HIGH-PERFORMANCE EMBEDDED COMPUTING

Architectures, Applications, and Methodologies

WAYNE WOLF

MORGAN KAUFMANN

High-Performance Embedded Computing

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江苏工业学院图书馆
藏书章

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MORGAN KAUFMANN PUBLISHERS IS AN IMPRINT OF ELSEVIER

MORGAN KAUFMANN PUBLISHERS

Publisher	Denise E. M. Penrose
Publishing Services Mgr.	George Morrison
Developmental Editor	Nate McFadden
Editorial Assistant	Kimberlee Honjo
Cover Design	Dick Hanus
Cover Image	Corbus Design
Text Design	Rebecca Evans & Associates
Composition	Multiscience Press, Inc.
Technical Illustration	diacriTech
Proofreader	Jodie Allen
Indexer	Steve Rath
Printer	Maple-Vail Book Manufacturing Group

Morgan Kaufmann Publishers is an imprint of Elsevier.
500 Sansome Street, Suite 400, San Francisco, CA 94111

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Library of Congress Cataloging-in-Publication Data

Application submitted

ISBN 13: 978-0-12-369485-0
ISBN 10: 0-12-369485-X

For information on all Morgan Kaufmann publications,
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Printed in the United States of America
06 07 08 09 10   5 4 3 2 1

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In Praise of *High-Performance Embedded Computing: Architectures, Applications, and Methodologies*

High-Performance Embedded Computing is a timely addition to the literature of system design. The number of designs, as well as the number of installed embedded systems, vastly surpasses those of general purpose computing, yet there are very few books on embedded design. This book introduces a comprehensive set of topics ranging from design methodologies to metrics to optimization techniques for the critical embedded system resources of space, time, and energy. There is substantial coverage of the increasingly important design issues associated with multiprocessor systems. Wayne Wolf is a leading expert in embedded design. He has personally conducted research on many of the topics presented in the book, as well as practiced the design methodologies on the numerous embedded systems he has built. This book contains information valuable to the embedded system veteran as well as the novice designer.

—Daniel P. Siewiorek, Carnegie Mellon University

High-Performance Embedded Computing addresses high-end embedded computers—certainly an area where a skilled balance between hardware and software competencies is particularly important for practitioners, and arguably a research domain which will be at the heart of the most interesting methodological evolutions in the coming years. Focusing on best industrial practices and real-world examples and applications, Wayne Wolf presents in an organized and integrated way an impressive amount of leading-edge research approaches, many of which will most likely become key differentiators for winning designs in the coming decade. This is a timely book ideally suited both for practitioners and students in advanced embedded computer engineering courses, as well as researchers and scientists who want to get a snapshot of the important research taking place at the confluence of computer architecture and electronic design automation.

—Paolo Ienne, Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland

As processors continue to leap off our desks and embed themselves into our appliances, our cars, our phones, and perhaps soon our clothing and our wallets, it's become clear that embedded computing is no longer a slow, boring sideshow in the architecture circus. It's moved to the center ring. Wayne Wolf's book pulls all the diverse hardware and software threads together into one solid text for the aspiring embedded systems builder.

—Rob A. Rutenbar, Carnegie Mellon University

Educators in all areas of computer systems and engineering should take a look at this book. Its contrasting perspective on performance, architecture, and design offer an enhanced comprehension of underlying concepts to students at all levels. In my opinion, it represents the shape of things to come for anyone seeking a career in "systems."

—Steven Johnson, Indiana University

More and more embedded devices are available, as people now walk around with cell phones, PDAs, and MP3 players at their side. The design and constraints of these devices are much different than those of a generic computing system, such as a laptop or desktop PC. *High-Performance Embedded Computing* provides an abundance of information on these basic design topics while also covering newer areas of research, such as sensor networks and multiprocessors.

—Mitchell D. Theys, University of Illinois at Chicago

High-Performance Embedded Computing not only presents the state of the art in embedded computing augmented with a discussion of relevant example systems, it also features topics such as software/hardware co-design and multiprocessor architectures for embedded computing. This outstanding book is valuable reading for researchers, practitioners, and students.

—Andreas Polze, Hasso-Plattner-Institute, Universität Potsdam

Embedded computer systems are everywhere. This state-of-the-art book brings together industry practices and the latest research in this arena. It provides an in-depth and comprehensive treatment of the fundamentals, advanced topics, contemporary issues, and real-world challenges in the design of high-performance embedded systems. *High-Performance Embedded Computing* will be extremely valuable to graduate students, researchers, and practicing professionals.

