

0704-0188

# REPORT DOCUMENTATION PAGE

Form Approved  
OMB No. 0704-0188

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1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE April 1979	3. REPORT TYPE AND DATES COVERED Final
4. TITLE AND SUBTITLE RELIABILITY EVALUATION OF COMPUTER SYSTEMS			5. FUNDING NUMBERS 61102F 2304/A6
6. AUTHOR(S) Edward J. McCluskey      M. Danielle Beaudry			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Stanford Electronics Laboratory Stanford University Stanford, CA 94305			8. PERFORMING ORGANIZATION REPORT NUMBER <i>TR-42-1304</i>
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) AFOSR BLDG 410 BAFB DC 20332-6448			10. SPONSORING/MONITORING AGENCY REPORT NUMBER AFOSR 77-3325
11. SUPPLEMENTARY NOTES			
12a. DISTRIBUTION/AVAILABILITY STATEMENT			12b. DISTRIBUTION CODE

1. ABSTRACT (Maximum 200 words)

**DTIC ELECTE**  
**NOV 28 1989**  
**S B D**

**DISTRIBUTION STATEMENT A**

Approved for public release;  
Distribution Unlimited

14. SUBJECT TERMS			15. NUMBER OF PAGES 63
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT

NSN 7540-01-280-5500

Standard Form 298 (890104 Draft)  
Prescribed by ANSI Std. Z39-18  
298-01

89 11 27 115

AD-A214 597



RELIABILITY EVALUATION OF COMPUTER SYSTEMS

FINAL SCIENTIFIC REPORT

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

Grant Number AFOSR 77-3325  
1 April 1977 to 30 April 1979

Principal Investigator: Professor Edward J. McCluskey

Project Leader: Dr. M. Danielle Beaudry

Submitted by

Center for Reliable Computing  
Computer Systems Laboratory  
Departments of Electrical Engineering and Computer Science  
Stanford University  
Stanford, California 94305

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ABSTRACT

This report summarizes research conducted at the Center for Reliable Computing with the support of the Air Force Office of Scientific Research from 1 April 1977 to 30 April 1979. Results and current work in various aspects of computer system reliability evaluation are described.

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## 1. INTRODUCTION

This final scientific report describes various activities at the Center for Reliable Computing (CRC) of Stanford University's Computer Systems Laboratory. Section 2 describes various research topics which appeared in publications by CRC personnel. Section 3 contains a list of technical conferences and meetings attended by CRC personnel. Section 4 contains a list of CRC personnel involved in reliability studies. The list of references in Section 5 contains both references and CRC publications. Throughout this report, references to CRC research publications are identified by a \*. Publications supported by this grant are identified by a +.

The principal research results have produced mathematically tractable means to analyze gracefully degrading computing systems from a reliability, performance, and diagnosibility point of view. Several actual computing systems were used as examples of techniques described in this report. These systems included:

1. DAIS, a multiprocessor for avionics applications,
2. PRIME, a multiprocessor developed at the University of California at Berkeley,
3. the Stanford Linear Accelerator Center's Triplex multiprocessor, and
4. SIRU, a dual redundant computer for navigation and control in avionics.

The testing of digital circuits for both permanent and intermittent failures was also extensively studied resulting in reasonable and practical methods for random and deterministic testing strategies. Design techniques for producing self-checking circuits which avoid duplication were shown to be useful in combinational circuit design. Redundant digital systems, resilient to synchronization and data matching problems, were described as well as design techniques for achieving tolerance to these failures.

## 2. RESEARCH DESCRIPTION

This section describes research efforts focussed on various aspects of the reliability evaluation of computer systems. McCluskey\* [1977+] discussed the importance of reliability and maintainability in the design of computer architectures. Reliability evaluation of fault-resistant systems concentrated on a study of gracefully degrading (also called fail-softly) computing systems, simulation techniques for reliability evaluation, and communication strategies for fault-tolerant computer networks. System level reliability analysis included studies of various multiprocessor computer systems. Computer system component reliability evaluation concentrated on the problems involved in testing and designing digital circuits.

### 2.1 RELIABILITY EVALUATION OF FAULT-RESISTANT COMPUTER SYSTEMS

The major modeling effort concentrated on fault-resistant computer systems. Fail-softly or gracefully degrading computing systems react to a detected failure by reconfiguring to a state which might have a decreased level of performance. For example, if a single processor of a multiprocessor system fails, the system may continue to operate without the faulty processor, but will have

decreased performance until the processor can be repaired and then reconfigured into the system. Three areas particularly relevant to the analysis of such systems were studied at the Center for Reliable Computing:

1. analytic modeling,
2. appropriate reliability measures, and
3. diagnosis models.

Other research explored the use of a general purpose simulator to study simulation as a means of reliability evaluation in digital systems. The problems of fault-tolerant communication in computer networks were also examined.

The use of Markov models for the reliability evaluation of gracefully degrading systems was described by Losq\* [1977]. His model analyzed the effects of failures on such systems and took into account the internal structure of the hardware, the characteristics of various detection mechanisms, and the unreliability of software. The system was partitioned into resources, e.g. processing, memory, and operating system software, and each resource was modeled independently. System optimization gave the best number of modules in a resource and demonstrated the trade-offs between hardware and software detection mechanisms. The model provided values for the system availability, mean time before failure (MTBF), and the proportion of time that the



system spent in degraded modes.

Many important sources of system failure are not adequately modeled by techniques which require the assumption of constant failure rates. Beaudry\* [1979B+] discussed the probabilistic structure of several sources of computing system failure. Non-homogeneous Poisson processes provided the mathematical framework in which to model these failure mechanisms. The detection latency of a physical failure is the time which elapses between the occurrence of the physical failure and the detection of that failure at the system level. The rate at which detections of physical failures occur is dependent on the failure rate, the system testing strategy, and, very importantly, on the usage characteristics of the failed circuit or system. If the system usage varies during operation of a computing system then the detection rate will also vary. Non-homogeneous Poisson processes provided a model for such time-dependent phenomena in computing systems with varying usage characteristics.

Beaudry\* [1976,1977,1978A+,1978D+] studied measures which were particularly relevant to the reliability evaluation of gracefully degrading systems. Differences in performance levels led to consideration of the computation capacity of a system as the amount of useful computation

(considering such performance factors as execution speed, throughput, response time, overhead and user demand) per unit time available on the system. The mean computation before failure, MCBF, and the computation availability were defined for such systems. These measures evaluated the system in terms of its capacity to execute computing tasks. Markov models permitted the development of measures to analyze the effects of distributing the computation load in a multiprocessor or gracefully degrading system. These measures were especially useful when evaluating systems where both reliability and performance were important.

