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A REVIEW OF RESEARCH IN INFORMATION PROCESSING

CARNEGIE-MELLON UNIVERSITY

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This is the final report for contract F44620-70-C-0107 monitored by the Air Force Office of Scientific Research, running from 1 July 1970 to 30 June 1973. A complete bibliography of reports produced during this period is presented at the end, organized by year and by author within year. A conventional set of headings for discussing the research is a division into Artificial Intelligence, Speech Understanding, Cmmmp (the multiminiprocessor), Programming Systems, Computer Structures, and Theoretical Studies.

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INTRODUCTION

This is the final report for contract F44620-70-C-0107 monitored by the Air Force Office of Scientific Research, running from 1 July 1970 to 30 June 1973.

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The three year period under review is an interval in a long term program of research at CMU into the nature of information processing. It started in 1962, originally as SD146, and came under AFOSR monitorship in May, 1966. The scope of the project has always included much of computer science. The focus was artificial intelligence and programming languages in the early years, shifting to artificial intelligence, programming systems, and computer structures in the period under discussion (as major faculty members joined and left the environment).

The product of a broad research program is never a single result, but a range of scientific advances, some smaller, some larger. The major indicators of these scientific advances are the scientific publications. Thus, the essential function of a final report is to provide an index into these documents -- one that provides enough context so that the total effect of the research environment can be seen. Such a view misses some things. One is the feeling for the environment as an intellectual climate -- a "thing" bought by the research contract as much as hardware, software or specific results. We have published for seven years now a Computer Science Annual Research Review, which consists of specially written short review articles and essays, and which by its style and content tries to convey the nature and excitement of the environment (Nissenson, 1966; Dewald, 1967; Lisle, 1968, 1969; Moran, 1971; Shoub, 1972; Anderson & Covaleski, 1973).

A second thing missed by the articles is the physical facilities created in the environment by the contract. This is appropriate for this report and we include a brief section on the facilities at the end of the report.

ARTIFICIAL INTELLIGENCE

CMU has always carried out a broad program of research into many aspects of artificial intelligence. A review of the general field can be found in Simon (1971a), an invited general paper at IFIP-71. This work has always gone on in close interaction with work on an information processing psychology, under the view that both operated to each other's advantage. The evidence appears favorable, and the trend of current work is, if anything, toward even greater interaction.

Problem Solving

The three years has seen the start of an intensive effort on chess, after a hiatus of several years. Hans Berliner brought into the environment a chess program developed at IBM and tested it both in tournament play and in the ACM Chess Machine Tournament (Berliner, 1970a). A new "technology" program was created (Gillogly, 1972), to verify the proposition that a chess program with little more than brute force search could play respectable chess (which had arisen with the surprising performance of a minicomputer during the First ACM Chess Tournament). In addition to the purely artificial intelligence attempts to understand chess, psychological studies on chess perception have produced strong evidence of the role of a very large organized long term memory in human master play (Chase & Simon, 1973; Simon and Gilmartin, 1973). These studies have implications for chess playing programs.

An effort by Fikes to design a general problem solver (called REF-ARF) has been followed up by an attempt to give it some more goal direction (Gibbons, 1972).

Understanding Programs

The main current effort on studying what is required for a program to understand a domain of knowledge has been a program called Merlin (Moore, 1971). This work has been an exploration into how a system assimilates new information in terms of what it already knows about (i.e., its existing structure). This notion can be made the basis for a general representation of knowledge.

A recent book has been published containing a number of studies, into meaning and the representation of information (Simon & Siklossy, 1972). Several of the studies are theses done in this research program during an earlier period. A recent exploration by a visiting scientist can be found in Sirovich (1972).

Design

The activity of design is common enough in computer science, from hardware, to software, to total systems. Much of of CS research involves design as the creatively essential step. Yet little is known about the intellectual activity of design -- what constitutes it, how humans perform it, etc. Part of the research at CMU over the last few years can be seen as a probe in this direction. It can conveniently be summarized under the rubric of artificial intelligence, though it might be considered a area in its own right.

One aspect has focused on spatial design, that is, one the design of floor plans, rooms, architectural sites, etc. (Eastman, 1971, 1972, 1973; Eastman & Yessios, 1972; Grason, 1970; Pfefferkorn, 1971). Another has focussed on the nature of software design (Freeman, 1970; Freeman & Newell, 1971).

Vision

A small effort has been carried on in some problems of vision. This has two aspects. One is an analogue of the speech work and focusses on input of external scenes and the their recognition and internal description in understandable form (Reddy & Montanari, 1971: see also Montanari, 1971, for some theoretical work). The other has to do with the process of visualization, i.e., where the system constructs images internally (Moran, 1973). This latter is also related to work in production systems and the nature of human visual processing.

Human Problem Solving and Production Systems

As noted, direct work on cognitive psychology per se is not part of the ARPA contract. However, the connections between AI and cognitive processes are extremely close and the two research efforts are carried on together (with most of the cognitive processes research under NIMH, NSF and foundation support). A general description of the relations between artificial intelligence and psychology can be found in (Newell, 1970).

The year 1972 saw the publication of a major book on information processing pychology (Newell & Simon, 1972; see Simon & Newell, 1971 for a brief statement). This work was the culmination of 17 years of study of human problem solving and put forth a theory for how the class of tasks studied (small formal symbolic tasks) were performed by humans.

One important component of the book was the use of production systems (as that term is used in theoretical computer science -- Post productions, Markoff productions) as the appropriate control structure for describing human cognition. This form of information processing structure makes connection between the higher level processes in the puzzles and games studied in the book and the detailed architectural structure studied in psychology by means of memory and reaction time experiments. We have been following up this lead and have applied production systems to some of these latter experiments (Newell, 1972, 1973). Work by Moran (1973) also explores this topic.

