Index Generation Functions

Synthesis Lectures on Digital Circuits and Systems

Editor
Mitchell A. Thornton, ***Southern Methodist University***

The *Synthesis Lectures on Digital Circuits and Systems* series is comprised of 50- to 100-page books targeted for audience members with a wide-ranging background. The Lectures include topics that are of interest to students, professionals, and researchers in the area of design and analysis of digital circuits and systems. Each Lecture is self-contained and focuses on the background information required to understand the subject matter and practical case studies that illustrate applications. The format of a Lecture is structured such that each will be devoted to a specific topic in digital circuits and systems rather than a larger overview of several topics such as that found in a comprehensive handbook. The Lectures cover both well-established areas as well as newly developed or emerging material in digital circuits and systems design and analysis.

Index Generation Functions
Tsutomu Sasao
2019

Microcontroller Programming and Interfacing with Texas Instruments MSP430FR2433 and MSP430FR5994 – Part II, Second Edition
Steven F. Barrett and Daniel J. Pack
2019

Microcontroller Programming and Interfacing with Texas Instruments MSP430FR2433 and MSP430FR5994 – Part I, Second Edition
Steven F. Barrett and Daniel J. Pack
2019

Synthesis of Quantum Circuits vs. Synthesis of Classical Reversible Circuits
Alexis De Vos, Stijn De Baerdemacker, and Yvan Van Rentergen
2018

Boolean Differential Calculus
Bernd Steinbach and Christian Posthoff
2017

Embedded Systems Design with Texas Instruments MSP432 32-bit Processor
Dung Dang, Daniel J. Pack, and Steven F. Barrett
2016

Fundamentals of Electronics: Book 4 Oscillators and Advanced Electronics Topics
Thomas F. Schubert and Ernest M. Kim
2016

Fundamentals of Electronics: Book 3 Active Filters and Amplifier Frequency
Thomas F. Schubert and Ernest M. Kim
2016

Bad to the Bone: Crafting Electronic Systems with BeagleBone and BeagleBone Black, Second Edition
Steven F. Barrett and Jason Kridner
2015

Fundamentals of Electronics: Book 2 Amplifiers: Analysis and Design
Thomas F. Schubert and Ernest M. Kim
2015

Fundamentals of Electronics: Book 1 Electronic Devices and Circuit Applications
Thomas F. Schubert and Ernest M. Kim
2015

Applications of Zero-Suppressed Decision Diagrams
Tsutomu Sasao and Jon T. Butler
2014

Modeling Digital Switching Circuits with Linear Algebra
Mitchell A. Thornton
2014

Arduino Microcontroller Processing for Everyone! Third Edition
Steven F. Barrett
2013

Boolean Differential Equations
Bernd Steinbach and Christian Posthoff
2013

Bad to the Bone: Crafting Electronic Systems with BeagleBone and BeagleBone Black
Steven F. Barrett and Jason Kridner
2013

Introduction to Noise-Resilient Computing
S.N. Yanushkevich, S. Kasai, G. Tangim, A.H. Tran, T. Mohamed, and V.P. Shmerko
2013

Atmel AVR Microcontroller Primer: Programming and Interfacing, Second Edition
Steven F. Barrett and Daniel J. Pack
2012

Representation of Multiple-Valued Logic Functions
Radomir S. Stankovic, Jaakko T. Astola, and Claudio Moraga
2012

Arduino Microcontroller: Processing for Everyone! Second Edition
Steven F. Barrett
2012

Advanced Circuit Simulation Using Multisim Workbench
David Báez-López, Félix E. Guerrero-Castro, and Ofelia Delfina Cervantes-Villagómez
2012

Circuit Analysis with Multisim
David Báez-López and Félix E. Guerrero-Castro
2011

Microcontroller Programming and Interfacing Texas Instruments MSP430, Part I
Steven F. Barrett and Daniel J. Pack
2011

Microcontroller Programming and Interfacing Texas Instruments MSP430, Part II
Steven F. Barrett and Daniel J. Pack
2011

Pragmatic Electrical Engineering: Systems and Instruments
William Eccles
2011

Pragmatic Electrical Engineering: Fundamentals
William Eccles
2011

Introduction to Embedded Systems: Using ANSI C and the Arduino Development Environment
David J. Russell
2010