The problem of self-diagnosis of multi-unit digital systems was considered by Blount\* [1977A,1977B,1978D+, 1978E+]. In such systems, each unit can test other units and/or be tested by other units. The system test consists of running and compiling test results from all unit tests in the system. As a result of the system test, a decision is made regarding the fault status (faulty or fault-free) of each unit. In Blount\* [1978C+,1978E+], procedures were developed for calculating probabilistic diagnosability measures for systems that could be modeled in earlier graph-theoretic diagnosis models. This model was extended by allowing the modeling of self-testing units and including the uncertainties and imperfections of the testing process. Procedures were given for calculating:

1. the probability that a specified fault condition is correctly diagnosed, and
2. the probability that correct diagnosis is performed when a system test is performed.

A procedure was also given for deriving a diagnosis strategy that results in optimal system-wide diagnosability. This model formed the basis for a study of diagnosis in fail-softly or gracefully degrading computer systems. If a system is to survive a failure, four steps must be successfully taken:

1. the fault must be detected,
2. the fault must be accurately diagnosed,
3. the faulty unit must be removed from the system, and
4. the data base and system software must be returned to some acceptable state.

Blount\* [1978A+,1978B+,1978E+] allowed the decision step of the diagnosis procedure to be implemented by a set of faulty and/or fault-free units, thereby modeling a possible source of error in the diagnosis process.

Thompson\* [1977B+,1977D+] described a simulation package designed to evaluate the reliability of digital systems. The simulator was designed to model many different types of systems, at varying levels of detail. The user was

given the capability to use the elements of the model in the way best suited to simulating the operation of a system in the presence of faults. The simulation package then generated random faults in a model using a Monte Carlo analysis to obtain reliability curves. When compared with other types of simulators, this simulator was found to provide a greater degree of flexibility in specifying the mode' for the system.

Betancourt\* [1979+] presented an excellent survey of available reliability evaluation computer programs. These programs can be classified into three main categories:

1. Fault tree analysis,
2. Reliability equations, and
3. Markov chain models.

References are provided for each program as well as a description of the computer language, input, output and underlying model.

The quality of service provided by a computer network is extremely sensitive to the performance of the inter-computer communication network. The loss of communication links or centers causes transmission delay, congestion, and can disconnect networks. Losq\* [1978A+, 1978B+] studied structures for communication networks that minimize the effects of failures on

performance. He proposed a measure for the fault-tolerance of store-and-forward packet switching networks which defined operational limits within a worst case response time. Properties of the networks led to simplification of routing algorithms and reconfiguration following failures.

## 2.2 SYSTEM LEVEL RELIABILITY ANALYSIS

Several actual computer systems have been analyzed using both analytical modeling and simulation. Losq\* [1977] applied his model to the PRIME system to derive the MTBF and availability of that system. The analysis examined both hardware and software failures and studied the effect of testing and hardware detection mechanisms on the overall system reliability.

Beaudry\* [1978A+,1978B+,1978C+] examined the effects of variations in system workloads on the overall system reliability and performance. A relationship was demonstrated between the system failure rate and the user demand for system resources. In particular, a strong relationship was shown between the arrival rate of batch jobs in a large multiprocessor and the failure rate of that multiprocessor computing system. Beaudry\* [1978A+,1978E+] presented an extensive statistical analysis of failures in the SLAC (Stanford Linear Accelerator Center) Triplex

multiprocessor. The analysis demonstrated the effect of system workload on the overall reliability. Performance-related as well as traditional reliability measures were calculated; hardware, software and operator-induced system failures were taken into account.

The behavior of time-dependent failure rates was studied by Beaudry\* [1979B+] in two computer systems, the SLAC Triplex multiprocessor and DAIS, a multiprocessor system for avionics applications. Recurrent failures occur when the recovery process following a failure in a computing system is incomplete or incorrect. Such failures were shown to be a significant source of system down time in the SLAC Triplex multiprocessor. Recurrent failures were also shown to be a critical consideration in the DAIS architecture.

Blount\* [1978A+,1978B+,1978E+] studied the PRIME system and determined the sensitivity of the system diagnosis to various levels of test quality. He took into account the imperfections in both the system test and the decision steps of the diagnosis process. This study demonstrated the use of fail-softly systems diagnosis models as a research tool for the general study of diagnosis techniques.

The SIRU dual redundant system was extensively analyzed by Thompson\* [1977A+,1977C+] using simulation to evaluate

the proposed design of this dual computer system. The system was modeled in sufficient detail to study the effects of certain design changes on the overall reliability. This study demonstrated that this simulation technique could be applied to complex systems and derived the conditions necessary to obtain a desired confidence in the results of the analysis.

### 2.3 COMPONENT LEVEL RELIABILITY ANALYSIS

Digital circuits must be designed to provide for both testability and maintainability. In [McCluskey\*, 1978A+, 1978B+], current techniques and issues in design for maintainability and testability are surveyed. CRC studied various testing strategies for intermittent and permanent failure detection, as well as issues involved in the reliable synchronization of redundant digital systems.

In digital circuits, intermittent failures are extremely difficult to detect. Their effects can disappear when a test is run and yet produce incorrect outputs. Losq\* [1978D+, 1978E+] studied the efficiency of test procedures to detect intermittent failures in combinational circuits. One of the factors contributing to the complexity of random testing is the fact that testing can never guarantee that a circuit is free from intermittent failures. As a

consequence, testing becomes a probabilistic problem and requires much information about the statistical properties of the failures and their effects on the circuit. If all this information is available, then it is possible to find the best test sequence and also to evaluate the confidence that the circuit is fault-free at the end of a test sequence when no error indication has been detected. The best test strategy is deterministic: it involves a given test sequence, or more exactly, a series of test sequences, depending upon the desired length of the test. This study of detection of intermittent failures in combinational circuits leads one to believe that the same results may apply to sequential circuits.

Random compact testing uses random inputs to test digital circuits. Losq\* [1978C+] studied the achievement of fault detection by comparing some statistic of the circuit under test, e.g., the frequency of logic ones at an output, with the value of that statistic previously determined for the fault-free circuit. He concluded that random compact testing can efficiently detect failures in both combinational and sequential circuits. Even though random compact testing cannot guarantee a specific confidence in its results, it is still an efficient way to detect most of the failures that can occur in circuits. With testing experiments of sufficient length, a very high detection



coverage can be obtained.