—Jie Hu, New Jersey Institute of Technology

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High-Performance Embedded Computing

About the Author

Wayne Wolf is a professor of electrical engineering and associated faculty in computer science at Princeton University. Before joining Princeton, he was with AT&T Bell Laboratories in Murray Hill, New Jersey. He received his B.S., M.S., and Ph.D. in electrical engineering from Stanford University. He is well known for his research in the areas of hardware/software co-design, embedded computing, VLSI, and multimedia computing systems. He is a fellow of the IEEE and ACM and a member of the SPIE. He won the ASEE Frederick E. Terman Award in 2003. He was program chair of the First International Workshop on Hardware/Software Co-Design. Wayne was also program chair of the 1996 IEEE International Conference on Computer Design, the 2002 IEEE International Conference on Compilers, Architecture, and Synthesis for Embedded Systems, and the 2005 ACM EMSOFT Conference. He was on the first executive committee of the ACM Special Interest Group on Embedded Computing (SIGBED). He is the founding editor-in-chief of *ACM Transactions on Embedded Computing Systems.* He was editor-in-chief of *IEEE Transactions on VLSI Systems* (1999–2000) and was founding co-editor of the Kluwer journal *Design Automation for Embedded Systems.* He is also series editor of the Morgan Kaufmann Series in Systems on Silicon.

To Nancy and Alec

Supplemental Materials

Resources for this book are available at *textbooks.elsevier.com/012369485X*. The instructor site, which is accessible to adopters who register at *textbooks.elsevier.com*, includes:

- Instructor slides (in .ppt format)
- Figures from the text (in .jpg and .ppt formats)
- Solutions to exercises (in .pdf format)

The companion site (accessible to all readers) features:

- Links to related resources on the Web
- A list of errata

Various additonal materials are also available at http://www.princeton.edu/~wolf/hiperf-book.

Preface

This book's goal is to provide a frame of reference for the burgeoning field of high-performance embedded computing. Computers have moved well beyond the early days of 8-bit microcontrollers. Today, embedded computers are organized into multiprocessors that can run millions of lines of code. They do so in real time and at very low power levels. To properly design such systems, a large and growing body of research has developed to answer questions about the characteristics of embedded hardware and software. These are real systems—aircraft, cell phones, and digital television—that all rely on high-performance embedded systems. We understand quite a bit about how to design such systems, but we also have a great deal more to learn.

Real-time control was actually one of the first uses of computers—Chapter 1 mentions the MIT Whirlwind computer, which was developed during the 1950s for weapons control. But the microprocessor moved embedded computing to the front burner as an application area for computers. Although sophisticated embedded systems were in use by 1980, embedded computing as an academic field did not emerge until the 1990s. Even today, many traditional computer science and engineering disciplines study embedded computing topics without being fully aware of related work being done in other disciplines.

Embedded computers are very widely used, with billions sold every year. A huge number of practitioners design embedded systems, and at least a half million programmers work on designs for embedded software. Although embedded systems vary widely in their details, there are common principles that apply to the field of embedded computing. Some principles were discovered decades ago while others are just being developed today. The development of embedded computing as a research field has helped to move embedded system design from a craft to a discipline, a move that is entirely appropriate given the important, sometimes safety-critical, tasks entrusted to embedded computers.

One reasonable question to ask about this field is how it differs from traditional computer systems topics, such as client-server systems or scientific computing. Are we just applying the same principles to smaller systems, or do we need to do something new? I believe that embedded computing, though it makes use of many techniques from computer science and engineering, poses some unique challenges.

First, most if not all embedded systems must perform tasks in real time. This requires a major shift in thinking for both software and hardware designers. Second, embedded computing puts a great deal of emphasis on power and energy consumption. While power is important in all aspects of computer systems, embedded applications tend to be closer to the edge of the energy-operation envelope than many general-purpose systems. All this leads to embedded systems being more heavily engineered to meet a particular set of requirements than those systems that are designed for general use.

This book assumes that you, the reader, are familiar with the basics of embedded hardware and software, such as might be found in *Computers as Components*. This book builds on those foundations to study a range of advanced topics. In selecting topics to cover, I tried to identify topics and results that are unique to embedded computing. I did include some background material from other disciplines to help set the stage for a discussion of embedded systems problems.

