

# Designing Logic Circuits for Probabilistic Computation in the Presence of Noise

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## ABSTRACT

As Si CMOS devices are scaled down into the nanoscale regime, current computer architecture approaches are reaching their practical limits. Future nano-architectures will confront devices and interconnections with a large number of inherent defects, which motivates the search for new architectural paradigms. In this paper, we examine probabilistic-based design methodologies for nanoscale computer architectures based on Markov random fields (MRF). The MRF approach can express arbitrary logic circuits and the logic operation is achieved by maximizing the probability of correct state configurations in the logic network depending on the interaction of neighboring circuit nodes. The computation proceeds via probabilistic propagation of states through the circuit. Crucially, the MRF logic can be implemented in modified CMOS-based circuitry that trades off circuit area and operation speed for the crucial fault tolerance and noise immunity. This paper builds on the recent demonstration that significant immunity to faulty individual devices or dynamically occurring signal errors can be achieved by the propagation of state probabilities over an MRF network. In particular, we are interested in CMOS-based circuits that work reliably at very low supply voltages ( $V_{DD} = 0.1$ – $0.2$  V), where standard CMOS would fail due to thermal and crosstalk noise, and transistor threshold variation. In this paper, we present results for simulated probabilistic test circuits for elementary logic components and well as small circuits taken from the MCNC91 benchmark suite and we show greatly improved noise immunity operating at very low  $V_{DD}$ . The MRF framework extends to all levels of a design, where formally optimum probabilistic computation can be implemented as a natural element of the processing structure.

## Categories and Subject Descriptors

B.8.1 [Performance and Reliability]: Reliability, Testing, and Fault-tolerance

## General Terms

Design, Reliability, Emerging technologies

## Keywords

noise immunity, reliability, subthreshold operation, probabilistic computing, Markov random fields, nanodevices

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## 1. INTRODUCTION

For several decades, mainstream silicon technology has relied on scaling down CMOS transistors following Moore's Law. Thus far, the semiconductor industry has successfully overcome many hurdles, including the current transition to silicon-on-insulator (SOI) technology [1]. Looking to the future, the next major challenges to Si CMOS include new materials (high- $\kappa$  and low- $\kappa$  dielectrics [2]), new device geometries (dual-gate or fin-FET devices [3]), and further downscaling of devices and supply voltages with attendant difficulties in manufacturing, power dissipation, and economics of commodity manufacturing [2].

Further into the future, the International Technology Roadmap for Semiconductors (ITRS) predicts that the continued shrinkage of individual transistors will stop, perhaps around 2015, due to unavoidable physical limits, with the ultimate transistor gate length near  $L_G \sim 10$  nm [4]. These ultimate transistors will be nanodevices in the true sense of the word. Working  $L_G \sim 6$  nm devices have already been reported [5], although there is some debate as to whether the performance gains of such small devices will provide adequate return to justify the enormous fabrication costs. The longer-term prospects of digital computation then diverge into two interrelated areas. On the system side, there are the computer architecture issues arising from the problem of integrating billions of transistors at the lowest possible supply voltage, with tremendous constraints on total power dissipation and device reliability. On the device integration front, there is hope that hybrid systems will emerge, combining CMOS-FET-based digital logic with any number of alternative devices, ranging from analog circuits, to more exotic alternatives (optical sources and detectors, quantum or molecular transistors, carbon nanotube devices, etc.) all on the same chip [6].

Currently, exotic materials — from carbon nanotubes to molecular transistors, to spin-based devices and superconducting junctions, to single-electron devices, all the way to DNA-based computing — are being touted as contenders for computational circuitry. According to some benchmarks, many of these devices are quite successful: they may be faster (tunneling-based devices), carry more current (carbon nanotubes), take up less area (molecular transistors), or have higher logic functionality than CMOS FETs. Yet the key issues of compatibility with the enormous installed base of VLSI fabrication tools and know-how, and with the usual operating parameters (room temperature, low-voltage, ultra-low static power consumption) remain elusive. Instead of targeting the integration of non-CMOS nanodevices into computational logic circuits, we propose to examine the performance of ultimate CMOS transistors in a new computing framework — that of probabilistic computing embedded in a Markov random network. The premises underlying this approach are as follows:

- Any computational scheme involving large numbers of nano-

# Reliable Computation In The Presence Of Noise

**David Crawley, K. Nikolic, M. Forshaw**



## **Reliable Computation In The Presence Of Noise:**

**Reliable Computation in the Presence of Noise** S. Winograd, Jack D. Cowan, 1963 *Reliable Computation in the Presence of Noise* International Business Machines Corporation. Research Division, N. Pippenger, 1986 Reliable Computation by Formulae in the Presence of Noise International Business Machines Corporation. Research Division, N. Pippenger, 1986 *Coding Approaches to Fault Tolerance in Combinational and Dynamic Systems* Christoforos N. Hadjicostis, 2012-12-06 Coding Approaches to Fault Tolerance in Combinational and Dynamic Systems describes coding approaches for designing fault tolerant systems i.e. systems that exhibit structured redundancy that enables them to distinguish between correct and incorrect results or between valid and invalid states Since redundancy is expensive and counter intuitive to the traditional notion of system design the book focuses on resource efficient methodologies that avoid excessive use of redundancy by exploiting the algorithmic dynamic structure of a particular combinational or dynamic system The first part of Coding Approaches to Fault Tolerance in Combinational and Dynamic Systems focuses on fault tolerant combinational systems providing a review of von Neumann's classical work on Probabilistic Logics including some more recent work on noisy gates and describing the use of arithmetic coding and algorithm based fault tolerant schemes in algebraic settings The second part of the book focuses on fault tolerance in dynamic systems Coding Approaches to Fault Tolerance in Combinational and Dynamic Systems also discusses how in a dynamic system setting one can relax the traditional assumption that the error correcting mechanism is fault free by using distributed error correcting mechanisms The final chapter presents a methodology for fault diagnosis in discrete event systems that are described by Petri net models coding techniques are used to quickly detect and identify failures From the Foreword Hadjicostis has significantly expanded the setting to processes occurring in more general algebraic and dynamic systems The book responds to the growing need to handle faults in complex digital chips and complex networked systems and to consider the effects of faults at the design stage rather than afterwards George Verghese Massachusetts Institute of Technology Coding Approaches to Fault Tolerance in Combinational and Dynamic Systems will be of interest to both researchers and practitioners in the area of fault tolerance systems design and control

**The Legacy of John von Neumann** American Mathematical Society, 1990 The ideas of John von Neumann have had a profound influence on modern mathematics and science One of the great thinkers of our century von Neumann initiated major branches of mathematics from operator algebras to game theory to scientific computing and had a fundamental impact on such areas as self adjoint operators ergodic theory and the foundations of quantum mechanics and numerical analysis and the design of the modern computer This volume contains the proceedings of an AMS Symposium in Pure Mathematics held at Hofstra University in May 1988 The symposium brought together some of the foremost researchers in the wide range of areas in which von Neumann worked These articles illustrate the sweep of von Neumann's ideas and thinking and document their influence on contemporary mathematics In addition some of those who knew von

Neumann when he was alive have presented here personal reminiscences about him This book is directed to those interested in operator theory game theory ergodic theory and scientific computing as well as to historians of mathematics and others having an interest in the contemporary history of the mathematical sciences This book will give readers an appreciation for the workings of the mind of one of the mathematical giants of our time

*Reliable Computation by Networks in the Presence of Noise* Tomás Feder,1988 Abstract We prove lower bounds on the depth of Boolean networks that can compute reliably in the presence of randomly occurring failures We also give a bound on the reliability that error tolerant networks can achieve this bound implies a limit strictly smaller than 1/2 on the failure probability per gate that can be tolerated Our results improve recently published bounds of Pippenger on the depth of error tolerant formulae and extend those bounds to the case of reliable computation by networks

**3D Nanoelectronic Computer Architecture and Implementation** David Crawley,K. Nikolic,M. Forshaw,2020-01-15 It is becoming increasingly clear that the two dimensional layout of devices on computer chips hinders the development of high performance computer systems Three dimensional structures will be needed to provide the performance required to implement computationally intensive tasks 3 D Nanoelectronic Computer Architecture and Implementation reviews the state of the art in nanoelectronic device design and fabrication and discusses the architectural aspects of 3 D designs including the possible use of molecular wiring and carbon nanotube interconnections This is a valuable reference for those involved in the design and development of nanoelectronic devices and technology