A general method for predicting the parity of the output of circuits that have one or more N bit wide inputs and a single N bit wide output is discussed by Khodadad-Mostashiry\* [1979A+,1979B+]. Error detection properties of the method are discussed for several special cases, e.g., bit-sliced circuits and iterative circuits. When these circuits are fault-free, the output parity can always be calculated in such a way as to preserve any single input error. The error detection properties of the circuit depend on the structure of the circuit. Some design techniques to improve these detection properties are presented. The output parity of any bit-sliced or iterative circuit can be predicted and the resulting circuit can be designed so that it is totally self-checking with respect to any single stuck-at fault. This property can also be demonstrated for circuits which have the following restrictions:

1. Only inputs have fanout.
2. Each fanout has only two outputs.

The main advantage of this scheme over duplication is the error-preserving property which allows a minimal number of checkers to assure detection of permanent failures. The method is especially suitable for byte-oriented circuits and iterative circuits.

Davies\* [1979+] identified concepts and defined terms useful in the study of synchronization and data matching in the presence of faults. A new class of faults having particular effect on redundant systems was described. Three general methods for performing synchronization and data matching were given and evaluated. Three examples were described to illustrate the general method:

1. a fault-tolerant clock,
2. a triple modular redundant microcomputer system, and
3. a quadruple redundant process controller.

This work provided a comprehensive guide to design techniques for reliable redundant systems.

### 3. MEETINGS

In addition to publishing scientific articles, CRC personnel participated in various technical conferences and meetings including:

1. NAECON, in Dayton, Ohio, during May 1977, attended by Prof. E.J. McCluskey and Dr. J.J. Losq,
2. FTCS-7, the Seventh Annual International Conference on Fault-Tolerant Computing, in Los Angeles, California, during June 1977, attended by Prof. E.J. McCluskey, Dr. J.J. Losq, Dr. M.D. Beaudry, Dr. M.L. Blount, and P.A. Thompson,
3. the 1978 IEEE International Solid-State Circuits Conference, in San Francisco, California, during February 1978, attended by Prof. E.J. McCluskey,
4. the Fifth Annual Symposium on Computer Architecture in Palo Alto, California, during April 1978, attended by Prof. E.J. McCluskey, Dr. M.D. Beaudry, Dr. M.L. Blount, and P.A. Thompson,
5. FTCS-8, the Eighth Annual International Conference on Fault-Tolerant Computing, in Toulouse, France during June 1978, attended by Dr. M.L. Blount,
6. NCC, the 1978 National Computer Conference, in Anaheim, California, during June 1978, attended by Prof. E.J. McCluskey and Dr. M.D. Beaudry,

7. the Third USA-Japan Computer Conference, in San Francisco, California, during October 1978, attended by Prof. E.J. McCluskey, Dr. M.D. Beaudry, and P.A. Thompson,
8. the Fourth Symposium on Computer Arithmetic, in Santa Monica, California, during October 1978, attended by Prof. E.J. McCluskey and Dr. M.D. Beaudry,
9. GOMAC, the Government Microcircuit Applications Conference, in Monterey, California, during November 1978, attended by Prof. E.J. McCluskey,
10. COMPCON 79, in San Francisco, California, During February 1979, attended by Prof. E.J. McCluskey and Dr. M.D. Beaudry,
11. the NASA workshop held by the Working Group on Validation Methods for Fault-Tolerant Avionics and Controls, in Hampton, Virginia, during March 1979, attended by Prof. E.J. McCluskey, and
12. the Second Annual Workshop on Design for Testability, in Boulder, Colorado, during April 1979, attended by Prof. E.J. McCluskey.

#### 4. PERSONNEL

##### 4.1 CURRENT PERSONNEL

Principal Investigator: E. J. McCluskey, Professor of  
Electrical Engineering and Computer  
Science

Research Staff: M. Danielle Beaudry, Research Associate  
Electrical Engineering

Visiting Professor: John P. Hayes, Dept. of Electrical  
Engineering and Computer Science  
University of Southern California  
Los Angeles, California

Research Assistants: Steve Butner, Electrical Engineering  
Peter L. Fu, Electrical Engineering  
Behzad Khodadad, Electrical Engineering  
David J. Lu, Electrical Engineering  
Daniel Miller, Electrical Engineering

##### 4.2 PAST PERSONNEL

Research Staff: Jacques Losq, Electrical Engineering  
Rodolfo Betancourt, Electrical Engineering  
Roy C. Ogus, Electrical Engineering

Research Assistants: Marion Elount, Electrical Engineering  
Daniel Davies, Electrical Engineering  
Peter A. Thompson, Electrical Engineering

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APPENDIX A

DESCRIPTION OF THE CENTER FOR RELIABLE COMPUTING

DESCRIPTION OF THE  
CENTER FOR RELIABLE COMPUTING

GENERAL INFORMATION

The Center for Reliable Computing, CRC, was created in 1976 to coordinate the research efforts in the domain of fault-tolerant computing. The center is part of the Computer Systems Laboratory. The Digital Systems Laboratory, created in 1969, has expanded greatly since that time and it has become appropriate to consolidate all the research oriented towards reliable computing under a single organization. The trend towards increased proliferation of computer systems in many critical applications and the continual demand for added safety and reliability motivated this regroupment.

The goal of the Center is to provide design methods and evaluation techniques that will meet the designer needs for present-day and future systems. The three major areas where most of the attention is centered are: the problem of testing, diagnosis and recovery; the evaluation of the various techniques used to enhance reliability; and the problem of software correctness.

BACKGROUND

This note presents a short summary of the reliability related research performed the Digital Systems Laboratory and continued at the Center for Reliable Computing. Initially, the research was focused on two main areas: fault properties and design of reliable operating systems.

Fault Properties and Testing

Faults inside digital circuits were extensively analysed for their effects on circuit behavior, [McCluskey, 1971; Boute, 1971; Mei, 1974], and also for their testability, [Mei, 1970; Boute, 1972]. This work led to procedures that provide efficient tests for combinational, [Wang, 1975A; Wang 1975B; Dias, 1975; Verdillon, 1975; Verdillon, 1976; Sziray, 1977A; Sziray, 1977B], and sequential circuits [Chesarek, 1972; Boute, 1974A; Boute, 1974B; Boute, 1975]. Special types of networks, such as unate networks and iterative logic arrays, were the object of special attention and powerful testing strategies are developed for them [Beranovic, 1973; Dias, 1976]. An algebraic model of combinational logic networks was developed in order to to simplify test generation procedures [Clegg, 1973], and was later refined [Resse, 1973]. The work on fault properties led to the investigation of the statistical

correctness of the outputs of circuits that have suffered internal failures [Parker, 1975A; Parker, 1975B; Ojus, 1974A; McCluskey, 1978; Parker, 1973]. Subsequently, it became possible to quantitatively evaluate the efficiency of both random testing techniques [Shedletsky, 1975A; Shedletsky, 1975B; Shedletsky, 1976A; Shedletsky, 1976B; Shedletsky, 1977] and compact testing methods [Parker, 1976A; Losq, 1976C; Losq, 1977B; Losq, 1978A] for both combinational and sequential circuits. Studies in this area also pointed to the practical advantages of a dynamic approach when choosing among random inputs for the candidates with the highest potential for detection of failures [Parker, 1973; Parker 1976B]. More recent work has produced many optimal strategies to test for intermittent failures [Savir, 1977A; Savir, 1977B; Savir, 1977C; Savir, 1977D; Losq, 1978B].

