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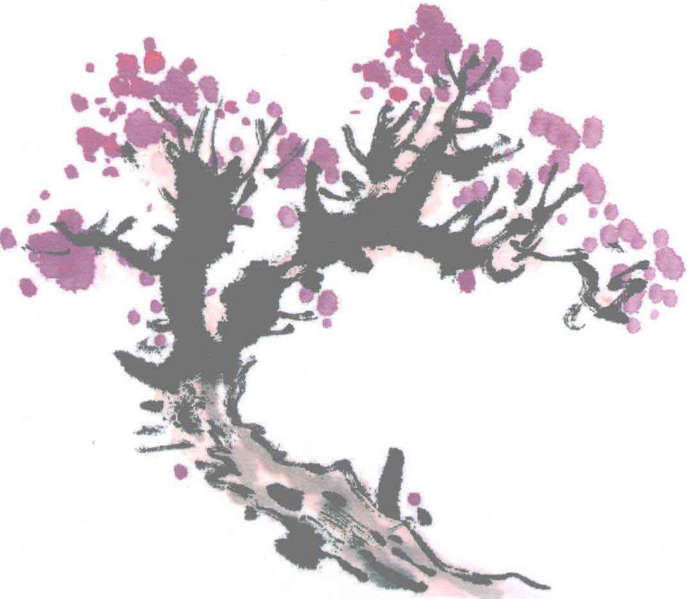
Embedded Systems
Architecture, Programming and Design
Second Edition

嵌入式系统（第2版）
体系结构、编程与设计



Raj Kamal 著

清华大学出版社

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北京

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Embedded Systems: Architecture, Programming and Design, Second Edition

EISBN: 0-07-066764-0

图书在版编目(CIP)数据

嵌入式系统:体系结构、编程与设计 = Embedded Systems: Architecture, Programming and Design: 第2版: 英文 /（印）卡玛尔（Kamal, R.）著. —影印本. —北京：清华大学出版社，2009.5

（大学计算机教育国外著名教材系列（影印版））

ISBN 978-7-302-19794-2

Ⅰ. 嵌…　Ⅱ. 卡…　Ⅲ. 微型计算机－系统开发－高等学校－教材－英文　Ⅳ. TP360.21

中国版本图书馆 CIP 数据核字（2009）第 045373 号

责任印制：王秀菊

出版发行：清华大学出版社　　**地　址**：北京清华大学学研大厦 A 座
http://www.tup.com.cn　　**邮　编**：100084
社 总 机：010-62770175　　**邮　购**：010-62786544
投稿与读者服务：010-62776969, c-service@tup.tsinghua.edu.cn
质量反馈：010-62772015, zhiliang@tup.tsinghua.edu.cn
印 刷 者：清华大学印刷厂
装 订 者：北京鑫海金澳胶印有限公司
发 行 者：全国新华书店
开　本：185×230　　**印张**：42.75
版　次：2009 年 5 月第 1 版　　**印　次**：2009 年 5 月第 1 次印刷
印　数：1~3000
定　价：66.00 元

本书如存在文字不清、漏印、缺页、倒页、脱页等印装质量问题，请与清华大学出版社出版部联系调换。联系电话： 010-62770177 转 3103　　产品编号：032185-01