The work on human problem solving has depended strongly on the interpretation of protocols of the verbal behavior of humans while solving problems. The task of analyzing protocols is both time consuming and has subjective aspects. We have undertaken the development of a system (PAS) for automatic analysis of protocols by means of an artificial intelligence program that can take in the transcribed verbal behavior (the linguistic string) plus a model of the subject (his so-called problem space) and produce an inferred trajectory of the subject through a series of states of knowledge about the task (Waterman and Newell, 1971, 1972). This task is an example of applied artificial intelligence. It also has a strong bond with the work on understanding, above.

In the summer of 1972 we held an intensive workshop for cognitive psychologiests to explore the new computer tools (production systems, automatic protocol analysis, simulations) by interactive operation on the computer (Newell, Simon, Hayes & Gregg, 1972). This was sponsored by the Mathematical Social Science Board with the computer aspects by this contact. Its interest lies not in being a workshop (these occur frequently), but in the attempt to use computer interaction throughout.

SPEECH UNDERSTANDING

In mid 1971 an ARPA study group issued its report, which resulted in the initiation of the ARPA Speech Understanding Effort (Newell, Barnett, Forgie, Green, Klatt, Licklider, Munson, Reddy & Woods, 1971). The distinctive feature of the effort (which gave to it the appellation "understanding" rather than "recognition") was the proposal to build systems that use the entire range of sources of knowledge about the utterance -- from acoustics, through phonological and lexical, to syntax and semantics.

The speech understanding effort at CMU predated this report, having been started here in 1969 when Prof. Reddy came to CMU from Stanford. The inital plans for the system are presented in Reddy, Erman & Neely (1970). A general view of how the field stood in 1971, at the start of the larger ARPA effort is given in an invited IFIP-71 survey paper (Reddy, 1971).

The development of an effective speech system involves much more than just the main performing program. Besides the various real time devices for communicating speech to the machine (by digitization and the extraction of initial parameters), systems are needed for displaying, editing and manipulating the speech data (Brooks, Erman & Neely, 1973). To do this latter we developed our own high quality graphic displays (see Computer Structures).

The first version of the CMU speech understanding system, called HEARSAY-I, became operational in June 1972. The task was Voice-chess, in which the person plays a game of chess with HEARSAY, giving the moves by voice. It realizes a particular view: a set of independent cooperative processes, each embodying a source of knowledge about speech, all working on a common data base that represents the evolving knowledge about the utterance under consideration. In HEARSAY-I there were three such processes: Acoustic, Syntactic, and Semantic. An overall description of HEARSAY-I can be found in Reddy, Erman and Neely (1973) with more detail in Neely (1973) (see also Reddy, 1973; Reddy, Erman & Neely, 1971). As of the end of the period (Summer 1973), the system was in routine operation and was being tuned on four tasks: Voice-chess, a desk calculator, a medical interview task, and the task of retrieval from the AP News Service. It was obtaining about 90% correct performance on Voice Chess, where there was a semantic component, and substantially less where there was no semantics (the other tasks, or with Voice Chess semantics turned off), but still syntax, and even less (around 45%) where there was only acoustics.

Besides the main-line attempt to construct a total system, a number of researches into aspects of the problem and its scientific foundations are also required. A number of these have been written up (Erman & Reddy, 1971; Neely & Reddy, 1971). The papers from the project are periodically gathered together into a series of Working Papers (Reddy, Erman & Neely, 1972).

Preliminary design is underway (at the end of the period) on HEARSAY-II. This is to follow the same general philosophy as HEARSAY-I, while permitting a richer global data structure, many more distinct processes, and the ability to work on a multiprocessing mode. This latter includes being able to capitalize on the C.mmp (Reddy, Bell & Wulf, 1971).

C.mmp: MULTIMINIPROCESSOR

In 1971, as the direct result of the design exercise on C.ai (see Computer Structures) and more long-standing requirements for the use of several minicomputers, we designed a multi-processor system called C.mmp (Bell, Broadley, Wulf, Newell, Pierson, Reddy & Rege, 1971). The underlying premise was the cost effectiveness of multiprocessor organizations with minicomputers as processors. The C.ai effort provided the design idea for a feasible large cross-bar switch.

The system was to consist of 16 PDP11 processors connected to a 16 port memory (with a total of a million words) through a 16x16 switch. The minicomputers would have addressable access to any subset of the total memory in pages of 4096 words (PDP11 words are 16 bits). A recent description of the system can be found in Wulf and Bell (1972).

Multiprocessors, other than dual configurations, are still rare. Thus a 16x16 multiprocessor represents an important point in the design space of computer structures and much is to be learned about the potentialities of this type of system. (Systems such as Illiac IV and STAR are parallel systems with different structure -- single control stream, parallel data streams.) We had at least one task, speech, which lent itself to a parallel organization, several areas of investigation that could exploit multiprocessing (e.g., network studies, Bell, Habermann, McCredie, Rutledge & Wulf, 1970), and a number of simpler uses of minicomputers which could benefit from being embedded in a large organization with access to additional facilities (e.g., peripherals, the PDP10's, etc.).

The original plan called for contracting out the 16x16 switch, the one large component in the system. No suitable manufacturers were found and we have instead designed and constructed the switch in our own laboratory, along with the other components of the system (a large clock, relocation devices for each processor, and processor modifications). We have constructed a 4x4 version as a way-station to the 16x16, both to check out the design and its implementation and to make a system availble for software development as soon as possible.

Inherent in the nature of multiprocessors is the problem of memory conflict -- of two processors wanting access to the same memory port at the same time. No matter how the conflict is resolved, machine cycles are lost; if it happens enough the multiprocessor fails to be cost effective. Simulation studies were done at the time of the original design (for one of them, see McCredie, 1973) that showed only modest degradation with a full 16x16 system. Current (though preliminary) experience seems to be bearing this out.

