

# Reversible Logic Circuit Synthesis

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## ABSTRACT

Reversible, or information-lossless, circuits have applications in digital signal processing, communication, computer graphics and cryptography. They are also a fundamental requirement for quantum computation. We investigate the synthesis of reversible circuits that employ a minimum number of gates and contain no redundant input-output line-pairs (temporary storage channels). We propose new constructions for reversible circuits composed of NOT, Controlled-NOT, and TOFFOLI gates (the *CNT* gate library) based on permutation theory. A new algorithm is given to synthesize optimal reversible circuits using an arbitrary gate library, and we describe much faster heuristic algorithms. We also pursue applications of the proposed techniques to the synthesis of quantum circuits.

## 1. INTRODUCTION

In most computing tasks, the number of output bits is relatively small compared to the number of input bits. For example, in a decision problem, the output is only one bit (yes or no), and the input can be as large as desired. However, computational tasks in digital signal processing, communication, computer graphics and cryptography require that all of the information encoded in the input be preserved in the output. Some of these tasks are important enough to justify new microprocessor instructions to HP PA-RISC (MAX and MAX-2), Sun SPARC (VRS), PowerPC (Altivec), IA-32 and IA-64 (MMX) instruction sets [15, 9]. In particular, new bit-permutation instructions were shown to vastly improve performance of several standard algorithms, including matrix transposition and DES, as well as recent cryptographic algorithms Twofish and Serpent [9]. Bit-permutations are a special case of *reversible functions*, that is,

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HALS 2002 June 4-7, 2002, New Orleans, Louisiana, USA.  
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functions that permute the set of possible input values. For example, the butterfly operation  $(a, b) \rightarrow (a + b, a - b)$  is reversible but isn't a bit permutation. It is a key element of Fast Fourier Transform algorithms and has been used in application-specific processors from Tensilica. One might expect to get further speed-ups by adding instructions to allow computation of an arbitrary reversible function; the problem of chaining such instructions together provides one motivation for studying reversible logic circuits, that is, logic circuits composed of gates computing reversible functions.

Reversible circuits are also interesting because the loss of bits of information implies energy loss [2]. Youssef and Knight [18] showed that some reversible circuits can be made asymptotically energy-lossless if their delay is allowed to be arbitrarily large. Currently, energy losses due to irreversibility are dwarfed by the overall power dissipation, but this may change if Moore's law holds until 2020 and power dissipation improves [11]. In particular, reversibility is important for nanotechnologies where switching devices with gain are difficult to build.

Finally, reversible circuits can be viewed as a special case of quantum circuits because quantum evolution must be reversible. Classical (non-quantum) reversible gates are subject to the same "circuit rules", whether they operate on classical bits or quantum states. In fact, popular universal gate libraries for quantum computation often contain, as their subsets, universal gate libraries for classical reversible computation. While the speed-ups which make quantum computing attractive are not available without purely quantum gates, logic synthesis for classical reversible circuits is a first step toward synthesis of quantum circuits. Moreover, algorithms for quantum communications and cryptography often do not have classical competitors because they act on quantum states, even if their action in a given computational basis corresponds to classical reversible functions on bit-strings. Another connection between classical and quantum computing comes from "pseudo-classical" circuits, as used, e.g., in Grover's search algorithm [4]. These circuits are close to classical reversible circuits [5] and their definition involves an arbitrary one-output (irreversible) Boolean function.

We now briefly review existing work on classical reversible circuits. Toffoli [16] gives constructions for an arbitrary reversible or irreversible function in terms of a certain gate library. However, his method makes use of a large (although linear in the input size) number of temporary storage channels, i.e. input-output wire-pairs other than those on which the function is computed. Sasao and Kinoshita show that any conservative function  $f(x)$  is conservative if  $\forall x, x$  and  $f(x)$  contain the same number of 1s in their binary expansions) has an implementation with only 3 temporary storage channels using a certain fixed library of conservative gates, although no explicit construction was given [12]. Kerntopf uses exhaustive search methods to examine small scale synthesis problems