### Design of Reliable Operating Systems

The original work on operating systems was centered around the problem of parallelism. Design and verification methodologies were obtained, [Bredt, 1971A; Bredt, 1971B; Bredt, 1971C; Bredt, 1973], and we were able to evaluate the various power of parallel system models such as Petri Nets and P-V systems [Peterson, 1974]. This work also led to the formal proof of direct correspondance between Petri Nets and final state machines and Turing machines [Peterson, 1976]. Subsequently, the investigation was broadened to include hierarchical design methods [Bredt, 1974; Saxena, 1975] and the associated verification problems [Saxena, 1976]. New languages for efficient specification of interrupt processing were developed along with formal verification methods and studies of the fault-tolerance of real-time systems [Phillips, 1976]. The resynchronization problem for parallel systems following the detection of errors was also investigated [Russel, 1975]. Recent work has been focused on verifying the correctness of concurrent programs [Owicki, 1977A; Owicki, 1977B].

### Ultra-Reliable Computer Systems

A third area of study, on structures for fault-tolerant systems, was initiated early in the program. Hybrid redundancy received much attention. A very efficient design was obtained, [Siewiorek, 1973A], and careful reliability evaluation was performed [Siewiorek, 1973B; Ojus, 1974C]. This did point out their extreme sensitivity to the unreliability of the fault-detection and switching mechanisms [Losq, 1975]. Significant performance increase was obtained by incorporating some fault-tolerance inside the fault-detection and switching mechanisms [Ojus, 1974B]. Alternatives to hybrid redundancy were also actively studied. The effects of compensating failures in NMR systems were

analyzed [Siewiorek, 1971; Siewiorek, 1974]. An algorithm for the exact reliability evaluation of TMR networks was obtained [Abraham, 1974]. Similarly, interwoven redundant systems were also precisely evaluated [Abraham, 1975]. Self-purging redundancy was shown to offer significant advantages over hybrid redundancy for many applications [Losq, 1974; Losq, 1976A; Losq, 1976B]. A practical design of a small TMR processor using LSI technology has been undertaken [Wakerly, 1975B; Wakerly, 1975C; Wakerly, 1976]. Duplex systems, because of their broad use, were also the focus of much attention [Beaudry, 1977A]. Analytical models were developed, [Fregni, 1974A], and special care was taken to incorporate the effects of incomplete or faulty recoveries [Fregni, 1974B]. A powerful and general simulator was developed in parallel with the analytical models [Thompson, 1976; Thompson, 1977A]. This simulator, which allows different subsystems to be described at different level of details, was used to determine very accurately the reliability of a dual redundant avionic system [Thompson, 1977B; Thompson, 1977C]. A different approach to evaluate highly redundant systems is presently being investigated. It consists of a general and automatic method to list all the combinations of failures that cause system crash [Losq, 1977C; Losq, 1977D].

#### Computer Systems with High Availability

At the same time, much work was devoted to the design and evaluation of systems with more modest reliability requirements. Immediate error circuitry [Usas, 1975B]. The problem of detection of errors in periodic signals, like clocks, was solved [Usas, 1974; Usas, 1975A; Usas, 1976]. Currently, a design of a LSI-based version of a self-checking computer is being completed [Wakerly, 1975D]. Much of the present effort in analytical modeling is directed towards the evaluation of gracefully degradable systems [McCluskey, 1977]. Analytical models which emphasize the computation reliability rather than the traditional system reliability have provided a method to quantify the effects of failures [Beaudry, 1977B; Beaudry, 1977c ; Beaudry, 1977D; Losq, 1977A]. Attempts have been made to obtain very accurate models for the the efficiency of the various recovery strategies [Blount, 1977A; Blount, 1977B]. Also, there is continued work on peripheral device reliability especially through the use of self-checking design [Lu, 1977].

#### Summary

Three other more detailed surveys of the research at the Center for Reliable Computing have been prepared [McCluskey, 1975A; McCluskey, 1975B; McCluskey, 1976].

Apologies are offered to all researchers, both at Stanford and elsewhere, whose work was not included. Space does not allow mention of all the work done at Stanford and no attempt has been made to credit the excellent research being carried out elsewhere because of this same limitation.

## FACILITIES

The Center for Reliable Computing is located in the Electronics Research Laboratory (ERL), on the Stanford campus. The Center takes advantage of the use of several laboratories, computing centers and libraries.

### Laboratories

- Digital Design Laboratory, in ERL
  - . intended for small circuit design
- Microprocessor Laboratory, in ERL
  - . intended for the development, at prototype level, of microprocessor based systems
  - . equipped with two Intellec, floppy disc based, development systems
- Testing Laboratory, in ERL
  - . intended for test generation for logic boards
  - . equipped with H.P. TEST-AID system

### Computing Centers

- PDP 11/20 system, in ERL
  - . intended for local computing by the personnel of the Digital Systems Laboratory
- IBM 370/158 system, Stanford Center for Information Processing (SCIP)
  - . large time-shared computing center
- PDP 10 based system, Artificial Intelligence Project
  - . large time-shared computing center running mostly LISP and SAIL-type languages
- PDP 10 based system, Low Overhead Time-Sharing System (LOTS)
  - . large time-shared computing center, intended for terminal-oriented processing
- Access to the ARPA network
  - . through one IMP in ERL and one node at the Artificial Intelligence Project building

### Libraries

- Stanford Engineering Library, Main Library building
- Computer Science Library, Polya building
- U.C. Berkeley Libraries through an exchange agreement between Stanford Libraries and the Libraries of the University of California, Berkeley

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APPENDIX B

RESUMES

E. J. McCLUSKEY

BIOGRAPHY

PERSONAL:

Born - October 16, 1929  
New York, New York

ADDRESS:

Computer Systems Laboratory  
Stanford University  
Stanford, California 94305  
(415) 497-1451

EDUCATION:

Sc.D. (Electrical Engineering) - M.I.T., 1956

B.S. and M.S. (Electrical Engineering) - M.I.T., 1953

A.B. (Physics and Mathematics), Summa Cum Laude - Bowdoin College, 1953

POSITIONS:

Professor of Electrical Engineering and Computer Science, Stanford University, 1967-

Director, Digital Systems Laboratory, Stanford University, 1969-1973

Director, Stanford Computer Forum, 1969-1978

Visiting Professor of Electrical Engineering and Computer Science, Stanford University, 1966-1967

Professor of Electrical Engineering, Princeton University, 1963-1966

Director of Computer Center, Princeton University, 1961-1966.