The operating software for a computer system is as critical as the hardware, turning it into a machine that can actually be used. In the case of multiprocessors the operating system is doubly critical, since the parallel nature of the system makes programming especially complex. Multiprocessing operating systems (again, excluding dual processors) are essentially non-existent. Thus, as part of the C.mmp there is has been a full scale design and construction of a multiprocessing operation system, called

HYDRA (Wulf, Cohen, Corwin, Jones, Levin, Pierson & Pollack, 1973). HYDRA provides a kernel, which is a scheme for the designation of resources and facilities and the arrangement of their protected access and use. Within the kernel one can build up subsystems of the standard facilities of schedulers, allocators, command languges, file systems, device handlers and so on.

Construction of HYDRA has been conducted in a higher level implementation language, BLISS-11 (Wulf, Apperson, Brender, Geschke, Kneuven, Weinstock, Zarella & Wile, 1972). This is a version of BLISS (see Programming Systems) which compiles on the PDP10 and produces PDP11 code.

An important aspect of C.mmp is the analysis of its performance At the design stage these are simulation and analytical studies, but with the operational system there must be extensive measurement on the running system. An important part of this is adequate instrumentation, which is well under way (Fuller, Swan & Wulf, 1973).

The status as of the end of the report period (mid 1973) is that the 4x4 system is running with reasonable reliability (though normally with only three 11/20 processors). HYDRA (the kernel) is essentially working. Work is in progress on a standard subsystem, to be completed in the coming year, after which the system will be available for use. The 16x16 switch is not yet operational, having been held up by delays in obtaining a chip; it is otherwise complete.

PROGRAMMING SYSTEMS

This section covers the work in programming systems exclusive of the work on HYDRA, which is taken as part of the C.mmp effort, though HYDRA also stands on its own as research into operating systems.

Implementation of Systems

A major effort at CMU during the three year period under review has been in implementation languages, which are tools for contructing other programming systems. The main effort has been on BLISS (Wulf, 1970, Wulf, Habermann & Russell, 1971), an implementation language for the PDP10. The language was fully operational at the beginning of the period and a substantial amount of experience has accumulated on its used (Wulf, Geschke, Wile & Apperson, 1971; Wulf, 1972a). It has been used for several large systems, for example, APL (Perlis, Fennell, Pollack, Price & Rizza, 1971), Algol, the chess programs, etc., as well as for BLISS itself and HYDRA.

The production of highly efficient object code is an important goal of BLISS, since it is to be used to produce programming languages and systems. Much attention has been directed to this (Geschke, 1973; Johnsson, 1973; Wile & Geschke, 1972).

Another implementation system, L*, has also been under development during the period (see Newell, Freeman, McCracken & Robertson, 1971 for an early version). Its characteristics are at the opposite pole from those of BLISS. It is highly interactive, does not worry about efficiency directly, and grows systems from a small kernel. It is still under development and has been used for AI programs (Merlin, PSG).

Besides the construction of language-systems for implementing software systems, work has been done in how to structure systems so that they can be implemented easily and faultlessly. Modularization has has been extensively studied by Parnas (1971a, 1971b, 1972b, 1972c; Robinson, 1973; Robinson and Parnas, 1973). The well structured character of programs has been studied by Shaw (1973).

Operating Systems

A concentrated intellectual attack has been made on the fundamental scientific problems of operating systems. A number of studies investigate the basic problem of synchronization of processes (Habermann, 1972a, 1972c; Lipton, 1973; Parnas, 1972d; Parnas & Habermann, 1972; Wodon, 1972). A number investigate the problem of protection (Habermann, 1971; Jones, 1973; Price, 1973). An initial investigation has been made into proving operating systems to be correct (Lauer, 1972).

Programming Languages

The study of programming languages has moved from the creation of total languages to the investigation of the basic mechanisms that go to make up a language. CMU has made a number of contributions to this study: the study of control structures (Wile, 1973; Wulf, 1971, 1972b); of the variability of language processors (Lindstrom, 1970); of the contraction of languages (Shaw, 1972a, 1972b); of the nature of parameter passing (call) mechanisms (Snyder, 1973); and of the programming implications of global variables (Wulf & Shaw, 1973). In addition a study has been made into error correction in context-free grammars (Teitelbaum, 1973).

COMPUTER STRUCTURES AND PERFORMANCE ANALYSIS

This section covers the work on design and construction of hardware systems and on the performance analysis of operating computer systems. It does not cover C.mmp, which is described in another section. An overview of CMU computer structure efforts as of 1971 may be found in Bell & Newell (1971b).

Representations for Computer Structures

Starting with a book on computer structures (Bell & Newell, 1971a) two notations were introduced: PMS to describe the highest system level of processors, memories and switches; and ISP to describe the instruction set in terms of the Register Transfer level. A number of efforts have been made to describe these notations in the literature (Barbacci, Bell and Newell, 1972; Barbacci, Bell and Siewiorek, 1973; Bell and Knudsen, 1972). A computer language system for PMS has been built (Knudsen, 1973) and one for ISP is underway.

C.ai: A Computer System for Artificial Intelligence

In Winter 1970 a study exercise was initiated by ARPA to explore the possibility of a computer system for the ARPA artificial intelligence community. All of the AI laboratories participated. The CMU contribution to this exercise was the design of C.ai (Bell & Freeman, 1971, 1972). C.ai was a large multiprocessor with PDP10-sized processors working into a multimillion word primary memory. The processors could be specialized and two examples were studied to assess the potentialities (Barbacci, Goldberg & Knudsen, 1971; McCracken & Robertson, 1971). The system was not highly specialized, because the list processing that forms the basis of most AI programs is already highly adapted to the current design of processors.