Arduino Microcontroller: Processing for Everyone! Part II
Steven F. Barrett
2010

Arduino Microcontroller Processing for Everyone! Part I
Steven F. Barrett
2010

Digital System Verification: A Combined Formal Methods and Simulation Framework
Lun Li and Mitchell A. Thornton
2010

Progress in Applications of Boolean Functions
Tsutomu Sasao and Jon T. Butler
2009

Embedded Systems Design with the Atmel AVR Microcontroller: Part II
Steven F. Barrett
2009

Embedded Systems Design with the Atmel AVR Microcontroller: Part I
Steven F. Barrett
2009

Embedded Systems Interfacing for Engineers using the Freescale HCS08 Microcontroller II: Digital and Analog Hardware Interfacing
Douglas H. Summerville
2009

Designing Asynchronous Circuits using NULL Convention Logic (NCL)
Scott C. Smith and JiaDi
2009

Embedded Systems Interfacing for Engineers using the Freescale HCS08 Microcontroller I: Assembly Language Programming
Douglas H.Summerville
2009

Developing Embedded Software using DaVinci & OMAP Technology
B.I. (Raj) Pawate
2009

Mismatch and Noise in Modern IC Processes
Andrew Marshall
2009

Asynchronous Sequential Machine Design and Analysis: A Comprehensive Development of the Design and Analysis of Clock-Independent State Machines and Systems
Richard F. Tinder
2009

An Introduction to Logic Circuit Testing
Parag K. Lala
2008

Pragmatic Power
William J. Eccles
2008

Multiple Valued Logic: Concepts and Representations
D. Michael Miller and Mitchell A. Thornton
2007

Finite State Machine Datapath Design, Optimization, and Implementation
Justin Davis and Robert Reese
2007

Atmel AVR Microcontroller Primer: Programming and Interfacing
Steven F. Barrett and Daniel J. Pack
2007

Pragmatic Logic
William J. Eccles
2007

PSpice for Filters and Transmission Lines
Paul Tobin
2007

PSpice for Digital Signal Processing
Paul Tobin
2007

PSpice for Analog Communications Engineering
Paul Tobin
2007

PSpice for Digital Communications Engineering
Paul Tobin
2007

PSpice for Circuit Theory and Electronic Devices
Paul Tobin
2007

Pragmatic Circuits: DC and Time Domain
William J. Eccles
2006

Pragmatic Circuits: Frequency Domain
William J. Eccles
2006

Pragmatic Circuits: Signals and Filters
William J. Eccles
2006

High-Speed Digital System Design
Justin Davis
2006

Introduction to Logic Synthesis using Verilog HDL
Robert B.Reese and Mitchell A.Thornton
2006

Microcontrollers Fundamentals for Engineers and Scientists
Steven F. Barrett and Daniel J. Pack
2006

© Springer Nature Switzerland AG 2022
Reprint of original edition © Morgan & Claypool 2020

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means—electronic, mechanical, photocopy, recording, or any other except for brief quotations in printed reviews, without the prior permission of the publisher.

Index Generation Functions

Tsutomu Sasao

ISBN: 978-3-031-79910-5 paperback
ISBN: 978-3-031-79911-2 ebook
ISBN: 978-3-031-79912-9 hardcover

DOI 10.1007/978-3-031-79911-2

A Publication in the Springer series
SYNTHESIS LECTURES ON DIGITAL CIRCUITS AND SYSTEMS

Lecture #57
Series Editor: Mitchell A. Thornton, *Southern Methodist University*
Series ISSN
Print 1932-3166 Electronic 1932-3174

Index Generation Functions

Tsutomu Sasao
Meiji University, Japan

SYNTHESIS LECTURES ON DIGITAL CIRCUITS AND SYSTEMS #57

ABSTRACT

Index generation functions are binary-input integer valued functions. They represent functions of content addressable memories (CAMs). Applications include: IP address tables; terminal controllers; URL lists; computer virus scanning circuits; memory patch circuits; list of English words; code converters; and pattern matching circuits.

