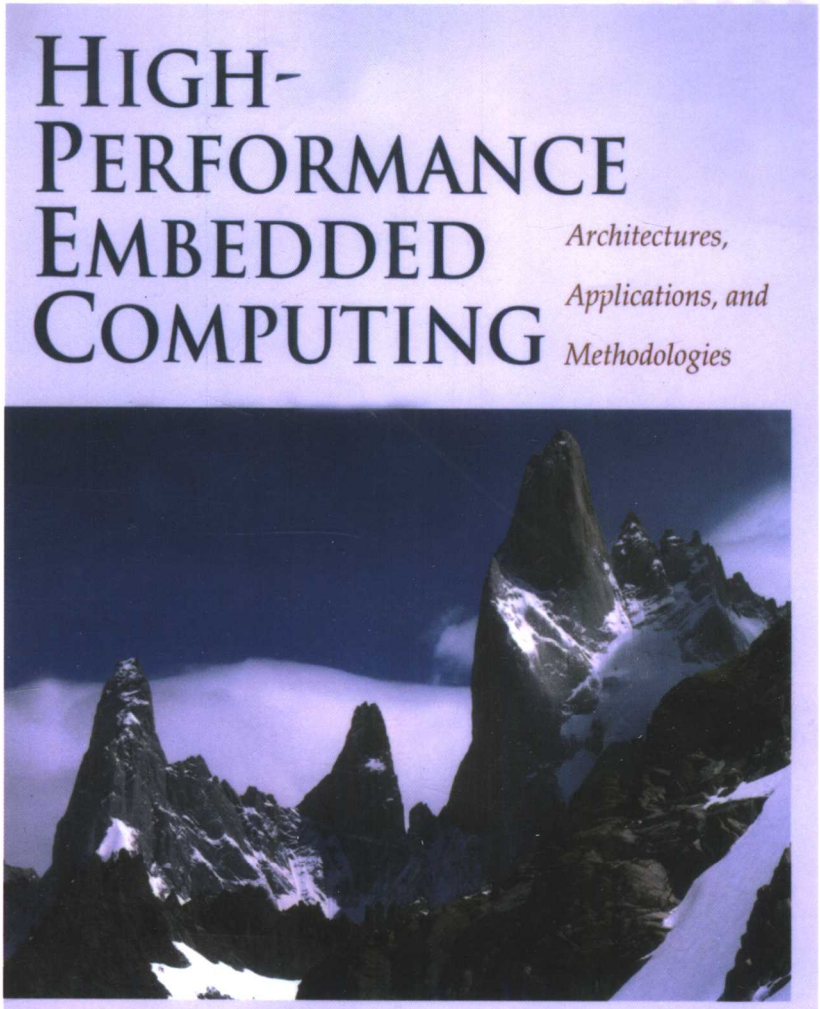
HZ BOOKS
经 典 原 版 书 库

高性能嵌入式计算

（英文版）



（美） Wayne Wolf 普林斯顿大学 著

机械工业出版社
China Machine Press

经 典 原 版 书 库

高性能嵌入式计算

（英文版）

High-Performance Embedded Computing

Architectures, Applications, and Methodologies

（美） Wayne Wolf
普林斯顿大学 著

机械工业出版社
China Machine Press

Wayne Wolf: High-Performance Embedded Computing: Architectures, Applications, and Methodologies (ISBN 13: 978-0-12-369485-0 ISBN 10: 0-12-369485-X).

ISBN 13: 978-981-259-672-7 ISBN 10: 981-259-672-0

本书版权登记号：图字：01-2006-6512

图书在版编目（CIP）数据

高性能嵌入式计算（英文版）/（美）沃尔夫（Wolf, W.）著. -北京：机械工业出版社，2007.1

（经典原版书库）

书名原文：High-Performance Embedded Computing: Architectures, Applications, and Methodologies

ISBN 7-111-20416-6

Ⅰ.高… Ⅱ.沃… Ⅲ.微型计算机-系统设计-英文 Ⅳ.TP360.21

中国版本图书馆CIP数据核字（2006）第139944号

机械工业出版社（北京市西城区百万庄大街22号 邮政编码 100037）

责任编辑：迟振春

北京京北制版印刷厂印刷·新华书店北京发行所发行

2007年1月第1版第1次印刷

170mm × 242mm · 34印张

定价：65.00元

凡购本书，如有倒页、脱页、缺页，由本社发行部调换

本社购书热线：（010）68326294

出版者的话

文艺复兴以降，源远流长的科学精神和逐步形成的学术规范，使西方国家在自然科学的各个领域取得了垄断性的优势；也正是这样的传统，使美国在信息技术发展的六十多年间名家辈出、独领风骚。在商业化的进程中，美国的产业界与教育界越来越紧密地结合，计算机学科中的许多泰山北斗同时身处科研和教学的最前线，由此而产生的经典科学著作，不仅擘划了研究的范畴，还揭橥了学术的源变，既遵循学术规范，又自有学者个性，其价值并不会因年月的流逝而减退。