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**Oscillations in Neural Systems** Daniel S. Levine,Vincent R. Brown,Timothy Shirey,1999-09-01 This book is the fourth in a series based on conferences sponsored by the Metroplex Institute for Neural Dynamics MIND an interdisciplinary organization of Dallas Fort Worth area neural network professionals in both academia and industry This topic was chosen as the focus for this special issue because of the

increasing interest by neuroscientists and psychologists in both rhythmic and chaotic activity patterns observed in the nervous system Neither the mathematical structure of neural oscillations nor their functional significance is precisely understood There are a great many open problems in both the structure and function of neural oscillations whether rhythmic chaotic or a combination of the two and many of these problems are dealt with in the chapters of this book     **The Informed Vision** David Hawkins,2002 An education classic is back in print Fifteen seminal essays explore how children develop their understanding of the world around them     Memory Mechanisms K. Geoffrey White,Wickliffe C. Abraham,Michael C. Corballis,2014-02-25 Presenting the work of researchers who are at the forefront of the study of memory mechanisms this volume addresses a wide range of topics including physiological and biophysical studies of synaptic plasticity neural models of information storage and recall functional and structural considerations of amnesia in brain damaged patients and behavioral studies of animal cognition and memory The book s coverage of diverse approaches to memory mechanisms is intended to help dissolve the borders between behavioral psychology cognitive neuropsychology and neurophysiology     Belief and Religion in Barbarian Europe c. 350-700 Marilyn Dunn,2013-11-28 This ground breaking study offers a new paradigm for understanding the beliefs and religions of the Goths Burgundians Sueves Franks and Lombards as they converted from paganism to Christianity between c 350 and c 700 CE Combining history and theology with approaches drawn from the cognitive science of religion Belief and Religion in Barbarian Europe uses both written and archaeological evidence to challenge many older ideas Beginning with a re examination of our knowledge about the deities and rituals of their original religions it goes on to question the assumption that the Germanic peoples were merely passive recipients of Christian doctrine arguing that so called Arianism was first developed as an entry level Christianity for the Goths Focusing on individual ethnic groupings in turn it presents a fresh view of the relationship between religion and politics as their rulers attempted to opt for Catholicism In place of familiar debates about post conversion pagan survivals contemporary texts and legislation are analysed to create an innovative cognitive perspective on the ways in which the Church endeavoured to bring the Christian God into people s thoughts and actions The work also includes a survey of a wide range of written and archaeological evidence contrasting traditional conceptions of death afterlife and funerary ritual with Christian doctrine and practice in these areas and exploring some of the techniques developed by the Church for assuaging popular anxieties about Christian burial and the Christian afterlife     Embodiments of Mind Warren S. McCulloch,2016-10-29 Writings by a thinker a psychiatrist a philosopher a cybernetician and a poet whose ideas about mind and brain were far ahead of his time Warren S McCulloch was an original thinker in many respects far ahead of his time McCulloch who was a psychiatrist a philosopher a teacher a mathematician and a poet termed his work experimental epistemology He said There is one answer only one toward which I ve groped for thirty years to find out how brains work Embodiments of Mind first published more than fifty years ago teems with intriguing concepts about the mind brain that are

highly relevant to recent developments in neuroscience and neural networks It includes two classic papers coauthored with Walter Pitts one of which applies Boolean algebra to neurons considered as gates and the other of which shows the kind of nervous circuitry that could be used in perceiving universals These first models are part of the basis of artificial intelligence Chapters range from What Is a Number that a Man May Know It and a Man that He May Know a Number and Why the Mind Is in the Head to What the Frog s Eye Tells the Frog s Brain with Jerome Lettvin Humberto Maturana and Walter Pitts Machines that Think and Want and A Logical Calculus of the Ideas Immanent in Nervous Activity with Walter Pitts Embodiments of Mind concludes with a selection of McCulloch s poems and sonnets This reissued edition offers a new foreword and a biographical essay by McCulloch s one time research assistant the neuroscientist and computer scientist Michael Arbib