Performance Analysis

Strecker (1970) provided a basic study in the analytic simulation of the gross instruction rate of computer structures (i.e., hardware systems not considering their operating software). Bhandarkar (1973) has extended Stecker's results to cover a broader class of structures (see also Bhatia, 1972). Aygun (1973) provided some software tools that made it possible to measure the basic performace of computer systems.

A series of studies have been made of the performance of time sharing systems (McCredie & Schlesinger, 1970; Courtois, 1971; McCredie, 1972a, 1972b; Bauer & McCredie, 1973).

Some investigation has been made into problems of reliability and the possibilities for designing for it (Siewiorek & Bhandarkar, 1972; Ingle & Siewiorek, 1973).

Impact of Semiconductor Technology

We sponsored a workshop in the Spring of 1973 to assess the impact of large-scale-integration (e.g., a processor on a chip or 4k bits of memory on a chip) on computer structures. Fuller and Siewiorek (1973) have reported the major conclusions.

Graphic Display Devices

The demands of the speech understanding research for the display of large amounts of data including graphs of the wave form and intensity level led us to design our own graphic displays. We have now developed a high quality display (Rosen, 1973) that provides above state of the art capabilities (4000 characters flicker free, with a resolution of 1000x1000 points). for modest cost ($25,000). Each display has its own PDP11/15 processor. The essential development was an extremely fast digital to analogue converter (Kriz, 1973). We have two displays in operation and will have six.

THEORETICAL STUDIES

We group under studies in theoretical computer science investigations into topics that have the possibility of making progre by formalization and proving properties about the formalization. Traditionally, automata theory and mathematical machine theory, mathematical logic and recursive function theory, and mathematical linguistics have tended to span this space. We do not imply that these studies do not have an empiricial component (they often can).

Program Verification

One area is that of verification of programs -- the proof that a program does what is is supposed to do. A decisive step was taken in study by Floyd, when at CMU, in the period before the one under review. This has come to be called the method of assertions, in which once various key assertions are made the rest can be filled in automatically and a proof problem posed which could possibly be settled by mechanical means. The first attempt to realize this system was by King (1970), called the Verifying Compiler. The subfield of verification has rapidly expanded since though not much of it has been done at CMU. However, recently a study has been made of how to apply the method of Floyd Assertions to APL (Gerhart, 1973). APL differs from many of the special somewhat simplified languages used in verification analysis so far, being both a real programming language and having a structure of many complex operators. It should be noted that this area has a close kinship with artificial intelligence.

Automatic Theorem Proving

A second theoretical area is that of automatic theorem proving in the predicate calculus. This field gained it present shape in 1965 from work of Robinson, which introduced a form of inference call Resolution. Since then there has been much activity to erect ever better schemes of inference that keep the combinatorial explosion under control when searching for a proof. Substantial contributions have been made to these attempts for several years by Don Loveland (1970a, 1970b, and additional papers on an NSF grant with Peter Andrews). Recently an interesting connection between the work in resolution theorem proving and work in using goal trees has been found (Loveland & Stickel, 1973). The work on theorem proving is also extremely close to work in artificial intelligence and is often considered to be a part of it.

Beyond these areas there have been a small number of studies in more traditional fields of automatic theory (Selman, 1970; Jones & Selman, 1972; Zalcstein, 1970a, 1970b, 1971).

FACILITIES

The total facilities of the environment consist of a computer system that is generally accessible to all members of the community, plus specialized hardware for speech and for C.mmp, plus a well equipped engineering laboratory, used for design, fabrication and maintenance. We describe only the computer facilities in this section.

The computer system consists of two DEC PDP10's (KA10 processors), the 10A and 10B systems, which operate independently of each other. The 10A is used for general computation. It has currently 176k of core, 5 DECTAPE drives, 2 magnetic tape drives, and 8 RP02 disc drives which provide 40 megawords of secondary storage. The 10B is used primarily for the speech understanding research, and has all the real time speech devices . (It supports general computation as well, in so far as capacity allows, to balance the load of the environment.) The 10B has 208k of core, 5 DECTAPE drives, 2 magnetic tape drives, and 3 RP02 plus 4 RP03 disc drives which provide 55 megawords of secondary storage.

The user interface to the computer system is interactively via teletypes and alphameric scopes. A total of 64 terminal lines are available. Both the 10A and 10B are interfaced to the ARPA Net, and this channel is used for communication between the two systems. In addition there are high quality graphics displays (as described earlier).

Output from the system is via two line printers, and via the XGP (Xerographic Printer) which provides variable width, variable font 8.5x11 page output (Reddy, Erman, Broadley, Johnson, Newcomer, Robertson & Wright, 1972). The XGP uses a PDP11/45 and is connected to the 10's via a direct line.

BIBLIOGRAPHY

Before 1970

Devold, H. (ed.), Computer Science Research Review, Computer Science Department, Carnegie-Mellon University, Pittsburgh, Pennsylvania (1967)

Lisle, C. (ed.), Computer Science Research Review, Computer Science Department, Carnegie-Mellon University, Pittsburgh, Pennsylvania (1968)

Lisle, C. (ed.), Computer Science Research Review, Computer Science Department, Carnegie-Mellon University, Pittsburgh, Pennsylvania (1969)

Nissenson, J. (ed.), Computer Science Research Review, Computer Science Department, Carnegie-Mellon University, Pittsburgh, Pennsylvania (1966)

1970

Bell, C. G., A. N. Habermann, J. McCredie, R. Rutledge and W. Wulf, "Computer Networks," Computer, 13-23 (1970)

Bell, C. G., A. Newell, "The PMS and ISP Descriptive Systems for Computer Structures," AFIPS Conference Proceedings, Spring Joint Computer Conference (1970) 351-374

Berliner, H., "Experiences Gained in Constructing and Testing a Chess Program," Proc. IEEE Symposium on System Science and Cybernetics, Pittsburgh, Pennsylvania (1970a)