Bibliography

Barkakati, N., *Microsoft C Bible*, SAMS, 1990.
Barker, L., *C Tools for Scientists and Engineers,* McGraw-Hill,1989.
Berry, R. E. and Meekings; B.A.E., *A Book on C*, Macmillan, 1987.
Hancock, L. and Krieger, M., *The C Primer*, McGraw-Hill, 1987.
Hunt, W.J., *The C Toolbox*, Addison-Weslary, 1985.
Hunter, B. H., *Understanding C*, Sybex, 1985.
Kernighan, B. W. and Ritchie, D. M., *The C Programming Language*, Prentice-Hall, 1977.
Kochan, S. G., *Programming in C*, Hyden, 1983.
Miller, L. H. and Quilici, E. A., *C Programming Language: An Applied Perspective*, John Wiley & Sons, 1987.
Purdum, J. J., *C Programming Guide*, Que Corporation,1985.
Radcliffe, R. A., *Encyclopaedia C*, Sybex 1990.
Schildt, H., *C Made Easy*, Osborne McGraw-Hill, 1987.
Schildt, H., *Advanced C*, Osborne McGraw-Hill, 1988.
Schildt, H., C*: The Complete Reference*, McGraw-Hill, 2000.
Tim Grady, M., *Turbo C! Programming Principles and Practices*, McGraw-Hill 1989.
WIS Staff, *C user's Handbook*, Addison-Wesely, 1984.
Wortman, L. A., and Sidebottom, T.O., *The C Programming Tutor*, Prentice-Hall, 1984.

出 版 说 明

进入21世纪，世界各国的经济、科技以及综合国力的竞争将更加激烈。竞争的中心无疑是对人才的竞争。谁拥有大量高素质的人才，谁就能在竞争中取得优势。高等教育，作为培养高素质人才的事业，必然受到高度重视。目前我国高等教育的教材更新较慢，为了加快教材的更新频率，教育部正在大力促进我国高校采用国外原版教材。

清华大学出版社从1996年开始，与国外著名出版公司合作，影印出版了“大学计算机教育丛书（影印版）”等一系列引进图书，受到国内读者的欢迎和支持。跨入21世纪，我们本着为我国高等教育教材建设服务的初衷，在已有的基础上，进一步扩大选题内容，改变图书开本尺寸，一如既往地请有关专家挑选适用于我国高校本科及研究生计算机教育的国外经典教材或著名教材，组成本套“大学计算机教育国外著名教材系列（影印版）”，以飨读者。深切期盼读者及时将使用本系列教材的效果和意见反馈给我们。更希望国内专家、教授积极向我们推荐国外计算机教育的优秀教材，以利我们把“大学计算机教育国外著名教材系列（影印版）”做得更好，更适合高校师生的需要。

清华大学出版社

About the Author

Raj Kamal did his M.Sc. at the age of 17, published his first research paper in a UK journal at the age of 18, wrote his first program in FORTRAN that ran at ICT 1904, also at the age of 18 and completed his Ph.D. from the Indian Institute of Technology, Delhi, at 22. He has 40 years of experience in research and teaching. He has so far successfully guided nine research students and has published about 90 research papers in journals and conferences of both international and national repute. Due to his constant drive for understanding emerging technologies and passion for acquiring the latest knowledge and its dissemination, he is lovingly referred by a few colleagues as the '*learning machine*' and by a few others as a '*human dynamo*'! He has authored ten textbooks (refer www.rajkamal.org) for students of Computers, Electronics, and Communication and Information Technology, which includes books on Embedded Systems, Computer Architecture (a Schaum Series adaptation) and Internet and Web technologies, published from McGraw-Hill India, McGraw-Hill China, McGraw-Hill South Korea, McGraw-Hill Singapore, and McGraw-Hill USA. He has been associated for several years with Punjab University, Punjab; Kalasalingam University, Tamilnadu; and Guru Nanak Engineering College, Andhra Pradesh. Currently, he is a Senior Professor in School of Computer Sciences and Electronics, Devi Ahilya Viswavidyalaya, Indore.

Preface to the Second Edition

Embedded system design needs hardware and software professionals as a team. Explaining both hardware and software concepts while keeping multidisciplinary undergraduates in mind in a single book is a difficult task. It appears that the earlier edition met this task successfully, considering the positive response it has received in India as well as internationally. A rough estimate is that 80000 engineering and professional training students became the first-time readers of this book in India alone. The book originally published in India has now McGraw-Hill translations published in China and South Korea, an International Students Edition and McGraw-Hill USA editions published from Singapore and New York.