近年，在全球信息化大潮的推动下，我国的计算机产业发展迅猛，对专业人才的需求日益迫切。这对计算机教育界和出版界都既是机遇，也是挑战；而专业教材的建设在教育战略上显得举足轻重。在我国信息技术发展时间较短、从业人员较少的现状下，美国等发达国家在其计算机科学发展的几十年间积淀的经典教材仍有许多值得借鉴之处。因此，引进一批国外优秀计算机教材将对我国计算机教育事业的发展起积极的推动作用，也是与世界接轨、建设真正的世界一流大学的必由之路。

机械工业出版社华章图文信息有限公司较早意识到“出版要为教育服务”。自1998年开始，华章公司就将工作重点放在了遴选、移译国外优秀教材上。经过几年的不懈努力，我们与Prentice Hall，Addison-Wesley，McGraw-Hill，Morgan Kaufmann等世界著名出版公司建立了良好的合作关系，从它们现有的数百种教材中甄选出Tanenbaum，Stroustrup，Kernighan，Jim Gray等大师名家的一批经典作品，以“计算机科学丛书”为总称出版，供读者学习、研究及庋藏。大理石纹理的封面，也正体现了这套丛书的品位和格调。

“计算机科学丛书”的出版工作得到了国内外学者的鼎力襄助，国内的专家不仅提供了中肯的选题指导，还不辞劳苦地担任了翻译和审校的工作；而原书的作者也相当关注其作品在中国的传播，有的还专程为其书的中译本作序。迄今，“计算机科学丛书”已经出版了近百个品种，这些书籍在读者中树立了良好的口碑，并被许多高校采用为正式教材和参考书籍，为进一步推广与发展打下了坚实的基础。

随着学科建设的初步完善和教材改革的逐渐深化，教育界对国外计算机教材的需求和应用都步入一个新的阶段。为此，华章公司将加大引进教材的力度，在“华章教育”的总规划之下出版三个系列的计算机教材：除“计算机科学丛书”之外，对影印版的教材，则单独开辟出“经典原版书库”；同时，引进全美通行的教学辅导书“Schaum's Outlines”系列组成“全美经典学习指导系列”。为了保证这三套丛书的权威性，同时也为了更好地为学校和老师们服务，华章公司聘请了中国科学院、北京大学、清华大

学、国防科技大学、复旦大学、上海交通大学、南京大学、浙江大学、中国科技大学、哈尔滨工业大学、西安交通大学、中国人民大学、北京航空航天大学、北京邮电大学、中山大学、解放军理工大学、郑州大学、湖北工学院、中国国家信息安全测评认证中心等国内重点大学和科研机构在计算机的各个领域的著名学者组成“专家指导委员会”，为我们提供选题意见和出版监督。

这三套丛书是响应教育部提出的使用外版教材的号召，为国内高校的计算机及相关专业的教学度身订造的。其中许多教材均已为M. I. T.，Stanford，U.C. Berkeley，C. M. U. 等世界名牌大学所采用。不仅涵盖了程序设计、数据结构、操作系统、计算机体系结构、数据库、编译原理、软件工程、图形学、通信与网络、离散数学等国内大学计算机专业普遍开设的核心课程，而且各具特色——有的出自语言设计者之手、有的历经三十年而不衰、有的已被全世界的几百所高校采用。在这些圆熟通博的名师大作的指引之下，读者必将在计算机科学的宫殿中由登堂而入室。

权威的作者、经典的教材、一流的译者、严格的审校、精细的编辑，这些因素使我们的图书有了质量的保证，但我们的目标是尽善尽美，而反馈的意见正是我们达到这一终极目标的重要帮助。教材的出版只是我们的后续服务的起点。华章公司欢迎老师和读者对我们的工作提出建议或给予指正，我们的联系方法如下：

电子邮件：hzjsj@hzbook.com
联系电话：（010）68995264
联系地址：北京市西城区百万庄南街1号
邮政编码：100037

专家指导委员会

（按姓氏笔画顺序）

尤晋元	王　珊	冯博琴	史忠植	史美林
石教英	吕　建	孙玉芳	吴世忠	吴时霖
张立昂	李伟琴	李师贤	李建中	杨冬青
邵维忠	陆丽娜	陆鑫达	陈向群	周伯生
周克定	周傲英	孟小峰	岳丽华	范　明
郑国梁	施伯乐	钟玉琢	唐世渭	袁崇义
高传善	梅　宏	程　旭	程时端	谢希仁
裘宗燕	戴　葵			

To Nancy and Alec

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

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

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

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.

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.

Contents