Berliner, H., "United States Computer Chess Championship," SIGART Newsletter 19, (1970b)

Freeman, P. A., "Sourcebook for OSD - An Operating System Designer," PhD Thesis, Department of Computer Science, Carnegie-Mellon University (1970)

Grason, J., "Methods for the Computer-Implemented Solution of a Class of 'Floor Plan' Design Problems," PhD Thesis, Department of Systems and Communication Sciences, Carnegie-Mellon University (1970)

King, James C., "A Program Verifier," PhD Thesis, Department of Computer Science, Carnegie-Mellon University (1970)

Lindstrom, Gary, "Variability in Language Processors," PhD Thesis, Department of Computer Science, Carnegie-Mellon University (1970)

Loveland, D., "Some Linear Herbrand Proof Procedures: An Analysis," Computer Science Department, Carnegie-Mellon University (1970a)

Loveland, D. A., "A Linear Format for Resolution," **Lecture Notes on Mathematics (Symposium on Automatic Demonstration) 125**, 147-162 (1970b)

McCredie, J., S. Schlesinger, "A Modular Simulation of TSS/360," **Fourth Conference on Applications of Simulation Proceedings** (1970) 220-206

Newell, A., "Remarks on the Relationship Between Artificial Intelligence and Cognitive Psychology," **Theoretical Approaches to Non-Numerical Problem Solving, Part IV**, edited by R. Banerji and J. D. Merarovic, Springer-Verlag, New York (1970) 363-400

Reddy, D. R., L. Erman and R. Neely, "The CMU Speech Recognition Project," **Proc. 1970 IEEE Cybernetics Conference** (1970)

Selman, A. L., "Applications of Forcing to the Degree-Theory of the Arithmetical Hierarchy," **Journal of the London Mathematical Society** (to appear), (1972)

Strecker, W. D., "An Analysis of the Instruction Rate in Certain Computer Structures," PhD Thesis, Department of Electrical Engineering, Carnegie-Mellon University (1970)

Wulf, W. A., **BLISS: A Systems Programming Language**, University of Pittsburgh Press (1970)

Zalcstein, Y., "A Note on Fast Cyclic Convolution," Computer Science Department, Carnegie-Mellon University (1970a)

Zalcstein, Y., "On Star-Free Events," **Conference Record of the 11th Annual IEEE Symposium on Switching and Automata Theory** (1970b) 76-80

<u>1971</u>

Barbacci, M., H. Goldberg and M. Knudsen, "C.ai (P.LISP)-A LISP processor for C.ai," Computer Science Department, Carnegie-Mellon University (1971)

Bell, C. G., "Minicomputer Architecture and Design," **Proc. Institute of Electrical and Electronics Engineers**, (1971)

Bell, C. G., W. Broadley, W. Wulf, A. Newell, C. Pierson, R. Reddy and S. Rege, "C.mmp: The CMU Multiminiprocessor Computer - Requirements and Overview of the Initial Design," Computer Science Department, Carnegie-Mellon University (1971)

Bell, C. G., P. Freeman, "C.ai: A Computing Environment for AI Research," Computer Science Department, Carnegie-Mellon University (1971)

Bell, C. G., J. McCredie, "The Impact of Minicomputers on Simulation - an Overview," **Simulation 16** (3), 98-101 (1971)

Bell, C. G., A. Newell, **Computer Structures: Readings and Examples**, McGraw-Hill (1971a)

Bell, C. G., A. Newell, "Possibilities for Computer Structures 1971," **AFIPS Conference Proceedings, Fall Joint Computer Conference** (1971b)

Corbin, K., W. Corwin, R. Goodman, E. Hyde, K. Kramer, E. Werme and W. Wulf, "A Software Laboratory: Preliminary Report," Computer Science Department, Carnegie-Mellon University (1971)

Courtois, P. J., "On the Near-Complete-Decomposibility of Networks of Queues and of Stochastic Models of Multiprogramming Computer Systems," Computer Science Department, Carnegie-Mellon University (1971)

Eastman, C. M., "Heuristic Algorithms for Automated Space Planning," **Proceedings of the Second International Joint Conference in Artificial Intelligence**, Imperial College, London (1971)

Erman, L. D., D. R. Reddy, "Implications of Telephone for Automatic Speech Recognition," **Proceedings of the Seventh International Congress on Acoustics, Volume 3**, Budapest (1971) 85-88

Freeman, P., A. Newell, "A Model for Functional Reasoning in Design," **Proceedings Second International Joint Computor Conference on Artificial Intelligence** (1971)

Habermann, A. N., "An Operating System Modeled as a Set of Interactive Processes," **Fifth Annual Princeton Conference on Information Sciences and Systems** (1971)

Hansen, P. B., "An Analysis of Response Ratio Scheduling," **Proceedings of the IFIP Congress**, Ljubljana, Yugoslavia (1971)

Loveland, D., "Brief Primer on Resolution Proof Procedures," Computer Science Research Review, Computer Science Department, Carnegie-Mellon University (1971)

McCracken, D., G. Robertson, "C.ai - An L* Processor for C.ai," Computer Science Department, Carnegie-Mellon University (1971)

McCredie, J.W., W. A. Wulf, "Quantitative Computer Selection," **Proceedings of the 1971 IEEE International Computer Society Conference**, New York (1971)

Mitchell, J., J. Newcomer, A. Perlis, H. Van Zoeren and D. Wile, "Conversational Programming -- LCC (A User's Manual for Conversational Computing)," Computer Science Department, Carnegie-Mellon University (1971)

Montanari, U., "Networks of Constraints: Fundamental Properties and Applications to Picture Processing," Computer Science Department, Carnegie-Mellon University (1971)