*Neural Network Dynamics* J.G. Taylor,E.R. Caianiello,R.M.J. Cotterill,J.W. Clark,2012-12-06 Neural Network Dynamics is the latest volume in the Perspectives in Neural Computing series It contains papers presented at the 1991 Workshop on Complex Dynamics in Neural Networks held at IIASS in Vietri Italy The workshop encompassed a wide range of topics in which neural networks play a fundamental role and aimed to bridge the gap between neural computation and computational neuroscience The papers which have been updated where necessary to include new results are divided into four sections covering the foundations of neural network dynamics oscillatory neural networks as well as scientific and biological applications of neural networks Among the topics discussed are A general analysis of neural network activity Descriptions of various network architectures and nodes Correlated neuronal firing A theoretical framework for analyzing the behaviour of real and simulated neuronal networks The structural properties of proteins Nuclear phenomenology Resonance searches in high energy physics The investigation of information storage Visual cortical architecture Visual processing Neural Network Dynamics is the first volume to cover neural networks and computational neuroscience in such detail Although it is primarily aimed at researchers and postgraduate students in the above disciplines it will also be of interest to researchers in electrical engineering medicine psychology and philosophy

**Cybernetics of the Nervous system**,1965-01-01 Cybernetics of the Nervous system

**Energy Minimization Methods in Computer Vision and Pattern Recognition** Marcello Pelillo,1997-04-29 This book constitutes the refereed proceedings of the International Workshop on Energy Minimization Methods in Computer Vision and Pattern Recognition EMMCVPR 97 held in Venice Italy in May 1997 The book presents 29 revised full papers selected from a total of 62 submissions Also included are four full invited papers and a keynote paper by leading researchers The volume is organized in sections on contours and deformable models Markov random fields deterministic methods object recognition evolutionary search structural models and applications The volume is the first comprehensive documentation of the application of energy minimization techniques in the areas of compiler vision and pattern recognition

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**Modern**

**Instrumentation** G Silverman, H Silver, 2024-11-01 Modern science and engineering relies heavily on understanding computer hardware and software in order to make effective use of these tools in the laboratory and industrial environments. The authors of *Modern Instrumentation: A Computer Approach* have succeeded in producing a highly readable source that will serve both newcomers to the field as well as experienced professionals. Including both fundamentals and applications, the book first describes the role of the computer in instrument systems and provides numerous practical examples. The second part of the book explores specific software packages and their capabilities for applications such as instrument design and simulation, data acquisition, data processing, and the potential of artificial intelligence in instrument design. Because of the full integration of theory with practical applications of leading software packages, this book is an extremely useful reference for those who use computer-based instrument technology for data acquisition and who are involved with hardware or software development for laboratory and process control.

*Self-Organizing Systems* F. Eugene Yates, 2012-12-06 Technological systems become organized by commands from outside as when human intentions lead to the building of structures or machines. But many natural systems become structured by their own internal processes; these are the self-organizing systems, and the emergence of order within them is a complex phenomenon that intrigues scientists from all disciplines. Unfortunately, complexity is ill-defined. Global explanatory constructs such as cybernetics or general systems theory, which were intended to cope with complexity, produced instead a grandiosity that has now mercifully run its course and died. Most of us have become wary of proposals for an integrated systems approach to complex matters; yet we must come to grips with complexity somehow. Now is a good time to reexamine complex systems to determine whether or not various scientific specialties can discover common principles or properties in them. If they do, then a fresh multidisciplinary attack on the difficulties would be a valid scientific task. Believing that complexity is a proper scientific issue and that self-organizing systems are the foremost example, R. Tomovic, Z. Damjanovic, and I arranged a conference, August 26–September 1, 1979, in Dubrovnik, Yugoslavia, to address self-organizing systems. We invited 30 participants from seven countries. Included were biologists, geologists, physicists, chemists, mathematicians, biophysicists, and control engineers. Participants were asked not to bring manuscripts but rather to present positions on an assigned topic. Any writing would be done after the conference when the writers could benefit from their experiences there.

**Nano and Molecular Electronics Handbook** Sergey Edward Lyshevski, 2018-10-03 There are fundamental and technological limits of conventional microfabrication and microelectronics. Scaling down conventional devices and attempts to develop novel topologies and architectures will soon be ineffective or unachievable at the device and system levels to ensure desired performance. Forward-looking experts continue to search for new paradigms to carry the field beyond the age of microelectronics, and molecular electronics is one of the most promising candidates. The *Nano and Molecular Electronics Handbook* surveys the current state of this exciting emerging field and looks toward future developments and opportunities.

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