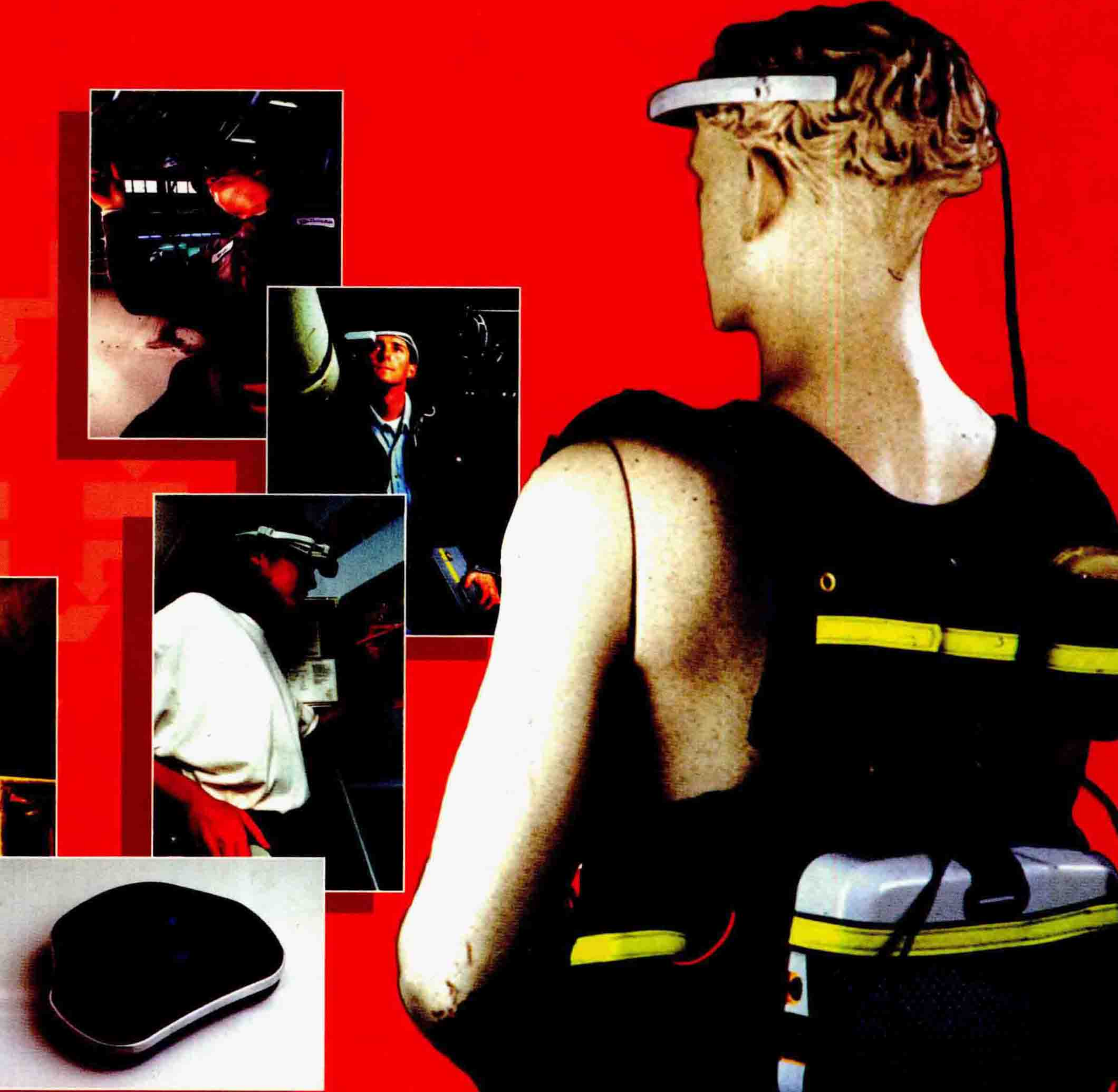
RELIABLE COMPUTER SYSTEMS

DESIGN AND EVALUATION THIRD EDITION

DANIEL P. SIEWIOREK and ROBERT S. SWARZ



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RELIABLE COMPUTER SYSTEMS

DESIGN AND EVALUATION

THIRD EDITION

Daniel P. Siewiorek

Carnegie Mellon University
Pittsburgh, Pennsylvania

Robert S. Swarz

Worcester Polytechnic Institute
Worcester, Massachusetts

A K Peters
Natick, Massachusetts

To Karon and Lonnie

A Special Remembrance:

During the development of this book, a friend, colleague, and fault-tolerant pioneer passed away. Dr. Wing N. Toy documented his 37 years of experience in designing several generations of fault-tolerant computers for the Bell System electronic switching systems described in Chapter 8. We dedicate this book to Dr. Toy in the confidence that his writings will continue to influence designs produced by those who learn from these pages.

PREFACE

System reliability has been a major concern since the beginning of the electronic digital computer age. The earliest computers were constructed of components such as relays and vacuum tubes that would fail to operate correctly as often as once every hundred thousand or million cycles. This error rate was far too large to ensure correct completion of even modest calculations requiring tens of millions of operating cycles. The Bell relay computer (c. 1944) performed a computation twice and compared results; it also employed error-detecting codes. The first commercial computer, the UNIVAC I (c. 1951), utilized extensive parity checking and two arithmetic logic units (ALUs) in a match-and-compare mode. Today, interest in reliability pervades the computer industry—from large mainframe manufacturers to semiconductor fabricators who produce not only reliability-specific chips (such as for error-correcting codes) but also entire systems.

Computer designers have to be students of reliability, and so do computer system users. Our dependence on computing systems has grown so great that it is becoming difficult or impossible to return to less sophisticated mechanisms. When an airline seat selection computer "crashes," for example, the airline can no longer revert to assigning seats from a manual