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**RD Boyd**



## **Reversible Logic Synthesis From Fundamen:**

**Reversible Logic Synthesis** Anas N. Al-Rabadi, 2012-12-06 For the first time in book form this comprehensive and systematic monograph presents the methods for the reversible synthesis of logic functions and circuits This methodology offers designers the capability to solve major problems in system design now and in the future such as the high rate of power consumption and the emergence of quantum effects for highly dense ICs The challenge addressed here is to design reliable systems that consume as little power as possible and in which the signals are processed and transmitted at very high speeds with very high signal integrity Researchers in academia or industry and graduate students who work in logic synthesis computer design computer aided design tools and low power VLSI circuit design will find this book a valuable resource

**Reversible Logic Synthesis Methodologies with Application to Quantum Computing** Saleem Mohammed Ridha Taha, 2015-09-24 This book opens the door to a new interesting and ambitious world of reversible and quantum computing research It presents the state of the art required to travel around that world safely Top world universities companies and government institutions are in a race of developing new methodologies algorithms and circuits on reversible logic quantum logic reversible and quantum computing and nano technologies In this book twelve reversible logic synthesis methodologies are presented for the first time in a single literature with some new proposals Also the sequential reversible logic circuitries are discussed for the first time in a book Reversible logic plays an important role in quantum computing Any progress in the domain of reversible logic can be directly applied to quantum logic One of the goals of this book is to show the application of reversible logic in quantum computing A new implementation of wavelet and multiwavelet transforms using quantum computing is performed for this purpose Researchers in academia or industry and graduate students who work in logic synthesis quantum computing nano technology and low power VLSI circuit design will be interested in this book Classical Cellular Automata. Homogeneous Structures V. Z. Aladjev, 2010-09 Book on cellular automata CA considers such questions as nonconstructible configurations extremal possibilities of CA complexity of finite configurations and global transition functions modeling in CA decomposition of global transition functions appendices of CA etc *Multiple-Valued Logic* D. Michael Miller, Mitchell A. Thornton, 2022-05-31 Multiple Valued Logic Concepts and Representations begins with a survey of the use of multiple valued logic in several modern application areas including electronic design automation algorithms and circuit design The mathematical basis and concepts of various algebras and systems of multiple valued logic are provided including comparisons among various systems and examples of their application The book also provides an examination of alternative representations of multiple valued logic suitable for implementation as data structures in automated computer applications Decision diagram structures for multiple valued applications are described in detail with particular emphasis on the recently developed quantum multiple valued decision diagram Table of Contents Multiple Valued Logic Applications MVL Concepts and Algebra Functional Representations Reversible and Quantum Circuits Quantum Multiple Valued Decision Diagrams

Summary Bibliography      Cellular Automata Alejandro Salcido,2011-04-11 Modelling and simulation are disciplines of major importance for science and engineering There is no science without models and simulation has nowadays become a very useful tool sometimes unavoidable for development of both science and engineering The main attractive feature of cellular automata is that in spite of their conceptual simplicity which allows an easiness of implementation for computer simulation as a detailed and complete mathematical analysis in principle they are able to exhibit a wide variety of amazingly complex behaviour This feature of cellular automata has attracted the researchers attention from a wide variety of divergent fields of the exact disciplines of science and engineering but also of the social sciences and sometimes beyond The collective complex behaviour of numerous systems which emerge from the interaction of a multitude of simple individuals is being conveniently modelled and simulated with cellular automata for very different purposes In this book a number of innovative applications of cellular automata models in the fields of Quantum Computing Materials Science Cryptography and Coding and Robotics and Image Processing are presented      *Introduction to Reversible Computing* Kalyan S. Perumalla,2013-09-10 Few books comprehensively cover the software and programming aspects of reversible computing Filling this gap Introduction to Reversible Computing offers an expanded view of the field that includes the traditional energy motivated hardware viewpoint as well as the emerging application motivated software approach Collecting scattered knowledge into one coherent account the book provides a compendium of both classical and recently developed results on reversible computing It explores up and coming theories techniques and tools for the application of reversible computing the logical next step in the evolution of computing systems The book covers theory hardware and software aspects fundamental limits complexity analyses practical algorithms compilers efficiency improvement techniques and application areas The topics span several areas of computer science including high performance computing parallel distributed systems computational theory compilers power aware computing and supercomputing The book presents sufficient material for newcomers to easily get started It provides citations to original articles on seminal results so that readers can consult the corresponding publications in the literature Pointers to additional resources are included for more advanced topics For those already familiar with a certain topic within reversible computing the book can serve as a one stop reference to other topics in the field      **Logic Design of NanoICS** Svetlana N. Yanushkevich,Vlad P. Shmerko,Sergey Edward Lyshevski,2017-12-19 Today s engineers will confront the challenge of a new computing paradigm relying on micro and nanoscale devices Logic Design of NanoICs builds a foundation for logic in nanodimensions and guides you in the design and analysis of nanoICs using CAD The authors present data structures developed toward applications rather than a purely theoretical treatment Requiring only basic logic and circuits background Logic Design of NanoICs draws connections between traditional approaches to design and modern design in nanodimensions The book begins with an introduction to the directions and basic methodology of logic design at the nanoscale then proceeds to nanotechnologies and CAD graphical representation of switching functions and networks word