Associate Professor of Electrical Engineering, Princeton University, 1959-1963

Member of Technical Staff, Bell Telephone Laboratories, Electronic Telephone Office Design, Whippany, New Jersey, 1955-1959

PROFESSIONAL SOCIETY POSITIONS AND HONORS:

AAAS - Fellow, 1967-

AACC - Representative on the Finite Automata Subcommittee of the IFAC Technical Committee on Control Theory

ACM - Associate Editor, ACM Journal, 1963-1969  
National Lectureship, 1965-1966  
Curriculum Committee, 1967-1969

AFIPS - Executive Committee, 1972-1974  
Member, Board of Directors, 1970-1974

IEEE - Long Range Planning Committee, 1971  
Proceedings Editorial Board, 1966-1968  
Fellow, 1965-

IEEE - Distinguished Visitor's Program Lecturer, 1970-  
Computer  
Group Chairman, 1970

Technical Committee on Fault Tolerant Computing,  
Member, 1970

Vice Chairman for Technical Activities, 1969

Fellows Committee, 1968-

Awards Committee, 1967-

San Francisco Computer Chapter  
Chairman, 1969-1970  
Vice-Chairman, 1968-1969  
Local Arrangements Chairman, 1967-1968

Technical Committee on Applications in Design  
Automation, Member, 1966

Publications Committee, 1965-1966

Administrative Committee, 1964-1970

Technical Committee on Switching and Automata Theory  
Chairman, 1964-1966  
Member, 1959-

Transactions on Computers  
Associate Editor, 1961-1965  
Review Editor, 1959-1961

IEEE - Chairman, Fellows Committee, 1975-1976  
Computer Society Junior Past President, 1972-1973

President, 1970-1971

PHI BETA KAPPA, SIGMA XI, ETA KAPPA NU, TAU BETA PI

CONFERENCE ACTIVITIES:

USA Program Chairman, 3rd USA-Japan Computer Conference, San Francisco, California, October 10-12, 1978

Chairman, The 5th Annual Symposium on Computer Architecture, Palo Alto, California, April 3-5, 1978

Program Vice-Chairman for North and South America, 1978 International Symposium on Fault-Tolerant Computing (FICS-8), Toulouse, France, June 21-23, 1978

COMPCON 77, Panel Discussions: Session 17 - Reliable Computer Architecture and Session 22 - Distributed Fault Tolerant Computer Systems, San Francisco, California, February 28 - March 3, 1977

Design Automation and Microprocessors Conference, Chairman of Panel Discussion: Testing of Microprocessor-Based Systems, Palo Alto, California, February 24-25, 1977

Fault Tolerant Workshop, San Diego, California, February 23, 1977

Session Chairman, 6th International Symposium on Multiple-Valued Logic, Utah State University, Logan, Utah, May 25-28, 1976

General Conference Chairman, 1973 International Symposium on Fault-Tolerant Computing (FICS-3), June 1973

General Chairman, Third Symposium on Operating Systems, 1971

Session Chairman, 1966 Design Automation Workshop

SEMINARS:

"Logic Design for Multi-Level Integrated Circuits," Distinguished Lecturer Series, Computer Science Dept., Carnegie-Mellon University, Pittsburgh, Pennsylvania, March 8, 1978

"Multi-Value Threshold Logic," Dept. of Electrical Engineering, Stanford University, Stanford, California, January 19, 1978

CONSULTING:

Battelle Corporation, 1978-  
Hughes Aircraft Company, 1978-  
Honeywell Corporation, 1977-  
Microtechnology Corporation, 1977-  
Palyn Associates, Inc., 1973-1975  
Signetics Corporation, 1971-  
Scientific Advisory Groups, General Precision, 1962-1966  
IDA Task Force on Computers in Command and Control, 1962  
IBM Scientific Center (Palo Alto, California), 1966-1967

SUMMER POSITIONS:

RCA, Design Automation, 1966  
MIT Lincoln Laboratory, Computers in Command and Control, 1961  
IBM, NOR Gate Design, 1960

OTHER PROFESSIONAL ACTIVITIES:

The Annals of the History of Computing, Editorial Board and Editor,  
AFIPS, 1978-

Visiting Committee for Information and Computer Science, Georgia  
Institute for Technology, 1978

Design Automation and Fault-Tolerant Computing, Editorial Board, 1977-

Patent Submission: Multivalued Integrated Injection Logic, 1976

Digital Processes, Editorial Board, Delta Publishing Company, Ltd.,  
Switzerland, 1975-

Computer Design and Architecture Series, Elsevier North-Holland, Inc.  
(formerly American Elsevier), New York, 1973-

National Academy of Science, Planning Group for Education, Computer  
Science and Engineering Board, 1968-1973

Commission on Engineering Education COSINE Committee, 1965-1972



Computer Science and Information Processing Series, Consulting  
Editor, Addison-Wesley, 1962-1966

Transactions on Computers, Associate Editor, IRE, 1959-1965

PUBLICATIONS:

Total number of publications: 123

Ph.D. THESES SUPERVISED

- Lewin, Morton H. "Negative-Resistance Elements as Digital Computer Components," Princeton University, 1960
- Stabler, Edward P. "Methods of Magnetic Logic," Princeton University, 1961
- Dolotta, Theodore A. "The Coding Problem in the Design of Switching Circuits," Princeton University, 1961
- Schorr, Herbert "Towards the Automatic Analysis and Synthesis of Digital Systems," Princeton University, 1962
- Brzozowski, Janusz A. "Regular Expression Techniques for Sequential Circuits," Princeton University, 1962
- Poage, James F. "The Derivation of Optimum Tests for Logic Circuits," Princeton University, 1962
- Eichelberger, Edward B. "Sequential Circuit Synthesis Using Hazards and Delays," Princeton University, 1963
- Gimpel, James F. "Some Minimization Problems in the Design of Gate-Type Combinational Switching Networks," Princeton University, 1966
- Clegg, Frederick Wingfield "Algebraic Properties of Faults in Logic Networks," Stanford University, 1970
- Bredt, Thomas H. "Control of Parallel Processes," Stanford University, 1970
- Chamberlin, Donald D. "Parallel Implementation of a Single Assignment Language," Stanford University, 1971
- Siewiorek, Daniel P. "Fault Tolerant Computers Using Self-Diagnosis and Hybrid Redundance," Stanford University, 1972
- Chesarek, Donald J. "Fault Detecting Experiments for Sequential Machines," Stanford University, 1972
- Fuller, Samuel H. "The Analysis and Scheduling of Devices Having Rotational Delays," Stanford University, 1972
- Boute, Raymond T. "Faults in Sequential Machines: Algebraic Properties and Detection Methods," Stanford University, 1972

