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 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

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

Robert J. Rosen

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 *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

Fundamentals of Quantum Data Structures N.B. Singh,426-01-01 Fundamentals of Quantum Data Structures is a

comprehensive guide that introduces the core concepts and principles underlying the marriage of quantum computing and data structures Tailored for students researchers and professionals in the field of quantum computing this book navigates through the essential foundations of quantum information processing offering insights into quantum bits qubits quantum gates and quantum algorithms With clear explanations and practical examples the book serves as an invaluable resource for those looking to grasp the fundamentals of organizing and manipulating data in the unique context of quantum computing

Foundations of Mathematical Biology Robert J. Rosen,2013-09-03 Foundations of Mathematical Biology Volume III is devoted to the treatment of behavior of whole organisms and groups of organisms The viewpoint taken throughout the book is a holistic phenomenological one That is the integrated behavior of these organisms and groups of organisms is not in general referred back to specific structural properties of interacting subunits as in a reductionist scheme but is rather treated on its own terms without invoking the properties of lower levels of organization The book begins with an overview of organization and control in physiological systems with emphasis on the mathematical techniques involved in more detailed investigations of specific physiological mechanisms Separate chapters cover the cardiovascular system with particular reference to blood flow gross problems of organic form a relational overview of physics biology and sociology the automata theory in the context of the central nervous system and populations of interacting organisms The final chapter discusses the material presented in the entire work some of its philosophical presuppositions and implications and the possibility of constructing a unified theory of mathematical biology **Oscillations in Neural Systems** Daniel S. Levine,Vincent R. Brown,Timothy Shirey,1999-09 Written for those interested in designing machines to perform intelligent functions those interested in studying how these functions are performed by living organisms this bk dicusses the mathematical structure functional significance of neural oscil Technical Abstract Bulletin Defense Documentation Center (U.S.),1964

Disordered Systems and Biological Organization E. Bienenstock,F. Fogelman Soulie,G. Weisbuch,2012-12-06 The NATO workshop on Disordered Systems and Biological Organization was attended in march 1985 by 65 scientists representing a large variety of fields Mathematics Computer Science Physics and Biology It was the purpose of this interdisciplinary workshop to shed light on the conceptual connections existing between fields of research apparently as different as automata theory combinatorial optimization spin glasses and modeling of biological systems all of them concerned with the global organization of complex systems locally interconnected Common to many contributions to this volume is the underlying analogy between biological systems and spin glasses they share the same properties of stability and diversity This is the case for instance of primary sequences of biopo Iymers I ike proteins and nucleic acids considered as the result of mutation selection processes P W Anderson 1983 or of evolving biological species G Weisbuch 1984 Some of the most striking aspects of our cognitive apparatus involved In learning and recognttlon J Hopfield 19821 can also be described in terms of stability and diversity in a suitable configuration space These interpretations and preoccupations merge with those of theoretical

biologists like S Kauffman 1969 genetic networks and of mathematicians of automata theory the dynamics of networks of automata can be interpreted in terms of organization of a system in multiple possible attractors The present introduction outlIines the relationships between the contributions presented at the workshop and brIefly discusses each paper in its particular scientific context   Cybernetics of the Nervous system ,1965-01-01 Cybernetics of the Nervous system   **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   **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   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 Molecular and Nano Electronics Explained Explore the fundamentals of device physics synthesis and design of molecular processing platforms and molecular integrated circuits within three dimensional topologies organizations and architectures as well as bottom up fabrication utilizing quantum effects and unique phenomena Technology in Progress Stay current with the latest results and practical solutions realized for nanoscale and molecular

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