Here is a brief tour through the book:

- Chapter 1 provides some important background for the rest of the chapters. It tries to define the set of topics that are at the center of embedded computing. It looks at methodologies and design goals. We survey models of computation, which serve as a frame of reference for the characteristics of applications. The chapter also surveys several important applications that rely on embedded computing to provide background for some terminology that is used throughout the book.
- Chapter 2 looks at several different styles of processors that are used in embedded systems. We consider techniques for tuning the performance of a processor, such as voltage scaling, and the role of the processor memory hierarchy in embedded CPUs. We look at techniques used to optimize embedded CPUs, such as code compression and bus encoding, and techniques for simulating processors.
- Chapter 3 studies programs. The back end of the compilation process, which helps determine the quality of the code, is the first topic. We spend a great deal of time on memory system optimizations, since memory behavior is a prime determinant of both performance and energy consumption. We consider performance analysis, including both simulation and worst-case

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execution time analysis. We also discuss how models of computing are reflected in programming models and languages.

- Chapter 4 moves up to multiple-process systems. We study and compare scheduling algorithms, including the interaction between language design and scheduling mechanisms. We evaluate operating system architectures and the overhead incurred by the operating system. We also consider methods for verifying the behavior of multiple process systems.
- Chapter 5 concentrates on multiprocessor architectures. We consider both tightly coupled multiprocessors and the physically distributed systems used in vehicles. We describe architectures and their components: processors, memory, and networks. We also look at methodologies for multiprocessor design.
- Chapter 6 looks at software for multiprocessors and considers scheduling algorithms for them. We also study middleware architectures for dynamic resource allocation in multiprocessors.
- Chapter 7 concentrates on hardware and software co-design. We study different models that have been used to characterize embedded applications and target architectures. We cover a wide range of algorithms for co-synthesis and compare the models and assumptions used by these algorithms.

Hopefully this book covers at least most of the topics of interest to a practitioner and student of advanced embedded computing systems. There were some topics for which I could find surprisingly little work in the literature: software testing for embedded systems is a prime example. I tried to find representative articles about the major approaches to each problem. I am sure that I have failed in many cases to adequately represent a particular problem, for which I apologize.

This book is about embedded computing; it touches on, but does not exhaustively cover, several related fields:

- Applications—Embedded systems are designed to support applications such as multimedia, communications, and so on. Chapter 1 introduces some basic concepts about a few applications, because knowing something about the application domain is important. An in-depth look at these fields is best left to others.
- VLSI—Although systems-on-chips are an important medium for embedded systems, they are not the only medium. Automobiles, airplanes, and many other important systems are controlled by distributed embedded networks.
- Hybrid systems—The field of hybrid systems studies the interactions between continuous and discrete systems. This is an important and interesting area, and many embedded systems can make use of hybrid system techniques, but hybrid systems deserve their own book.

- Software engineering—Software design is a rich field that provides critical foundations, but it leaves many questions specific to embedded computing unanswered.

I would like to thank a number of people who have helped me with this book: Brian Butler (Qualcomm), Robert P. Adler (Intel), Alain Darte (CNRS), Babak Falsafi (CMU), Ran Ginosar (Technion), John Glossner (Sandbridge), Graham Hellestrand (VaSTSystems), Paolo Ienne (EPFL), Masaharu Imai (Osaka University), Irwin Jacobs (Qualcomm), Axel Jantsch (KTH), Ahmed Jerraya (TIMA), Lizy Kurian John (UT Austin), Christoph Kirsch (University of Salzburg), Phil Koopman (CMU), Haris Lekatsas (NEC), Pierre Paulin (ST Microelectronics), Laura Pozzi (University of Lugano), Chris Rowen (Tensilica), Rob Rutenbar (CMU), Deepu Talla (TI), Jiang Xu (Sandbridge), and Shengqi Yang (Princeton).

I greatly appreciate the support, guidance, and encouragement given by my editor Nate McFadden, as well as the reviewers he worked with. The review process has helped identify the proper role of this book, and Nate provided a steady stream of insightful thoughts and comments. I'd also like to thank my longstanding editor at Morgan Kaufmann, Denise Penrose, who shepherded this book from the beginning.

I'd also like to express my appreciation to digital libraries, particularly those of the IEEE and ACM. I am not sure that this book would have been possible without them. If I had to find all the papers that I have studied in a bricks-and-mortar library, I would have rubbery legs from walking through the stacks, tired eyes, and thousands of paper cuts. With the help of digital libraries, I only have the tired eyes.

And for the patience of Nancy and Alec, my love.

Wayne Wolf
Princeton, New Jersey

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