level and linear word level data structures 3 D topologies based on hypercubes multilevel circuit design and fault tolerant computation in hypercube like structures The authors propose design solutions and techniques going beyond the underlying technology to provide more applied knowledge This design oriented reference is written for engineers interested in developing the next generation of integrated circuitry illustrating the discussion with approximately 250 figures and tables 100 equations 250 practical examples and 100 problems Each chapter concludes with a summary references and a suggested reading section

*Lock-in Thermography* Otwin Breitenstein, Wilhelm Warta, Martin Langenkamp, 2013-03-09 Although the first publication on lock in thermography appeared in 1988 concerning electronic device testing this technique only became popular in the 1990s in connection with the nondestructive testing of materials NDT especially photothermal and thermoelastic investigations In the early 1990s our group at the Max Planck Institute of Microstructure Physics in Halle had the task to image small leakage currents in silicon solar cells We soon realized that neither conventional steady state thermography nor the only available lock in thermography system of that time was sensitive enough to image the tiny temperature differences caused by these leakage currents Therefore we developed the Dynamic Precision Contact Thermography technique DPCT which was the first lock in thermography system having a detection limit below 100 J LK However this system turned out to be too impracticable for general use since it worked in a mechanical contacting mode and its measurement time was necessarily many hours With the availability of highly sensitive focal plane array thermocameras at the end of the 1990s the way was opened to construct highly sensitive IR based lock in thermography systems This was done independently by groups working in NDT and by us working in electronic device testing whereby the different demands in the different fields lead to partly different approaches in the realization For photothermal investigations a low lock in frequency is usually used in order to see sub surface details and for thermoelastic investigations the thermocamera cannot usually be synchronized to the temperature modulation

Advanced Intelligent Computing Theories and Applications. With Aspects of Theoretical and Methodological Issues De-Shuang Huang, Donald C. Wunsch, Daniel S. Levine, Kang-Hyun Jo, 2008-09-08 The International Conference on Intelligent Computing ICIC was formed to provide an annual forum dedicated to the emerging and challenging topics in artificial intelligence machine learning bioinformatics and computational biology etc It aims to bring together researchers and practitioners from both academia and industry to share ideas problems and solutions related to the multifaceted aspects of intelligent computing ICIC 2008 held in Shanghai China September 15 18 2008 constituted the 4th International Conference on Intelligent Computing It built upon the success of ICIC 2007 ICIC 2006 and ICIC 2005 held in Qingdao Kunming and Hefei China 2007 2006 and 2005 respectively This year the conference concentrated mainly on the theories and methodologies as well as the emerging applications of intelligent computing Its aim was to unify the picture of contemporary intelligent computing techniques as an integral concept that highlights the trends in advanced computational intelligence and bridges theoretical research with applications Therefore the theme for this