checklist; since the addition of round-trip check-in service, there is no way of telling which seats have been assigned to passengers who have not yet checked in without consulting the computer. The last resort is a free-for-all rush for seats. The computer system user must be able to understand the advantages and limitations of the state-of-the-art in reliability design; determine the impact of those advantages and limitations upon the application or computation at hand; and specify the requirements for the system's reliability so that the application or computation can be successfully completed.

The literature on reliability has been slow to evolve. During the 1950s reliability was the domain of industry, and the quality of the design often depended on the cleverness of an individual engineer. Notable exceptions are the work of Shannon [1948] and Hamming [1950] on communication through noisy (hence error-inducing) channels, and of Moore and Shannon [1956] and von Neumann [1956] on redundancy that survives component failures. Shannon and Hamming inaugurated the field of coding theory, a cornerstone in contemporary systems design. Moore, Shannon, and von Neumann laid the foundation for development and mathematical evaluation of redundancy techniques.

During the 1960s the design of reliable systems received systematic treatment in industry. Bell Telephone Laboratories designed and built an Electronic Switching System (ESS), with a goal of only two hours' downtime in 40 years [Downing, Nowak, and Tuomenoksa, 1964]. The IBM System/360 computer family had extensive serviceability features [Carter et al., 1964]. Reliable design also found increasing use in the aerospace industry, and a triplicated computer helped man land on the moon [Cooper and Chow, 1976; Dickinson, Jackson, and Randa, 1964]. The volume of literature also increased. In 1962 a Symposium on Redundancy Techniques held in Washington, D.C., led to the first comprehensive book on the topic [Wilcox and Mann, 1962]. Later, Pierce [1965] published a book generalizing and analyzing the Quadded Redundancy technique proposed by Tryon and reported in Wilcox and Mann [1962]. A community of reliability theoreticians and practitioners was developing.