- Salisbury, Alan B. "Evaluating Microprogrammed Emulators," Stanford University, 1973
- Wang, David T. W. "An Algorithm for the Generation of Test Sets for Combinational Logic Networks," Stanford University, 1974
- Mitarai, Hajime "The Use of Semiconductor ROM for Logic," Stanford University, 1974
- Wakerly, John F. "Low-Cost Error Detection Techniques for Small Computers," Stanford University, 1974
- Shapiro, Gerald N. "A Functional Approach to Structured Combinational-Logic Design," Stanford University, 1974
- Svobodova, Liba "Computer Performance Measurement and Evaluation Methods: Analysis and Application," Stanford University, 1974
- Abraham, Jacob A. "Reliability Analysis of Digital Systems Protected by Massive Redundancy," Stanford University, 1974
- Ogus, Poy C. "Design and Evaluation of Ultra-Reliable Digital Systems," Stanford University, 1975
- Price, Thomas G. Jr. "Probability Methods of Multi-Programmed Computer Systems," Stanford University, 1975
- Mei, Kenyon C. Y. "Fault Dominance of Bridging and Stuck-at Faults," Stanford University, 1975
- Losq, Jacques "Modelling and Reliability of Redundant Digital Systems," Stanford University, 1975
- Dias, Francisco J.O. "Multiple Fault Analysis in Combinational Logic Circuits," Stanford University, 1975
- Kolupaev, Stephen G. "Cutting Planes and Self-Checking Networks," Stanford University, 1976
- Parker, Kenneth P. "Probabilistic Test Generation," Stanford University, 1976
- Shedletsky, John J. "Error Latency in Digital Circuits," Stanford University, 1976
- Usas, Alan M. "Error/Management in Digital Computer Input/Output Systems," Stanford University, 1976

- Betancourt, Rodolfo "Analysis and Synthesis of Sequential Circuits Using Flip-Flops," Stanford University, 1976
- Savir, Jacob S. "Detection of Intermittent Failures in Combinational Circuits," Stanford University, 1977
- Beaudry, M. Danielle "Performance Considerations for the Reliability Analysis of Computing Systems," Stanford University, 1978
- Blount, Marion L. "Probabilistic Fault Diagnosis Models for Digital Systems," Stanford University, 1978

## TECHNICAL REPORTS

1. "An Essay on Prime Implicant Tables," (with I.B. Pyne), Tech. Rpt. No. 1, Digital Systems Laboratory, Princeton University, Princeton, New Jersey, October 1960.
2. "Minimal P-Point Functions on N-Cubes," (with T.A. Dolotta), Tech. Rpt. No. 2, Digital Systems Laboratory, Princeton University, Princeton, New Jersey, November 1960.
3. "Introduction to State Tables," Tech. Rpt. No. 3, Digital Systems Laboratory, Princeton University, Princeton, New Jersey, February 1961.
4. "Signal Flow Graph Techniques for Sequential Circuit State Diagrams," (with J.A. Brzozowski), Tech. Rpt. No. 5, Digital Systems Laboratory, Princeton University, Princeton, New Jersey, April 1961.
5. "The Reduction of Redundancy in Solving Prime Implicant Tables," (with I.B. Pyne), Tech. Rpt. No. 9, Digital Systems Laboratory, Princeton University, Princeton, New Jersey, May 1961.
6. "A Modified Version of ALGOL for Logical Programming," (with A. Grasselli), Tech. Rpt. No. 11, Digital Systems Laboratory, Princeton University, Princeton, New Jersey, May 1961.
7. "Minimal Sums for Boolean Functions Having Many Unspecified Fundamental Products," Tech. Rpt. No. 12, Digital Systems Laboratory, Princeton University, Princeton, New Jersey, June 1961.
8. "Computers in Command and Control," Tech. Rpt. No. 61-12, Institute for Defense Analyses, Arlington, Virginia, November 1961.
9. "Transient Behavior of Combinational Logic Networks," Tech. Note No. 13, Digital Systems Laboratory, Princeton University, Princeton, New Jersey, January 1962.
10. "Minimum-State Sequential Circuits for a Restricted Class of Incompletely Specified Flow Tables," Tech. Rpt. No. 14, Digital Systems Laboratory, Princeton University, Princeton, New Jersey, February 1962.
11. "Essential Multiple-Output Prime Implicants," (with H. Schorr), Tech. Rpt. No. 23, Digital Systems Laboratory, Princeton University, Princeton, New Jersey, April 1962.
12. "Derivation of Optimum Test Sequences for Sequential Machines," (with J.F. Hughes), Tech. Rpt. No. 27, Digital Systems Laboratory, Princeton University, Princeton, New Jersey, June 1962.
13. "Reduction of Feedback Loops in Sequential Circuits and Carry Leads in Iterative Networks," Tech. Rpt. No. 28, Digital Systems Laboratory, Princeton University, Princeton, New Jersey, August 1962.

14. "Fundamental Mode and Pulse Mode Sequential Circuits," Tech. Rpt. No. 29, Digital Systems Laboratory, Princeton University, Princeton, New Jersey, August 1962.
15. "Logical Design Theory of NOR Gate Networks with No Complemented Inputs," Tech. Rpt. No. 34, Digital Systems Laboratory, Princeton University, Princeton, New Jersey, August 1963.
16. "Algebraic Properties of Faults in Logic Networks," (with F.W. Clegg), Tech. Rpt. No. 4, Digital Systems Laboratory, Stanford University, Stanford, California, March 1970.
17. "A Model for Parallel Computer Systems," (with T.H. Bredt), Tech. Rpt. No. 5, Digital Systems Laboratory, Stanford University, Stanford, California, April 1970.
18. "Fault Equivalence in Sequential Machines," (with R. Boute), Tech. Rpt. No. 15, Digital Systems Laboratory, Stanford University, Stanford, California, June 1971.
19. "An Iterative Cell Switch Design for Hybrid Redundancy," (with D.P. Siewiorek), Tech. Rpt. No. 20, Digital Systems Laboratory, Stanford University, Stanford, California, December 1971.
20. "A Measure of Switch Complexity in Systems with Standby Spares," (with D.P. Siewiorek), Tech. Rpt. No. 21, Digital Systems Laboratory, Stanford University, Stanford, California, December 1971.
21. "Design of a Parallel Encoder/Decoder for the Hamming Code Using ROM," (with H. Mitarai), Tech. Rpt. No. 36, Digital Systems Laboratory, Stanford University, Stanford, California, November 1972.
22. "Sequential Circuit Output Probabilities from Regular Expressions," (with K.P. Parker), Tech. Rpt. No. 93, Digital Systems Laboratory, Stanford University, Stanford, California, June 1975.
23. "Center for Reliable Computing," (with J. Wakerly and R.C. Ogus), Tech. Rpt. No. 100, Digital Systems Laboratory, Stanford University, Stanford, California, October 1975.
24. "Research in the Digital Systems Laboratory: August 1975-July 1976," (with ESL Faculty), Tech. Rpt. No. 123, Digital Systems Laboratory, Stanford University, Stanford, California, July 1976.