After the publication of the earlier edition, there have been two developments: (1) numerous technology advancements occurred at a fast pace, and (2) many universities introduced syllabi on an Embedded Systems course at the Bachelors of Technology level in multiple engineering disciplines, for example, Computer Science and Engineering, Information Technology, Electronics and Communication, and Instrumentation and control engineering.

The new edition has been written to take the above-mentioned developments into account, besides providing a simpler presentation, keeping the multidisciplinary undergraduates in mind.

The new edition includes several new topics, the important ones being 'Design Process in Embedded Systems', 'Formalism of System Design', 'Wireless Communication Devices', 'Internet Enabled Systems', Wireless and Mobile System Protocols', and 'Windows CE and RTLinux RTOSes'.

The reader will find application of software engineering practices and UML modeling in all case studies and also three additional case studies (Digital Camera, Robot Orchestra and Mobile Phone SMS Creating and Sending).

Further, since the publication of the earlier edition I have been interacting with a number of teachers and students, and receiving feedback from them almost at regular intervals. The chapters of the new edition have also been reviewed by a few young, forthright and dedicated engineering college teachers. It is hoped that this edition takes care of most of their valuable suggestions and criticisms.

This book caters to young minds, who constantly crave for knowledge and would also be a useful reference for professionals, who are required to learn latest topics. The following are new to this edition.

1. Design process in embedded systems and formalism of system design (Chapter 1)
2. 8051 basics, real-world interfacing and introduction to advanced architectures (Chapter 2)
3. Additional topics for port interfacing, for example, touch screen interfacing, an inclusion of SDIO, wireless communication devices, *internet enabled systems*, wireless and mobile system protocols (Chapter 3)
4. Examples of software interrupts and interrupt service routines, and interrupt service threads as second-level interrupt handlers (Chapter 4)
5. Timer and event functions, basic design using a real-time operating system (Chapter 8, *Chapter 9 of the earlier edition*)
6. Host- and target-based, and self-host based development approaches, and types of RTOSes (Chapter 9, *Chapter 10 of the earlier edition*)
7. Two new RTOSes—Windows CE and RTLinux (Chapter 10, *a new chapter*)
8. Use of software engineering and UML modeling practices in seven case studies, and three more case studies—Digital Camera, Robot Orchestra and Mobile Phone SMS Creating and Sending (Chapter 11 and Chapter 12)
9. Select bibliography at the end of the book, (a highlight of the previous edition) has been more enriched.

I would encourage every reader to login at the book's website for accessing the entire information. The new edition has a number of enhancements in the web supplement accompanying this book. A chapter titled 'Software Engineering Practices in the Embedded Software Development Process' in the earlier edition is included in the web supplement at http://www.mhhe.com/kamal/emb2

A student can hone his/her problem-solving and system design skills using modeling practices and learn more key concepts in embedded hardware architecture, interfaces, buses, software programming design and RTOSes from the new edition.

This book is expected to find even more favour internationally than the first edition. It would be helpful to

- Undergraduate and post-graduate engineering students of computer science, information technology, electronics and communication, instrumentation and control
- Software professional trainers, and
- Embedded system design professionals.

Salient Features

- Thorough explanation of embedded hardware architecture, interfacing techniques, buses and protocols, hardware and software interrupts, embedded software programming, modeling, inter-process synchronization and real-time operating systems
- Comprehensive explanation with examples for learning the widely used RTOSes—µCOS-II, VxWorks, Windows CE, OSEK and RTLinux
- Insight into the fundamental aspects that form the basis of hardware and software designing of Embedded Systems
- Explains modeling of programs and software engineering practices for system design using case studies of systems for automatic chocolate vending machine, digital camera, TCP/IP stack creation, robot orchestra, automatic cruise control, smart card and mobile phone
- Incorporates pedagogical features such as a large number of examples, sample codes and demonstrates how to use design and program a system. Also includes chapter-end glossary of terms, review questions and practice exercises
- Detailed selected bibliography of books, journal references and important web links at the end of the book to facilitate building a startup library for further studies in embedded systems