Moore, J., "The Design and Evaluation of a Knowledge Net for Merlin," Computer Science Department, Carnegie-Mellon University (1971)

Moran, T. (ed.), **Computer Science Research Review**, Computer Science Department, Carnegie-Mellon University, Pittsburgh, Pennsylvania (1971)

Neely, R. B., D. R. Reddy, "Speech Recognition in the Presence of Noise," **Proceedings of the Seventh International Congress on Acoustics, Volume 3**, Budapest (1971) 177-180

Newell, A., J. Barnett, J. W. Forgie, C. Green, D. Klatt, C. R. Licklider, J. Munson, D. R. Reddy and W. A. Woods, **Speech Understanding Systems: Final Report of a Study Group**, North-Holland/American Elsevier Publishing Company, New York, New York (1973)

Newell, A., P. Freeman, D. McCracken and G. Robertson, "The Kernal Approach to Building Software Systems," Computer Science Research Review, Computer Science Department, Carnegie-Mellon University (1971)

Newell, A., D. McCracken, G. Robertson and L. DeBenedetti, "L*F," Computer Science Department, Carnegie-Mellon University (1971)

Parnas, D. L., "A Paradigm for Software Module Specification With Examples," Computer Science Department, Carnegie-Mellon University (1971a)

Parnas, D. L., **Information Distribution Aspects of Design Methodology**, North-Holland Publishing Company, New York, New York (1971b)

Perlis, A. J., R. D. Fennell, F. J. Pollack, W. R. Price and M. F. Rizzo, "Conversational Programming-APL: An Implementation in BLISS," Computer Science Department, Carnegie-Mellon University (1971)

Pfefferkorn, C., "Computer Design of Equipment Layouts Using the Design Problem Solver (DPS)," PhD Thesis, Department of Computer Science, Carnegie-Mellon University (1971)

Reddy, D. R., "Speech Recognition: Prospects for the Seventies," **Proceedings of the IFIP Congress**, Ljubljana, Yugoslavia (1971) 1-5 to 1-13

Reddy, D. R., C.G. Bell and W.A. Wulf, "Speech Recognition in a Multiprocessor Environment," **Proceedings of the IEEE Conference on Automatic Control**, Miami, Florida (1971)

Reddy, D. R., L. D. Erman and R. B. Neely, "A Mechanistic Model of Speech Perception," Proceedings of the AFCRL-IEEE Conference on Speech Communication and Processing, Boston, Massachusetts (1971) 334-337

Reddy, D. R., U. Montanari, "Computer Processing of Natural Scenes: Some Unsolved Problems," AGARD Conference Proceedings on Artificial Intelligence, Volume 94, Rome (1971)

Simon, H. A., "The Theory of Problem Solving," Proceedings of the IFIP Congress, Ljubljana, Yugoslavia (1971) 249-266

Simon, H.A., A. Newell, "Human Problem Solving: The State of the Theory in 1970," American Psychologist 26 (2), 145-159 (1971)

Waterman, D.A., A. Newell, "Protocol Analysis as a Task for Artificial Intelligence," Artificial Intelligence Journal 2 (3/4), 285-318 (1971)

Wulf, W. A., "Programming Without the GOTO," Proceedings of the IFIP Congress, Ljubljana, Yugoslavia (1971)

Wulf, W.A., C. Geschke, D. Wile and J. Apperson, "Reflections on a Systems Programming Language," Proceedings of SIGPLAN Symposium on Languages for Systems Implementation, Lafayette, Indiana (1971) 42-49

Wulf, W.A., A.N. Habermann and D. Russell, "BLISS: A Language for Systems Programming," Communications of the ACM, (1971)

Zalcstein, Y., "Locally Testable Events and Semigroups," Computer Science Department, Carnegie-Mellon University (1971)

<u>1972</u>

Barbacci, M., C. G. Bell and A. Newell, "ISP: A Language to Describe Instruction Sets and Other Register Transfer Systems," Proceedings COMPCON 72, San Francisco, California (1972)

Bell, C. G., P. Freeman, "C.ai-A Computer Architecture for AI Research," AFIPS Conference Proceedings, Fall Joint Computer Conference, Anaheim, California (1972) 779-790

Bell, C. G., M. Knudsen, "PMS: A Notation to Describe Computer Structures," Proceedings COMPCON 72, San Francisco, California (1972) 227-230

Bhatia, S., "Techniques for Designing Balanced Extensible Computer Systems," PhD Thesis, Department of Computer Science, Carnegie-Mellon University (1972)

Eastman, C. M., "Preliminary Report on a Language for General Space Planning," Communications of the ACM 15 (2), 76-87 (1972)

Eastman, C. M., C. Yessios, "An Efficient Algorithm for Finding the Union, Intersection, and Differences of Spatial Domains," Computer Science Department, Carnegie-Mellon University (1972)

Gibbons, G. D., "Beyond REF-ARF: Toward an Intelligent Processor for a Nondeterministic Programming Languages," PhD Thesis, Department of Computer Science, Carnegie-Mellon University (1972)

Gillogly, J. J., "The Technology Chess Program," Artificial Intelligence 3, 145-163 (1972)

Habermann, A. N., "Synchronization of Communication Processes," Communications of the ACM 15 (3), (1972a)

Habermann, A. N., "Parallel Neighbor Sort," Computer Science Department, Carnegie-Mellon University (1972b)

Habermann, A.N., "On a Solution and A Generalization of the Cigarette Smoker's Problem," Computer Science Department, Carnegie-Mellon University (1972c)

Jones, N., A.L. Selman, "Turing Machines and the Spectra of First Order Forumulas with Equality," Proceedings of Fourth Annual ACM Symposium on Theory of Computing (1972)

Lauer, H. C., "Correctness in Operating Systems," PhD Thesis, Department of Computer Science, Carnegie-Mellon University (1972)