During the 1970s interest in system reliability expanded explosively. Companies were formed whose major product was a reliable system (such as Tandem). Due to the effort of Algirdas Avizienis and other pioneers, a Technical Committee on Fault Tolerant Computing (TCFTC) was formulated within the Institute of Electrical and Electronic Engineers (IEEE). Every year since 1971, the TCFTC has held an International Symposium on Fault-Tolerant Computing.

In 1982, when the first edition of *The Theory and Practice of Reliable System Design* was published, the time was ripe for a book on the design of reliable computing structures. The book was divided into two parts—the first being devoted to the fundamental concepts and theory and the second being populated with a dozen chapters that represented detailed case studies. The second edition follows the same basic structure, but is divided into three parts. Part I deals with the theory and Parts II and III with the practice of reliable design. The appendices provide detailed information on coding theory, design for testability, and the MIL-HDBK-217 component reliability model.

In recent years, the number of reliability and redundancy techniques has continued to expand, along with renewed emphasis on software techniques, application of older techniques to newer areas, and in-depth analytical evaluation to compare and contrast many techniques. In Part I, Chapters 3 and 5 have been expanded to include these new results. More case studies have been developed on the frequency and manifestation of hardware and software system failures. Chapter 2 has been updated to include summaries of this new material. Likewise, Chapter 4 has been enlarged to cover testing techniques commencing with prototypes through manufacturing, field installation, and field repair. The new additions to Part I have resulted in over a 50 percent increase in the number of references cited in the second edition over the first edition.

Part II of the second edition has undergone an even more dramatic change. In the first edition, Part II surveyed twelve different computer systems, ranging from one-of-a-kind research vehicles to mass-produced general-purpose commercial systems. The commercial systems focused on error detection and retry and represented three of the case studies. Four case studies represented one-of-a-kind research systems. Three other systems sought limited deployment in aerospace and message-switching applications. Only two of the case studies represented wider-spread deployment of fault-tolerant systems numbering in the thousands. Furthermore, each case study represented almost a unique architecture with little agreement as to the dominant approach for building fault-tolerant systems.

In the intervening years between the first and second editions, fault tolerance has established itself as a major segment of the computing market. The number of deployed fault-tolerant systems is measured in the tens of thousands. Manufacturers are developing the third- and fourth-generation systems so that we can look back at the evolutionary trajectory of these "fault-tolerant computer families." There has also been a convergence with respect to the system architecture of preference. While the commercial systems still depend upon error detection and retry, the high-reliability systems rely upon triplication and voting, and the high-availability systems depend upon duplication and matching. The case studies have been reduced to nine in order for more space to be devoted to technical details as well as evolutionary family growth. Two case studies represent general-purpose commercial systems, three represent research and aerospace systems, and four represent high-availability systems. The approaches used in each of these three application areas can be compared and contrasted. Of special interest are the subtle variations upon duplication and matching used by all four high-availability architectures. In total, almost 50 percent of the material in the second edition is new with respect to the first edition.

This book has three audiences. The first is the advanced undergraduate student interested in reliable design; as prerequisites, this student should have had courses in introductory programming, computer organization, digital design, and probability. In 1983, the IEEE Computer Society developed a model program in computer science and engineering. This program consisted of nine core modules, four laboratory modules, and fifteen advanced subject areas. One of those advanced subject areas was "fault-tolerant computing." Table P–1 illustrates how this book can be used in support of the module on fault-tolerant computing.

TABLE P–1
Mapping of the book to modules in Subject Area 20: Fault-Tolerant Computing, of the 1983 IEEE Computer Society Model Undergraduate Program in Computer Science and Engineering