There is an accompanying web supplement at http://www.mhhe.com/kamal/emb2 that is periodically updated and includes

- Solution guide to review questions and practice exercises
- Write-up on 'Software Engineering for Embedded Systems Design'
- Additional details of seven case studies described in the book
- Multiple-choice questions (with answers) for each chapter to test the understanding of concepts and their solutions
- PowerPoint slides for each chapter to supplement lecture presentations

Although much care has been taken to ensure an error-free text, yet a few mistakes may have crept in—I shall be grateful if they are pointed out. The feedback on the content of the book as well as online PPTs and web supplement material at the McGraw-Hill site from readers will be highly appreciated through 'Query' or 'Contact me' links at my website (*http://www.rajkamal.org*).

June 2008 RAJ KAMAL

Acknowledgements

I am immensely grateful to my teachers at the Indian Institute of Technology, Delhi (1966–72), and the University of Uppsala, Sweden (1978–79, 1984), for teaching me the importance of self-learning and the essence of keeping up with emerging technology. I would like to thank Prof. MS Sodha, FNA, for his support and blessings throughout my academic life. I acknowledge my Indore colleagues—Dr PC Sharma, Dr PK Chande, Dr Sanjeev Tokekar, Mrs Vrinda Tokekar, Dr AK Ramani, Dr Maya Ingle, Dr Sanjay Tanwani, Ms Preeti Saxena, Ms Shraddha Masih, Ms Aparna Dev, and Ms Vasanti G Parulkar and other university academicians, Dr PS Grover (Delhi), Dr Harvinder Singh Saini (Hyderabad), Dr S Radhakrishnan (Srivilliputtur), Dr TV Gopal (Anna University) and Dr KM Mehata (Anna University)—for their constant encouragement and appreciation of my efforts. I am thankful to the editorial team at McGraw-Hill Education India for their reviews and suggestions. I acknowledge my late colleague Dr MK Sahu, Head, Computer Centre of the University, who will miss seeing this new edition as he passed away during the last phase of the preparation of this book.

I would also like to thank all those reviewers who took out time to go through the script and give me their feedback. Their names are listed below.

S Ramanaryan Reddy
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Indira Gandhi Institute of Technology, New Delhi

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Stanley Johnson
Invensys India Pvt. Ltd., Chennai

Finally, I acknowledge my wife, Sushil Mittal, and my family members—Shalin Mittal, Needhi Mittal, Dr Atul Kondaskar, Dr Shilpi Kondaskar, and Ms Arushi Kondaskar—for their immense love, understanding, and support during the writing of this revised edition.

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1.1 EMBEDDED SYSTEMS

1.1.1 System

A system is a way of working, organizing or doing one or many tasks according to a fixed plan, program, or set of rules. A system is also an arrangement in which all its units assemble and work together according to the plan or program.

Consider a watch. It is a time-display system. Its parts are its hardware, needles and battery with the beautiful dial, chassis and strap. *These parts organize to show* the real time every second and continuously update the time every second. The system-program updates the display using three needles after each second. *It follows a set of rules*. Some of these rules are as follows: (i) All needles move only clockwise. (ii) A thin and long needle rotates every second such that it returns to same position after a minute. (iii) A long needle rotates every minute such that it returns to same position after an hour. (iv) A short needle rotates every hour such that it returns to same position after twelve hours. (v) All three needles return to the same inclination after twelve hours each day.

Consider a washing machine. It is an automatic clothes-washing system. The important hardware parts include its status display panel, the switches and dials for user-defined programming, a motor to rotate or spin, its power supply and control unit, an inner water-level sensor, a solenoid valve for letting water in and another valve for letting water drain out. *These parts organize* to wash clothes automatically according to a program preset by a user. *The system-program* is activated to wash the dirty clothes placed in a tank, which rotates or spins in preprogrammed steps and stages. *It follows a set of rules*. Some of these rules are as follows: (i) Follow the steps strictly in the following sequence. Step I: Wash by spinning the motor according to a programmed period. Step II: Rinse in fresh water after draining out the dirty water, and rinse a second time if the system is not programmed in water-saving mode. Step III: After draining out the water completely, spin the motor fast for a programmed period for drying by centrifuging out water from the clothes. Step IV: Show the wash-over status by a blinking display. Sound the alarm for a minute to signal that the wash cycle is complete. (ii) At each step, display the process stage of the system. (iii) In case of an interruption, execute only the remaining part of the program, starting from the position when the process was interrupted. There can be no repetition from Step I unless the user resets the system by inserting another set of clothes and resets the program.

