

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- κ and low- κ 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

Warren S. McCulloch



Reliable Computation In The Presence Of Noise:

Reliable Computation in the Presence of Noise International Business Machines Corporation. Research Division,N. Pippenger,1986 **Reliable Computation in the Presence of Noise** S. Winograd,Jack D. Cowan,1963 **Reliable**

Computation by Formulae in the Presence of Noise International Business Machines Corporation. Research Division,N. Pippenger,1986 *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 **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 **3D Nanoelectronic Computer Architecture and Implementation** D. 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 *The Legacy of John Von Neumann* James G. Glimm, John Impagliazzo, Isadore Singer, 2006-09-08 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 *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 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 [Adaptive Processing of Sequences and Data Structures](#)

C. Lee Giles, 1998-03-25 Tenascin a recently characterized extracellular matrix ECM protein which is expressed during embryonic and fetal development wound healing and various benign and malignant tumors but highly restricted in normal adult tissues is believed to affect a number of cellular functions such as cellular growth differentiation adhesion and motility It has been extensively studied in recent years to elucidate cellular phenomena that are associated with development tissue regeneration and neoplastic growth and behavior It may be a potential target in the treatment of cancers and other disorders This book focuses mainly on tissue expression and the poorly known biological role of this ECM protein

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

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.

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.

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 *Catalog of Copyright Entries. Third Series* Library of Congress. Copyright Office,1967 Includes Part 1 Number 1 Books and Pamphlets Including Serials and Contributions to Periodicals January June **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 **Computers, Software Engineering, and Digital Devices** Richard C. Dorf,2018-10-03 In two editions spanning more than a decade The Electrical Engineering Handbook stands as the definitive reference to the multidisciplinary field of electrical engineering Our knowledge continues to grow and so does the Handbook For the third edition it has expanded into a set of six books carefully focused on a specialized area or field of study Each book represents a concise yet definitive collection of key concepts models and equations in its respective domain thoughtfully gathered for convenient access Computers Software Engineering and Digital Devices examines digital and logical devices displays testing software and computers presenting the fundamental concepts needed to ensure a thorough understanding of each field It treats the emerging fields of programmable logic hardware description languages and parallel computing in detail Each article includes defining terms references and sources of further information Encompassing the work of the world s foremost experts in their respective specialties Computers Software Engineering and Digital Devices features the latest developments the broadest scope of coverage and new material on secure electronic commerce and parallel computing

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