Module	Appropriate Chapter
1. Need for Fault-Tolerant Systems: Applications, fault avoidance, fault tolerance, levels of implementation elements	Ch. 1, Fundamental Concepts Ch. 3, Reliability Techniques
2. Faults and Their Manifestations: Sources, characteristics, effects, modeling	Ch. 2, Faults and Their Manifestations
3. Error Detection: Duplication, timeouts, parity checks	Ch. 3, Reliability Techniques
4. Protective Redundancy: Functional replication, information redundancy, temporal methods	Ch. 3, Reliability Techniques
5. Fault-Tolerant Software: N-version programming, recovery blocks, specification validation, proof, mutation	Ch. 3, Reliability Techniques
6. Measures of Fault Tolerance: Reliability models, coverage, availability, maintainability	Ch. 5, Evaluaton Criteria Ch. 6, Financial Considerations
7. Case Studies	Introduction to Part II and further examples from Chapters 7 to 11 as time permits

The second audience is the graduate student seeking a second course in reliable design, perhaps as a prelude to engaging in research. The more advanced portions of Part I and the system examples of Part II should be augmented by other books and current research literature as suggested in Table P–2. A project, such as design of a dual system with a mean-time-to-failure that is an order of magnitude greater than nonredundant systems while minimizing life-cycle costs, would help to crystallize the material for students. An extensive bibliography provides access to the literature.

The third audience is the practicing engineer. A major goal of this book is to provide enough concepts to enable the practicing engineer to incorporate comprehensive reliability techniques into his or her next design. Part I provides a taxonomy of reliability techniques and the mathematical models to evaluate them. Design techniques are illustrated through the series of articles in Part II, which describe actual implementations of reliable computers. These articles were writen by the system designers. The final chapter provides a methodology for reliable system design and illustrates how this methodology can be applied in an actual design situation (the DEC VAXft 310).

Acknowledgments. The authors wish to express deep gratitude to many colleagues in the fault-tolerant computing community. Without their contributions and assistance this book could not have been written. We are especially grateful to the authors of the papers who shared their design insights with us.

Special thanks go to Joel Bartlett (DEC-Western), Wendy Bartlett (Tandem), Thomas Bissett (DEC), Doug Bossen (IBM), William Bruckert (DEC), Richard Carr (Tandem), Kate Connolly (IBM), Stanley Dickstein (IBM), Dave Garcia (Tandem), Jim Gray (Tandem), Jeffrey P. Hansen (CMU), Robert Horst (Tandem), M.Y. Hsiao (IBM), Robert Jardine (Tandem), Doug Jewett (Tandem), Robert W. Kocsis (Jet Propulsion Lab.), Dan Lenoski (Tandem), Dix McGuire (Tandem), Bob Meeker (IBM), Dick Merrall (IBM), Larry Miller (IBM), Louise Nielsen (IBM), Les Parker (IBM), Frank Sera (IBM), Mandakumar Tendolkar (IBM), Liane Toy (AT&T), Wing Toy (AT&T), and Steven Webber (Stratus).

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Jeff Hansen, David Lee, and Michael Schuette provide material on mathematical modeling, computer aids, and techniques. Comments from several reviewers and students were particularly helpful.

Special thanks are due to colleagues at both Carnegie-Mellon University and Digital Equipment Corporation (DEC) for providing an environment conducive to generating and testing ideas, especially Steve Director, Dean of the Engineering College, and Nico Habermann, Dean of the School of Computer Science. The entire staff of Digital Press provided excellent support for a timely production.

The professionalism of the staff at Technical Texts is deeply appreciated as they provided invaluable assistance throughout the production of the book. A special acknowledgment is also due Sylvia Dovner whose countless suggestions and attention to details contributed towards her goal of a "user friendly" book. The manuscript