This book shows memory-based realization of index generation functions. It shows:

1. methods to implement index generation functions by look-up table (LUT) cascades and index generation units (IGU),
2. methods to reduce the number of variables using linear transformations, and
3. methods to estimate the sizes of memories,

with many illustrations, tables, examples, exercises, and their solutions.

KEYWORDS

affine equivalence, code converter, constant-weight code, computer virus scanning, equivalence class, functional decomposition, hash function, incompletely specified function, index generation function, index generation unit, IP address table, irreducible index generation function, linear decomposition, linear transformation, LUT cascade, minimization of variables, m-out-of-n code, random function, SAT solver, symmetric function, upper bound, URL list

Contents

Preface

In 2002, the Cluster Project (the first stage) of the MEXT (Ministry of Education, Culture, Sports, Science and Technology of Japan) started. In the MEXT Cluster Project, we received a large amount of research funds for many years. The final goal was to develop a commercial product by doing joint research with industry. At the end of the first stage of the Cluster Project, we encountered the concept of **index generator** as the key device in the network hardware.

An **index generation function** is an integer valued function. It is a mapping from a set of n-bit vectors to the set of integers from 0 to k.

For example, in the case of $n = 32$ and $k = 255$, the function maps $k = 255$ different two-valued vectors into $k = 255$ distinct integers.

An index generation function can be directly implemented by a Content Addressable Memory (CAM). Unfortunately, CAMs dissipate much power and are expensive. Thus, I invented a better realization than CAM for this function. The **Index Generation Unit** (IGU) can realize index generation functions quite efficiently. Its operation is as fast as a CAM, and can be reconfigured quickly.

The design problem of an IGU can be formulated as a minimization problem of the variables for an incompletely specified function. This method is quite efficient, and we can easily implement a practical pattern matching network by using a field programming gate array (FPGA) and memories. An IGU can easily implement a circuit for $k > 10^6$. Furthermore, if we use a linear decomposition, we can drastically reduce the size of the memory. With this idea, many papers have been published, especially with regard to interesting mathematical problems, thus becoming a fruitful research endeavor.

This book considers design methods for index generation functions. Main applications include: IP address table lookup, packet filtering, terminal access controllers, whitelists and blacklists for URLs, virus scan circuits, memory patch circuits, fault map of memory, and pattern matching.

This book also introduces linear decomposition, which efficiently realizes index generation functions.

This book is suitable for both researchers on circuit design and computer-aided design (CAD) tool developers. To read the book, a basic knowledge of logic design is required. It will help with the understanding of the material if the reader has knowledge in linear algebra and statistics. Each chapter contains many examples, and essential chapters contain exercises. Solutions for the exercises are also provided.

Tsutomu Sasao
November 2019

Acknowledgments

This research is supported in part by the Grants in Aid for Scientific Research of JSPS, the grants of MEXT knowledge Cluster Project. Many people were involved in this project: Jon T. Butler, Masayuki Chiba, Yukihiro Iguchi, Kazunari Inoue, Hisashi Iwamoto, Munehiro Matsuura, Alan Mishchenko, Hiroki Nakahara, Shinobu Nagayama, Radomir S. Stankovic, and Akira Usui.

Most materials in this book have been presented at various conferences: International Workshop on Logic and Synthesis (IWLS), EUROMICRO Conference on Digital System Design, Architectures, Methods and Tools (DSD), International Symposium on Multi-Valued Logic (ISMVL), International Conference on Computer-Aided Design (ICCAD), ACM/IEEE Design Automation Conference (DAC), Asia South-Pacific Design Automation Conference (ASPDAC), and Workshop on Synthesis and System Integration of Mixed Information technologies (SASIMI), as well as journals: *IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems*, *The Institute of Electronics, Information and Communication Engineers (IEICE)*, and *Journal of Multi-Valued Logic and Soft Computing*. In many cases, reviewers comments considerably improved the quality of the materials.

Numerous ideas were proposed by the brilliant students of Kyushu Institute of Technology, and Meiji University: Takaaki Nakamura, Masato Maeta, Yuji Urano, Ichido Fumishi, Kyu Matsuura, and Kazuyuki Kai.

Prof. Jon T. Butler read through the entire manuscript repeatedly and made important corrections and improvements. Dr. Alan Mishchenko motivated me to write this book.

Tsutomu Sasao
November 2019