conference was Emerging Intelligent Computing Technology and Applications Papers focusing on this theme were solicited addressing theories methodologies and applications in science and technology Quantum Computing Fundamentals William (Chuck) Easttom II, 2021-06-17 ONE VOLUME INTRODUCTION TO QUANTUM COMPUTING Clearly explains core concepts terminology and techniques Covers the foundational physics math and information theory you need Provides hands on practice with quantum programming The perfect beginner's guide for anyone interested in a quantum computing career Dr Chuck Easttom brings together complete coverage of basic quantum computing concepts terminology and issues along with key skills to get you started Drawing on 30 years as a computer science instructor consultant and researcher Easttom demystifies the field's underlying technical concepts and math shows how quantum computing systems are designed and built explains their implications for cyber security and previews advances in quantum resistant cryptography Writing clearly and simply he introduces two of today's leading quantum programming languages Microsoft Q and QASM and guides you through sample projects Throughout tests projects and review questions help you deepen and apply your knowledge Whether you're a student professional or manager this guide will prepare you for the quantum computing revolution and expand your career options too Master the linear algebra and other mathematical skills you'll need Explore key physics ideas such as quantum states and uncertainty Review data structures algorithms and computing complexity Work with probability and set theory in quantum computing Familiarize yourself with basic quantum theory and formulae Understand quantum entanglement and quantum key distribution Discover how quantum computers are architected and built Explore several leading quantum algorithms Compare quantum and conventional asymmetric algorithms See how quantum computing might break traditional cryptography Discover several approaches to quantum resistant cryptography Start coding with Q Microsoft's quantum programming language Simulate quantum gates and algorithms with QASM **Fundamentals of Software Engineering** Hossein Hojjat, Georgiana Caltai, 2025-03-20 This book constitutes the proceedings of the 11th IFIP WG 2.2 International Conference on Fundamentals of Software Engineering FSEN 2025 held in Västerås Sweden during April 7-8 2025 The 11 full papers and 1 short paper included in this book were carefully reviewed and selected from 30 submissions They deal with all aspects of formal methods with a strong emphasis on promoting their industrial applications and integrating them with practical engineering practices **Intelligent Control and Computer Engineering** Sio-Iong Ao, Oscar Castillo, He Huang, 2010-12-07 A large international conference on Advances in Intelligent Control and Computer Engineering was held in Hong Kong March 17-19 2010 under the auspices of the International MultiConference of Engineers and Computer Scientists IMECS 2010 The IMECS is organized by the International Association of Engineers IAENG Intelligent Control and Computer Engineering contains 25 revised and extended research articles written by prominent researchers participating in the conference Topics covered include artificial intelligence control engineering decision supporting systems automated planning automation systems systems identification modelling and simulation communication

systems signal processing and industrial applications Intelligent Control and Computer Engineering offers the state of the art of tremendous advances in intelligent control and computer engineering and also serves as an excellent reference text for researchers and graduate students working on intelligent control and computer engineering     Quantum-Dot Cellular

Automata Based Digital Logic Circuits: A Design Perspective Trailokya Nath Sasamal,Ashutosh Kumar Singh,Anand Mohan,2019-12-16 This book covers several futuristic computing technologies like quantum computing quantum dot cellular automata DNA computing and optical computing In turn it explains them using examples and tutorials on a CAD tool that can help beginners get a head start in QCA layout design It discusses research on the design of circuits in quantum dot cellular automata QCA with the objectives of obtaining low complexity robust designs for various arithmetic operations The book also investigates the systematic reduction of majority logic in the realization of multi bit adders dividers ALUs and memory

Design and Testing of Reversible Logic Ashutosh Kumar Singh,Masahiro Fujita,Anand Mohan,2019-07-29 The book compiles efficient design and test methodologies for the implementation of reversible logic circuits The methodologies covered in the book are design approaches test approaches fault tolerance in reversible circuits and physical implementation techniques The book also covers the challenges and the reversible logic circuits to meet these challenges stimulated during each stage of work cycle The novel computing paradigms are being explored to serve as a basis for fast and low power computation     **Machine Learning, Image Processing, Network Security and Data Sciences** Arup

