews, Distinguish Human Paranoid Patients From a Computer Simulation of Paranoid Processes? Stanford Artificial Intelligence Project Memo AIM-182. Computer Science Department, Stanford University, December 1972.

Computer Simulation of Belief Systems. In *Computer Models of Thought and Language*, R. Schank R. and K.M. Colby, (Eds) W.H. Freeman, San Francisco, 1973.

K.M. Colby, The Rationale for Computer Based Treatment of Language Difficulties in Nonspeaking Autistic Children. Stanford Artificial Intelligence Laboratory Memo AIM-193. Computer Science Department, Stanford University, March 1973. (To appear in *Journal of Autism and Childhood Schizophrenia*),

_____ and F.D. Hilf, MultiDimensional Analysis in Evaluating a Simulation of Paranoid Thought Processes. Stanford Artificial Intelligence Laboratory Memo AIM-194. Computer Science Department, Stanford University, May 1973.

H. Enea and K.M. Colby, 'Idiolectic' Language Analysis for Understanding Doctor-Patient Dialogues. *Proc. 3IJCAI*, Stanford University, 1973.

R. Schank and K.M. Colby (Eds.), *Computer Models of Thought and Language*. W.H. Freeman, San Francisco, 1973.

K. Colby, Artificial Paranoia (in press 1974).

Numerical Analysis Group

The numerical analysis group at Stanford includes Professor Gene H. Golub and Professor John G. Herriot as the permanent faculty members, and about ten graduate students; their interests are supplemented by those of visiting scholars who are at Stanford for various parts of each year. The research in numerical analysis involves two closely related aspects: development of mathematically based theory to solve a particular problem; and implementation of appropriate computer algorithms, with emphasis on programming considerations such as coding efficiency, numerical accuracy, generality of application, data structures, and machine independence.

A fairly broad library of programs to solve numerical problems is informally maintained by the numerical analysis group, in cooperation with the Stanford Campus Computation Center. Connections are also maintained with the program library efforts of the NATS project at Argonne, Illinois, and the Nottingham Algorithms Group in England.

Recent publications include:

- Concus, P., and G. H. Golub, "Use of Fast Direct Methods for the Efficient Numerical Solution of Nonseparable Elliptic Equations", to appear in *SIAM Journal of Numerical Analysis*.
- Dent, W., and G.H. Golub, "Computation of the Limited Information Maximum Likelihood Estimator", in *Proceedings of the Computer Science and Statistics Sixth Annual Symposium on the Interface*, M. Tarter (ed.), Western Periodicals Co., pp. 60-65 (1972).
- Forsythe, G.E., and E.H. Lee, "Variational Study of Nonlinear Spline Curves", *SIAM Review*, 15, No. 1, pp. 120-133 (1973).
- Gill, P., G. H. Golub, W. Murray, and M. Saunders, "Methods for Modifying Matrix Factorizations", to appear in *Mathematics of Computation*, already published as Stanford Computer Science Report CS 322, Nov. 1972.
- Golub, G.H., "Some Modified matrix Eigenvalue Problems", *SIAM Review*, 15 pp. 318-344 (1973).
- Golub, G.H., and V. Pereyra, "The Differentiation of Pseudo-Inverses and Nonlinear Least Squares whose Variables Separate", *SIAM Journal of Numerical Analysis*, 10, No. 2, pp. 413-432 (1973).
- Herriot, J.G., and C. Reinsch, "ALGOL 60 Procedures for the Calculation of Interpolating Natural Spline Functions", to appear in *Communications of the ACM*, Dec. 1973, already published as Stanford Computer Science Report CS 200, Feb. 1971.
- Kaufman, L., "The LZ Algorithm to Solve the Generalized Eigenvalue Problem", -Stanford Computer Science Report CS 363, May 1973.
- Malcolm, M. and J. Palmer, "A Fast Method for Solving a Class of Tri-diagonal Linear Systems", to appear in *Communications of the ACM*, Jan. 1974, already published as Stanford Computer Science Report CS 323, Nov. 1972.
- Saunders, M. A., "Large-Scale Linear Programming using the Cholesky Factorization", Stanford Computer Science Report CS 252, 1972.