McCredie, J. W., "A Tandem Queueing Model of a Time-Shared Computer System," Proceedings of the ACM, Volume 2 (1972a) 991-1000

McCredie, J. W., "Analytic Models of Time-Shared Computing Systems:New Results, Validations, and Uses," PhD Thesis, Graduate School of Industrial Administration, Carnegie-Mellon University (1972b)

Newell, A., "A Note on Process-Structure Distinctions in Developmental Psychology," Information Processing in Children, edited by Sylvia Farnham-Diggory, Academic Press, New York, New York (1972) 125-139

Newell, A., "A Theoretical Exploration of Mechanisms for Coding the Stimulus,' Coding Processes in Human Memory, edited by A. W. Melton and E. Martin, Winston and Sons, Washington, D. C. (1972) 337-434

Newell, A., H.A. Simon, Human Problem Solving, Prentice-Hall, Inc., Englewood Cliffs, New Jersey (1972)

Newell, A., H. A. Simon, R. Hayes and L. Gregg, "Report on a Workshop in New Techniques in Cognitive Research," Departments of Psychology and Computer Science, Carnegie-Mellon University (1972)

Parnas, D. L., "On the Criteria to be used in Decomposing Systems into Modules," **Communications of the ACM 15** (12), (1972a)

Parnas, D. L., "On the Problem of Producing Well Structured Programs," Computer Science Research Review, Computer Science Department, Carnegie-Mellon University (1972b)

Parnas, D. L., "Some Conclusions from an Experiment in Software Engineering Techniques," Computer Science Department, Carnegie-Mellon University (1972c)

Parnas, D.L., "On a Solution to the Cigarette Smokers' Problem (withouth conditional statements)," Computer Science Department, Carnegie-Mellon University (1972d)

Parnas, D. L., A. N. Habermann, "Comment on Deadlock Prevention Method," **Communications of the ACM 15** (9), (1972)

Parnas, D. L., D. P. Siewiorek, "Use of the Concept of Transparency in the Design of Hierarchically Structured Systems," Computer Science Department, Carnegie-Mellon University (1972)

Pfefferkorn, C., "The Design Problem Solver: A System for Designing Equipment or Furniture Layouts," Computer Science, Carnegie-Mellon University (1972)

Reddy, D. R., L. Erman and R. Neely, "Working Papers in Speech Recognition," Computer Science Department, Carnegie-Mellon University (1972)

Reddy, D. R., L. D. Erman, R. W. Broadley, R. K. Johnsson, J. Newcomer, G. Robertson and J. Wright, "XCRIBL - A Hardcopy Scan Line Graphics System for Document Generation," **Information Processing Letters**, 246-251 (1972)

Richardson, L., "Specification Techniques for Interactive Computer Systems," PhD Thesis, Department of Systems and Communication Sciences, Carnegie-Mellon University (1972)

Shaw, M., "Reduction of Compilation Costs Through Language Contraction," Computer Science Department, Carnegie-Mellon University (1972a)

Shaw, M., "Language Structure for Contractible Compilers," PhD Thesis, Department of Computer Science, Carnegie-Mellon University (1972b)

Shoub, H. (ed.), **Computer Science Research Review**, Computer Science Department, Carnegie-Mellon University, Pittsburgh, Pennsylvania (1972)

Siewiorek, D. P., D. P. Bhandarkar, "The Effect of Checker on System Reliability," Computer Science Department, Carnegie-Mellon University (1972)

Simon, H. A., K. Gilmartin, "A Simulation of Memory for Chess Positions," **Cognitive Psychology 5** (1), (1972)

Simon, H. A., L. Siklossy (eds.), **Representation and Meaning: Experiments with Information Processing Systems**, Prentice-Hall, Englewood Cliffs, New Jersey (1972)

Sirovich, F., "Memory System of a Problem Solver Generator," Computer Science Department, Carnegie-Mellon University (1972)

Waterman, D. A., A. Newell, "Preliminary Results with a System for Automatic Protocol Analysis," CIP Working Paper No. 211, Departments of Psychology and Computer Science, Carnegie-Mellon University (1972)

Wile, D. S., C. M. Geschke, "An Implementation Base for Efficient Data Structuring," **International Journal of Computer and Information Sciences**, (1972)

Wodon, P. L., "Still Another Tool for Synchronizing Cooperating Processes," Computer Science Department, Carnegie-Mellon University (1972)

Wulf, W. A., "Systems for System Implementors: Some Experience from Bliss," **AFIPS Conference Proceedings, Fall Joint Computer Conference**, Anaheim, California (1972a) 943-948

Wulf, W.A., "A Case Against the GO TO," **Proceedings of the ACM National Conference**, Boston, Massachusetts (1972b)

Wulf,W.A., J. Apperson, R. Brender, C. Geschke, P. Knueven, C. Weinstock, J. Zarella and D. Wile, "A Basic Language for the Implementation of Systems Software for the PDP-11," Computer Science Department, Carnegie-Mellon University (1972)

Wulf, W. A., J. L. Apperson, C. M. Geschke, R. K. Johnsson, C. B. Weinstock, D. S. Wile, R. F. Brender, P. A. Knueven and M. R. Pellegrini, "Bliss-11 Programmers Manual," Computer Science Department, Carnegie-Mellon University (1972)

Wulf, W. A., C. G. Bell, "C.mmp: A Multi-Mini-Processor," **AFIPS Conference Proceedings, Fall Joint Computer Conference**, Anaheim, California (1972) 765-778

<u>1973</u>

Anderson, B. (ed.), **Computer Science Research Review**, Computer Science Department, Carnegie-Mellon University, Pittsburgh, Pennsylvania (1973)