TABLE P–2
Proposed structure for graduate course

Chapters	Augmentation
Ch. 1, Fundamental Concepts	
Ch. 2, Faults and Their Manifestations	Ross [1972] and/or Shooman [1968] for random variables, statistical parameter estimation ARINC [1964] for data collection and analysis
Ch. 3, Reliability and Availability Techniques	Appendix A, Peterson and Weldon [1972] for coding theory; Sellers, Hsiao, and Bearnson [1968b] for error-detection techniques *Proceedings of Annual IEEE International Symposium on Fault-Tolerant Computing* Special issues of the IEEE *Transactions on Computers* on Fault-Tolerant Computing (e.g., November 1971, March 1973, July 1974, May 1975, June 1976, June 1980, July 1982, 1986, April 1990) Special issues of *Computer* on Fault-Tolerant Computing (e.g., March 1980, July 1984, July 1990)
Ch. 4, Maintainability and Testing Techniques	Breuer and Friedman [1976] for testing; *Proceedings of Cherry Hill Test Conference* Special issues of *Computer* on Testing (e.g., October 1979) ARINC [1964] for maintenance analysis
Ch. 5, Evaluation Criteria	Ross [1972], Howard [1971], Shooman [1968], Craig [1964] for Markov models and their solutions
Ch. 6, Financial Considerations	Phister [1979]
Part II	October 1978 special issue of the *Proceedings of the IEEE*

provided many unforeseen "challenges," and Sylvia's perseverance was the glue that held the project together. That the book exists today is due in no small part to Sylvia's efforts.

This book would not have been possible without the patience and diligence of Mrs. Laura Forsyth, who typed, retyped, and mailed the many drafts of the manuscript. Her activities as a "traffic controller" were vital to the project.

Finally, the support and understanding of our families is the central ingredient that made this book possible. From the occupation of the dining room table for weeks at a time for reorganizing text or double-checking page proofs to missing social events or soccer games, their patience and sacrifice over the last five years enabled the project to draw to a successful conclusion.

REFERENCES*

ARINC [1964]; Breuer and Friedman [1976]; Carter et al. [1964]; Cooper and Chow [1976]; Craig [1964]; Dickinson, Jackson, and Randa [1964]; Downing, Nowak, and Toumenoksa [1964]; Hamming [1950]; Howard [1971]; Moore and Shannon [1956]; Peterson and Weldon [1972]; Phister [1979]; Pierce [1965]; Ross [1972]; Sellers, Hsiao, and Bearnson [1968b]; Shannon [1948]; Shooman [1968]; von Neumann [1956]; Wilcox and Mann [1962].

* For full citations of the shortened references at the end of each chapter, see References at the back of the book.

CONTENTS

I THE THEORY OF RELIABLE SYSTEM DESIGN

Part I of this book presents the many disciplines required to construct a reliable computing system. Chapter 1 explains the motivation for reliable systems and provides the theoretical framework for their design, fabrication, and maintenance. It presents the hierarchy of physical levels into which a computer system is customarily partitioned and introduces the stages into which the life of a computer system is divided. Chapter 1 also provides a detailed discussion of two stages in a system's life: manufacturing and operation. Lastly, the chapter identifies several of the costs of ownership for a computer system and specifies some of the parameters that the designer can control to increase customer satisfaction.

Chapter 2 discusses errors and fault manifestations in a computer system. A review of applicable probability theory is presented as an aid to understanding the mathematics of the various fault distributions. Common techniques for matching empirical data to fault distributions, such as the maximum likelihood estimator, linear regression, and the chi-square goodness-of-fit test, are discussed. Chapter 2 also introduces methods for estimating permanent failure rates, including the MIL-HDBK-217 procedure, a widely used mathematical model of permanent faults in electronic equipment, and the life-cycle testing and data analysis approaches. It addresses the problem of finding an appropriate distribution for intermittent and transient errors by analyzing field data from computer systems of diverse manufacturers.

Chapter 3 deals with reliability techniques, or ways to improve the mean time to failure. It presents a comprehensive taxonomy of reliability and availability techniques. There is also a catalog of techniques, along with evaluation criteria for both hardware and software.

Chapter 4 deals with maintainability techniques, or ways to improve the mean time to repair of a failed computer system. It provides a taxonomy of testing and maintenance techniques, and describes ways to detect and correct sources of errors at each stage of a computer's life cycle. Specific strategies for testing during the manufacturing phase are discussed. The chapter explains several logic-level acceptance