Stanford **Artificial** Intelligence Laboratory

Director: John McCarthy
Associate Director & Executive Officer: Lester Earnest
Associate Director: Jerome Feldman

Research group leaders: Jerome Feldman, Cordell I Green, David Luckham, John McCarthy, Lynn Quam, Arthur Samuel, Richard Weyhrauch, Yorick Wilks

The Artificial Intelligence Laboratory is located in the D. C. Power Building, about five miles from campus, near Felt Lake. Currently, there are 120 faculty, staff, and graduate students doing research in artificial intelligence and related fields. Laboratory facilities include a timesharing system based on PDP-10 and FOP-6 computers with 64 display terminals attached. A DEC PDP 11/45 and an SPS-41 signal processor are currently being added to aid work in computer vision and manipulation.

The largest project in the laboratory is devoted to "Hand-Eye" systems, in which the computer attempts to perceive three-dimensional objects from digitized television images and to manipulate these objects using computer-control led mechanical arms. Recent efforts have led to the fully automated assembly of an automobile water pump; other more complex tasks are currently being undertaken. Potential application areas include industrial **assembly** tasks and planetary exploration missions.

(Feldman)

Another vision-oriented project is developing interactive photo-interpretation systems. These techniques are being used to examine photographs of Mars returned by the Mariner Satellites, with the aim of finding features that have changed between observations. A number of interesting features have been found.

(Quam)

Work on mathematical theory of computation and automatic theorem proving is developing a theoretical basis for making mathematical proofs of what certain computer programs do or don't do. In the long run, it is hoped that imperfect program debugging techniques can be replaced by rigorous proofs.

(McCarthy, Green, Luckham, Weyhrauch)

There are small projects on computer recognition of human speech, machine translation (currently, English to French), and symbolic computation. Some computer support is also being provided to members of the Stanford Music Department, for work on computer-generated music.

(Samuel, Wilks)

Considerable effort has gone into the development of support facilities. Current projects include improvements to SAIL and the development of LISP 70. SAIL is an ALGOL-based language for artificial intelligence that includes a rich collection of data structures incorporated into an associative memory, while LISP 70 is intended to be an extensible, compiler-based language with pattern **matching** and back track capabilities.

Recent Articles

Vision and Manipulation

Gerald J. Agin and Thomas O. Binford, Computer Description of 'Curved Objects, *Proc. 3IJCAI*, Stanford University, August 1973,

Ruzena Bajcsy, Computer Description of Textured Scenes, *Proc. 3IJCAI*, Stanford University, August 1973.

Thomas O. Binford, Sensor Systems for Manipulation, in E. Heer (Ed.), *Remotely Manned Systems*, Calif. Inst. of Technology, 1973,

Thomas Binford and Jay M. Tenenbaum, Computer Vision, *Computer (IEEE)*, May 1973.

Manfred H. Hueckel, A Local Visual Operator which Recognizes Edges and Lines, *J. ACM*, October 1973.

Boris M. Dobrotin and Victor D. Scheinman, Design of a Computer Controlled Manipulator for Robot Research, *Proc. 3IJCAI*, Stanford University, August 1973.

Ramakant Nevatia and Thomas O. Binford, Structured Descriptions of Complex Objects, *Proc. 3IJCAI*, Stanford University, August 1973,

Irwin Sobel, On Calibrating Computer Controlled Cameras for Perceiving 3-D Scenes, *Proc. 3IJCAI*, Stanford University, August 1973.

Yoram Yakimovsky and Jerome A. Feldman, A Semantics-Based Decision-Theoretic Region Analyzer, *Proc. 3IJCAI*, Stanford University, August 1973,

Theorem Proving and Mathematical Theory of Computation

E. Ashcroft, Z. Manna, and A. Pnueli, Decidable Properties of Monadic Functional Schemas, *J. ACM*, July 1973,

Stephen J. Garland and David C. Luckham, Program Schemas, Recursion Schemas, and Formal Languages, *J. Computer and System Sciences*, 7, No. 2, April 1973.

Shmuel Katz and Zohar Manna, A Heuristic Approach to Program Verification, *Proc. 3IJCAI*, Stanford University, August 1973.

R. Kieburtz and D. Luckham, Computability and Complexity of Refinements of the Resolution Principle, *SIAM J. on Computing*, 1-4, 1973.

David C. Luckham, Automatic Problem Solving, *Proc. 3IJCAI*, Stanford University, August 1973.