## TECHNICAL NOTES

1. "Analysis and Synthesis of Control Mechanisms for Parallel Processes," (with T.H. Bredt), Tech. Note No. 1, Digital Systems Laboratory, Stanford University, Stanford, California, June 1969.
2. "On the Necessity of Mutual Exclusion for Mutual Exclusion," (with T.H. Bredt), Tech. Note No. 6, Digital Systems Laboratory, Stanford University, Stanford, California, November 1970.
3. "Fault Equivalence in Combinational Logic Networks," (with F.W. Clegg), Tech. Note No. 10, Digital Systems Laboratory, Stanford University, Stanford, California, March 1971.
4. "Switch Designs for Hybrid Redundancy," (with D.P. Siewiorek), Tech. Note No. 13, Digital Systems Laboratory, Stanford University, Stanford, California, December 1971.
5. "Probabilistic Treatment of General Combinational Networks," (with K.P. Parker), Tech. Note No. 20, Digital Systems Laboratory, Stanford University, Stanford, California, November 1973.
6. "Analysis of Logic Circuits with Faults Using Input Signal Probabilities," (with K.P. Parker), Tech. Note No. 21, Digital Systems Laboratory, Stanford University, Stanford, California, January 1974.
7. "A Gate Equivalent Model for Combinational Logic Network Analysis," (with R.D. Reese), Tech. Note No. 28, Digital Systems Laboratory, Stanford University, Stanford, California, January 1973.
8. "Design of Low-Cost General-Purpose Self-Diagnosing Computers," (with J.F. Wakerly), Tech. Note No. 38, Digital Systems Laboratory, Stanford University, Stanford, California, January 1974.
9. "The Error Latency of a Fault in a Combinational Digital Circuit," (with J.J. Shedletsky), Tech. Note No. 55, Digital Systems Laboratory, Stanford University, Stanford, California, November 1974.
10. "The Error Latency of a Fault in a Sequential Digital Circuit," (with J.J. Shedletsky), Tech. Note No. 56, Digital Systems Laboratory, Stanford University, Stanford, California, December 1974.
11. "Micros, Minis and Networks," Tech. Note No. 58, Digital Systems Laboratory, Stanford University, Stanford, California, June 1975.
12. "Busbar Network Probabilities and Network Design," (with K.P. Parker and J.J. Shedletsky), Tech. Note No. 60, Digital Systems Laboratory, Stanford University, Stanford, California, July 1975.

13. "A Survey of Research at the Center for Reliable Computing," Tech. Note No. 95, Digital Systems Laboratory, Stanford University, Stanford, California, October 1976.
14. "Comparative Architecture of High-Availability Computer Systems," (with R.C. Gupta), Tech. Note No. 107, Digital Systems Laboratory, Stanford University, Stanford, California, December 1976.
15. "Center for Reliable Computing," (with CRC Staff), Tech. Note No. 112, Digital Systems Laboratory, Stanford University, Stanford, California, (in preparation).
16. "Reliability and Computer Architecture," Tech. Note No. 122, Digital Systems Laboratory, Stanford University, Stanford, California, December 1977.
17. "Design for Maintainability and Testability," Tech. Note No. 145, Computer Systems Laboratory, Stanford University, Stanford, California, September 1978.



E. J. McCLUSKEY

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3. (With E.C. Riekeman and A. Glovazky) "Determination of Redundancies in a Set of Patterns," IRE Trans. on Information Theory, Vol. IT-3, No. 2, pp. 167-168, June 1957.
4. "Iterative Combinational Switching Networks - General Design Considerations," IRE Trans. on Electronic Computers, Vol. EC-7, No. 4, pp. 285-291, December 1958.
5. "Error-Correcting Codes - A Linear Programming Approach," B.S.T.J., Vol. 38, No. 6, pp. 1485-1512, November 1959.
6. (With S.H. Unger) "A Note on the Number of Internal Variable Assignments for Sequential Switching Circuits," IRE Trans. on Electronic Computers, Vol. EC-8, No. 4, pp. 439-440, December 1959.
7. "A Comparison of Sequential and Iterative Circuits," Trans. AIEE, Pt. 1, Vol 78 (Communications and Electronics), pp. 1039-1044, January 1960.
8. (With T.A. Dolotta) "Encoding of Incompletely Specified Boolean Matrices," Proc., Western Joint Computer Conference, Vol. 17, pp. 231-238, May 1960.

18. "Transients in Combinational Logic Circuits," Redundancy Techniques for Computing Systems, pp. 9-46, R.H. Wilcox and W.C. Mann, Editors, Spartan Books, Washington, D.C., 1962.
19. (With H. Schnorr) "Essential Multiple Output Prime Implicants," Proc., Symposium on Mathematical Theory of Automata, Vol. XII, pp. 437-457, Polytechnic Institute of Brooklyn, New York, New York, April 1962.
20. (With I.B. Pyne) "The Reduction of Redundancy in Solving Prime Implicant Tables," IRE Trans. on Electronic Computers, Vol. EC-11, No. 4, pp. 473-482, August 1962.
21. "Fundamental Mode and Pulse Mode Sequential Circuits," Proc., 2nd Int'l Federation on Information Processing Congress, pp. 725-730, Munich, West Germany, August 27-September 1, 1962 (North-Holland Publishing Company, Amsterdam, Netherlands).
22. "Minimal Sums for Boolean Functions Having Many Unspecified Fundamental Products," Trans. AIEE, Pt. 1, Vol. 81 (Communication and Electronics), pp. 387-392, November 1962.
23. "Minimum-State Sequential Circuits for a Restricted Class of Incompletely Specified Flow Tables," B.S.T.J., Vol. 41, No. 6, pp. 1759-1968, November 1962.
24. (With J.A. Brzozowski) "Signal Flow Graph Techniques for Sequential Circuit Diagrams," IEEE Trans. on Electronic Computers, Vol. EC-13, No. 2, pp. 67-76, April 1963.
25. "Reduction of Feedback Loops in Sequential Circuits and Carry Leads in Iterative Networks," Information and Control, Vol. 6, No. 2, pp. 99-118, June 1963.
26. "Logical Design Theory of NOR Gate Networks with No Complemented Inputs," Proc., 4th Annual Symposium on Switching Circuit Theory and Logical Design, S-156, pp. 137-148, IEEE, Chicago, Illinois, September 1963.