Bhattacharjee,Samir Kr. Borgohain,Badal Soni,Gyanendra Verma,Xiao-Zhi Gao,2020-06-24 This two volume set CCIS 1240 1241 constitutes the refereed proceedings of the Second International Conference on Machine Learning Image Processing Network Security and Data Sciences MIND 2020 held in Silchar India Due to the COVID 19 pandemic the conference has been postponed to July 2020 The 79 full papers and 4 short papers were thoroughly reviewed and selected from 219 submissions The papers are organized according to the following topical sections data science and big data image processing and computer vision machine learning and computational intelligence network and cyber security     **Advanced Logic**

**Synthesis** André Inácio Reis,Rolf Drechsler,2017-11-15 This book provides a single source reference to the state of the art in logic synthesis Readers will benefit from the authors expert perspectives on new technologies and logic synthesis new data structures big data and logic synthesis and convergent logic synthesis The authors describe techniques that will enable readers to take advantage of recent advances in big data techniques and frameworks in order to have better logic synthesis algorithms     **Demystifying AI and ML for Cyber-Threat Intelligence** Ming Yang,Sachi Nandan Mohanty,Suneeta

Satpathy,Shu Hu,2025-08-16 This book simplifies complex AI and ML concepts making them accessible to security analysts IT professionals researchers and decision makers Cyber threats have become increasingly sophisticated in the ever evolving digital landscape making traditional security measures insufficient to combat modern attacks Artificial intelligence AI and machine learning ML have emerged as transformative tools in cybersecurity enabling organizations to detect prevent and

respond to threats with greater efficiency This book is a comprehensive guide bridging the gap between cybersecurity and AI ML by offering clear practical insights into their role in threat intelligence Readers will gain a solid foundation in key AI and ML principles including supervised and unsupervised learning deep learning and natural language processing NLP while exploring real world applications such as intrusion detection malware analysis and fraud prevention Through hands on insights case studies and implementation strategies it provides actionable knowledge for integrating AI driven threat intelligence into security operations Additionally it examines emerging trends ethical considerations and the evolving role of AI in cybersecurity Unlike overly technical manuals this book balances theoretical concepts with practical applications breaking down complex algorithms into actionable insights Whether a seasoned professional or a beginner readers will find this book an essential roadmap to navigating the future of cybersecurity in an AI driven world This book empowers its audience to stay ahead of cyber adversaries and embrace the next generation of intelligent threat detection

**Reconfigurable Computing: Architectures, Tools and Applications** Pedro C. Diniz, Eduardo Marques, Koen Bertels, Marcio Merino Fernandes, Joao M.P. Cardoso, 2007-06-04 This book constitutes the refereed proceedings of the Third International Workshop on Applied Reconfigurable Computing ARC 2007 held in Mangaratiba Brazil in March 2007 The 27 full papers and 10 short papers presented together with a late comer contribution from ARC 2006 are organized in topical sections on architectures mapping techniques and tools arithmetic and applications *Towards a Design Flow for Reversible Logic* Robert Wille, Rolf Drechsler, 2010-07-28 The development of computing machines found great success in the last decades But the ongoing miniaturization of integrated circuits will reach its limits in the near future Shrinking transistor sizes and power dissipation are the major barriers in the development of smaller and more powerful circuits Reversible logic provides an alternative that may overcome many of these problems in the future For low power design reversible logic offers significant advantages since zero power dissipation will only be possible if computation is reversible Furthermore quantum computation profits from enhancements in this area because every quantum circuit is inherently reversible and thus requires reversible descriptions However since reversible logic is subject to certain restrictions e.g fanout and feedback are not directly allowed the design of reversible circuits significantly differs from the design of traditional circuits Nearly all steps in the design flow like synthesis verification or debugging must be redeveloped so that they become applicable to reversible circuits as well But research in reversible logic is still at the beginning No continuous design flow exists so far In this book contributions to design flow for reversible logic are represented This includes advanced methods for synthesis optimization verification and debugging *Reversible Computing* Alexis De Vos, 2011-08-04 Written by one of the few top internationally recognized experts in the field this book concentrates on those topics that will remain fundamental such as low power computing reversible programming languages and applications in thermodynamics It describes reversible computing from various points of view Boolean algebra group theory logic circuits low power electronics communication software quantum



computing It is this multidisciplinary approach that makes it unique Backed by numerous examples this is useful for all levels of the scientific and academic community from undergraduates to established academics

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