Zohar Manna, Program Schemas, in *Currents in the Theory of Computing* (A.V. Aho, Ed.), Prentice-Hall, Englewood Cliffs, N.J., 1973,

Zohar Manna, *Introduction To Mathematical Theory of Computation*, McGraw-Hill, New York, 1974.

Zohar Manna, Stephen Ness, Jean Vuillemin, Inductive Methods for Proving Properties of Programs, *Comm. ACM*, August 1973.

Natural Language and Machine Translation

Y. Wilks and A. Herskovits, An Intelligent Analyser and Generator of Natural Language, *Proc. Int. Conf. on Computational Linguistics, Pisa, 1973. Proc. 3IJCAI*, Stanford University, August 1973.

Roger C. Schank, Neil Goldman, Charles J. Rieger III, Chris Riesbeck, MARGIE: Memory, Analysis, Response Generation and Inference on English, *Proc. 3IJCAI*, Stanford University, August 1973.

Picture Processing

L. Quam, R. Tucker, B. Eross, J. Veverka and Carl Sagan, Mariner 5 Picture Differencing at Stanford, *Sky and Telescope*, August 1973.

C. Sagan, J. Veverka, P. Fox, R. Dubisch, J. Lederberg, E. Levinthal, L. Quam, R. Tucker, J. B. Pollack, and B. A. Smith, Variable Features on Mars: Preliminary Mariner 5 Television Results, *Icarus*, 17:346-372, 1972.

Language Development

J.A. Feldman, J.R. Low, D.C. Swinehart, and R.H. Taylor, Recent Developments in SAIL, *AFIPS Fall joint Conference* 1972, pp 1193-1202.

David C. Smith and Horace J. Enea, Backtracking in MLISP2, *Proc. 3IJCAI*, Stanford University, August 1973.

Lawrence G. Tesler, Horace J. Enea, and David C. Smith, The LISP70 Pattern Matching System, *Proc. 3IJCAI*, Stanford University, August 1973.

Music

John M. Chowning, The Synthesis of Complex Audio Spectra by means of Frequency Modulation, *J. Audio Engineering Society*, September 1973.

Leland Smith, Editing and Printing Music by Computer, *J. Music Theory*, Fall 1973.

Recent AI Reports

Theorem Proving

Newey, Malcolm. AXIOMS AND THEOREMS FOR INTEGERS, LISTS AND FINITE SETS IN LCF
CS 330, January 1973

Milner, Robin. MODELS OF LCF
CS 332, January 1973

Chandra, Ashok and Manna, Zohar. ON THE POWER OF PROGRAMMING FEATURES
CS 333, February 1973

Chandra, Ashok. ON THE PROPERTIES AND APPLICATIONS OF PROGRAMMING SCHEMAS
CS 336, March 1973

Igarashi, Shigeru, Luckham, David C., London, Ralph L.,
AUTOMATIC PROGRAM VERIFICATION I. LOGICAL BASIS AND ITS IMPLEMENTATION
CS 365, May 1973

Speech Recognition

Thosar, R. B. ESTIMATION OF PROBABILITY DENSITY USING SIGNATURE TABLES FOR
APPLICATION TO PATTERN RECOGNITION
CS 364, May 1973

Thosar, R.B. RECOGNITION OF CONTINUOUS SPEECH: SEGMENTATION AND CLASSIFICATION
USING SIGNATURE TABLE ADAPTATION
CS 365, September 1973

Natural Language and Machine Translation

Schank, Roger. THE FOURTEEN PRIMITIVE ACTIONS AND THEIR INFERENCES
CS 344, February 1973

Schank, Roger C., THE DEVELOPMENT OF CONCEPTUAL STRUCTURES IN CHILDREN
CS 363, May 1973

Wilks, Yorick, PREFERENCE SEMANTICS
CS 377, July 1973

Herskovits, Annette. THE GENERATION OF FRENCH FROM A SEMANTIC REPRESENTATION
CS 384, September 1973

Other

Gips, James and Stiny, George. AESTHETICS SYSTEMS
CS 337, February 1973

Moorer, James Anderson, THE HETRODYNE METHOD OF ANALYSIS OF TRANSIENT WAVEFORMS
CS 379, June 1973

Baumgart, Bruce G., IMAGE CONTOURING AND COMPARING
CS 398, December 1973