Aygun, B.O., "Environments for Monitoriing and Dynamic Analysis of Execution," Proceedings Symposium on the Simulation of Computer Systems, National Bureau of Standards, Gaithersburg, Maryland (1973)

Barbacci, M., C. G. Bell and D. P. Siewiorek, "ISP: A Notation to Describe a Computer's Instruction Set," Computer 6 (3), 22-24 (1973)

Bauer, M. J., W. J. McCredie, "AMS: A Software Monitor for Performance Evaluation and System Control," First Annual SIGME Symposium on Measurement and Evaluation, Palo Alto, California (1973) 147-160

Bhandarkar, D. P., S. H. Fuller, "A Survey of Techniques for Anaylzing Memory Interference in Multiprocessor Computer Systems," Computer Science Department, Carnegie-Mellon University (1973)

Brooks, C., L. D. Erman and R. B. Neely, "JABBERWOCKY: A Semiautomated System for the Transcription of Verbal Protocols," Behavioral Research Methods and Instrumentation, (1973)

Chase, W. G., H. A. Simon, "Perception in Chess," Cognitive Psychology 4, 55-81 (1973)

Cohen, E. S., "Symmetric Multi-Mini Processors: A Better Way To Go," Computer Decisions, (1973)

Eastman, C., "Automated Space Planning," Artificial Intelligence, 41-64 (1973)

Fuller, S. H., D. P. Siewiorek, "Some Observations on Semiconductor Technology and the Architecture of Large Digital Modules," IEEE Transactions on Computers 16 (10), 14-21 (1973)

Fuller, S. H., R. J. Swan and W. A. Wulf, "The Instrumentation of C.mmp: A Multi-Mini-Processor," Proceedings COMPCON 73, New York, New York (1973) 173-176

Gerhardt, D., D. L. Parnas, "Window: A Formally Specified Graphics-Based Text Editor," Computer Science Department, Carnegie-Mellon University (1973)

Gerhart, S. L., "Verification of APL Programs," PhD Thesis, Department of Computer Science, Carnegie-Mellon University (1973)

Geschke, C. M., "Global Program Optimizations," Computer Science, Carnegie-Mellon University (1973)

Habermann, A. N., "Intergrated Designer," SIGPLAN/SIGOPS Interface Meeting, Harriman, New York (1973)

Ingle, A. D., D. P. Siewiorek, "Extending the Error Correction Capability of Linear Codes," Computer Science Department, Carnegie-Mellon University (1973)

Johnsson, R. K., "A Survey of Register Allocation," Computer Science Department, Carnegie-Mellon University (1973)

Jones, A., "Protection in Programmed Systems," PhD Thesis, Department of Computer Science, Carnegie-Mellon University (1973)

Knudsen, M. J., "PMSL: An Interactive Language for System-Level Description and Analysis of Computer Structures," PhD Thesis, Department of Computer Science, Carnegie-Mellon University (1973)

Kriz, S., "Hardware for High-Speed Digital Vector Drawing," **SID International Symposium Digest**, New York (1973) 52-53

Lipton, R., "On Synchronization Primitive Systems," PhD Thesis, Department of Computer Science, Carnegie-Mellon University (1973)

Loveland, D. L., M. E. Stickel, "A Hole in Goal Trees: Some Guidance from Resolution Theory," Computer Science Department, Carnegie-Mellon University (1973)

McCredie, J. W., "Analytic Models as Aids in Multiprocessor Design," **Proceedings Seventh Princeton Conference on Information Sciences and Systems**, Princeton, New Jersey (1973)

Moran, T. P., "The Cognitive Structure of Spatial Knowledge," **Proceedings Fourth Environmental Design Research Association Conference, Volume 2**, Stroudsburg, Pennsylvania (1973)

Neely, R., "On the Use of Syntax and Semantics in a Speech Undersanding System," PhD Thesis, Stanford University (1973)

Newell, A., "Production Systems: Models of Control Structures," **Visual Information Processing**, edited by William G. Chase, Academic Press (1973)

Price, W. R., "Implications of a Virtual Memory Mechanism for Implementing Protection in a Family of Operating Systems," PhD Thesis, Department of Computer Science, Carnegie-Mellon University (1973)

Reddy, D. R., "Eyes and Ears for Computers," **Conference on Cognitive Processes and Artificial Intelligence**, Hamburg (1973)

Reddy, D. R., L. D. Erman and R. B. Neely, "A Model and a System for Machine Recognition of Speech," **IEEE Trans. on Audio and Electroacoustics AU-21** (3), 229-238 (1973)

Robinson, L., "Design and Implementation of a Multi-Level System Using Software Modules," Computer Science Department, Carnegie-Mellon University (1973)

Robinson, L., D. L. Parnas, "A Program Holder Module," Computer Science Department, Carnegie-Mellon University (1973)

Rosen, B., "The Architecture of a High-Performance Graphic Display Terminal," SID International Symposium Digest, New York (1973) 50-51

Shaw, M., "A System for Structured Programming," SIGPLAN Notices 8 (6), (1973)

Snyder, L., "An Analysis of Parameter Evaluation for Recursive Procedures," Ph.D Thesis, Department of Computer Science, Carnegie-Mellon University (1973)

Teitlebaum, T., "Context-Free Error Correction by Evaluation of Algebraic Power Series," 5th Annual ACM Symposium on Theory of Computing (1973)

Wile, D. S., "A Generative, Nested-Sequential, Basis for General Purpose Programming Languages," SIGPLAN Notices 8 (6), (1973)

Wulf, W. A., E. Cohen, W. Corwin, A. Jones, R. Levin, C. Pierson and F. Pollack, "HYDRA: The Kernal of a Multiprocessor Operating System," Computer Science Department, Carnegie-Mellon University (1973)

Wulf, W. A., Shaw, M., "Global Variable Considered Harmful," SIGPLAN Notices 8 (2), (1973)