27. "Development of Switching Theory, Elektronische Rechenanlagen, Heft 6, Seite 249, 5 Jahrgang, December 1963.
28. "Switching Functions," Progress in Circuit Theory - 1960-1963, L. Weinberg, Editor; IEEE Trans. on Circuit Theory, Vol. CT-11, No. 1, pp. 22-25, March 1964.
29. (With T.A. Dolotta) "The Coding of Internal States of Sequential Circuits," IEEE Trans. on Electronic Computers, Vol. EC-13, No. 5, pp. 549-562, October 1964.
30. (With J.F. Poage) "Derivation of Optimum Test Sequences for Sequential Machines," Proc., 5th Annual Symposium on Switching Circuit Theory and Logical Design, S-164, pp. 121-128, IEEE, Princeton, New Jersey, October 1964.
31. Introduction to the Theory of Switching Circuits, McGraw-Hill Book Co., New York, New York, 1965.
32. (With J.B. Dennis, D.C. Evans, W.H. Huggins, M. Karnaugh, J.F. Kaiser, F.F. Kuo, S. Seely, W.H. Surber, M.E. Van Valkenburg and L.A. Zadeh) "Computer Sciences in Electrical Engineering," Cosine Committee, Commission on Engineering Education, September 1967.
33. (With W.F. Atchison, S.D. Conte, J.W. Hamblen, T.E. Hull, T.A. Keenan, W.B. Kehl, S.O. Navarro, W.C. Rheinboldt, E.J. Schweppe, W. Viavant, and D.M. Young) "Curriculum 68," Communications of the ACM, Vol. II, No. 3, pp. 151-197, March 1968.
34. (With C.G. Bell, Y. Chu, C.L. Coates, W. Lichtenberger, F. Luconi and W. Viavant) "An Undergraduate Electrical Engineering Course on Computer Organization," Cosine Committee, Commission on Engineering Education, October 1968.
35. (With T. Eredt) Chapter 14, "Analysis and Synthesis of Control Mechanisms for Parallel Processes," Parallel Processor Systems, Technologies, and Applications, pp. 287-295, L.C. Hobbs, Editor, Spartan Books, New York, New York, 1970.

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37. (With T. Brett) "A Model for Parallel Computer Systems," Tech. Note No. 5, Digital Systems Laboratory, Stanford University, Stanford, California, April 1970.
38. (With T. Brett) "On the Necessity of Mutual Exclusion for Mutual Exclusion," Tech. Note No. 6, Digital Systems Laboratory, Stanford University, Stanford, California, November 1970.
39. (With C.L. Coates, B. Arden, T.C. Bartee, C.G. Bell, F.F. Kuo, and W.H. Surber) "An Undergraduate Computer Engineering Option for Electrical Engineering," Proc., IEEE, Vol. 59, No. 6, pp. 854-860, June 1971.
40. (With R. Boute) "Fault Equivalence in Sequential Machines," Proc., Symposium on Computers and Automata, Vol. 21, pp. 483-507, Polytechnic Institute of Brooklyn, New York, New York, 1971.
41. "Test and Diagnosis Procedure for Digital Networks," Computer, Vol. 4, No. 1, pp. 17-20, January/February 1971.
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43. (With F.W. Clegg) "The Algebraic Approach to Faulty Logic Networks," Digest, 1971 Int'l Symposium on Fault-Tolerant Computing, pp. 44-45, Pasadena, California, March 1-3, 1971.
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EDUCATION:

B.S.	M.I.T.	Physics	1969
M.S.	Stanford	Electrical Engineering	1974
M.S.	Stanford	Statistics	1977
Ph.D.	Stanford	Electrical Engineering with Computer Science minor	1978

EDUCATIONAL HONORS:

National Merit Scholarship 1965-1969  
National Honor Society Scholarship (declined) 1965  
IBM Graduate Fellowship 1974-1976

PROFESSIONAL ACTIVITIES:

Member of AAAS, ACM, IEEE Computer Society, SWE, WISE, Sigma Xi  
Treasurer of Santa Clara Group of IEEE Computer Society (1977-1978)  
Publicity Chairwoman for Fifth Annual Symposium on Computer  
Architecture, Palo Alto, 3-5 April 1978  
Session Chairwoman for 3rd USA-Japan Computer Conference, San Francisco,  
10-12 October 1978

PROFESSIONAL EXPERIENCE:

Lecturer in Computer Science (April-June 1979)

Computer Science Department, Stanford University

Computer Science 105, Introduction to Computing. Undergraduate  
course using the programming language PASCAL.

Research Associate (April 1978 - present)

Center for Reliable Computing, Computer Systems Laboratory  
Stanford University

Research on performance and reliability evaluation of computing  
systems. Supervisor: Prof. Edward J. McCluskey.

Teaching assistant (October-December 1977)

Electrical Engineering Department, Stanford University

Computer Science 311, (also Electrical Engineering 482), Advanced Computer Organization. Graduate course in computer architecture.

Research assistant (July 1976 - September 1977 and January-April 1978)

Digital Systems Laboratory, Stanford University

Research on the performance and reliability of gracefully degrading computing systems. Supervisor: Prof. Edward J. McCluskey.

IBM Graduate fellow (October 1974 - June 1976)

Digital Systems Laboratory, Stanford University

Research on dual redundant and gracefully degrading computer systems. Supervisor: Prof. Edward J. McCluskey.

Research assistant (April 1974 - September 1974)

Digital Systems Laboratory, Stanford University

Research on dual redundant computer systems.  
Supervisor: Prof. Edward J. McCluskey.

Systems engineer (April 1973 - March 1974)

Hewlett-Packard Corporation, Santa Clara, California

Programming support for graphics package and instrument interfaces for Fourier Analyzer computer systems.

Programmer (October 1969 - March 1973)

Fairchild Semiconductor, Mountain View, California

Programming in computer-aided design of integrated circuits.

CONSULTING:

National Semiconductor, 1978

Hughes, 1978-

Technology Development Corporation, 1979

PUBLICATIONS:

"A Markov model for reconfigurable computer systems," (with E. Fregni),  
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