1.1.2 Embedded System

Definition One of the definitions of *embedded system* is as follows:

"*An embedded system is a system that has embedded software and computer-hardware, which makes it a system dedicated for an application(s) or specific part of an application or product or a part of a larger system.*"

Embedded systems have been defined in books published recently in several ways. Given below is a series of definitions from others in the field:

Wayne Wolf author of *Computers as Components – Principles of Embedded Computing System Design:* "What is an *embedded computing system*? Loosely defined, it is any device that includes a programmable computer but is not itself intended to be a general-purpose computer" and "a fax machine or a clock built from a microprocessor is an embedded computing system".

Todd D. Morton author of *Embedded Microcontrollers*: "*Embedded Systems* are electronic systems that contain a microprocessor or microcontroller, but we do not think of them as computers—the computer is hidden or embedded in the system."

David E. Simon author of *An Embedded Software Primer*: "People use the term *embedded system* to mean any computer system hidden in any of these products."

Tim Wilmshurst author of *An Introduction to the Design of Small Scale Embedded Systems* with examples from PIC, 80C51 and 68HC05/08 microcontrollers: (1) "An embedded system is a system whose principal function is not computational, but which is controlled by a computer embedded within it. The computer is likely to be a microprocessor or microcontroller. The word embedded implies that it lies inside the overall system, hidden from view, forming an integral part of [the] greater whole". (2) "An embedded system is a microcontroller-based, software-driven, reliable, real time control system, autonomous, or human- or network-interactive, operating on diverse physical variables and in diverse environments, and sold into a competitive and cost-conscious market".

A computer is a system that has the following or more components.

1. A microprocessor
2. A large memory of the following two kinds:
   (a) Primary memory (*semiconductor* memories: Random Access Memory (RAM), Read Only Memory (ROM) and fast accessible caches)
   (b) Secondary memory [(*magnetic* memory located in hard disks, diskettes and cartridge tapes, *optical* memory in CD-ROMs or memory sticks (in mobile computers)] using which different user programs can be loaded into the primary memory and run
3. I/O units such as touch screen, modem, fax cum modem, etc.
4. Input units such as keyboard, mice, digitizer, scanner, etc.
5. Output units such as an LCD screen, video monitor, printer, etc.
6. Networking units such as an Ethernet card, front-end processor-based server, bus drivers, etc.
7. An operating system (OS) that has general purpose user and application software in the secondary memory

An embedded system is a system that has three main components embedded into it:

1. It embeds hardware similar to a computer. Figure 1.1 shows the units in the hardware of an embedded system. As its software usually embeds in the ROM or flash memory, it usually do not need a secondary hard disk and CD memory as in a computer
2. It embeds main application software. The application software may concurrently perform a series of tasks or processes or threads
3. It embeds a real-time operating system (RTOS) that supervises the application software running on hardware and organizes access to a resource according to the priorities of tasks in the system. It provides a mechanism to let the processor run a process as scheduled and context-switch between the various processes. (The concept of process, thread and task explained later in Sections 7.1 to 7.3.) It sets the rules during the execution of the application software. (A small-scale embedded system may not embed the RTOS.)

Characteristics An embedded system is characterized by the following: (1) Real-time and multirate operations define the ways in which the system works, reacts to events, interrupts and schedules the system's functioning in real time. It does so by following a plan to control latencies and to meet deadlines. (Latency refers to the waiting period between running the codes of a task or interrupt service routine and the instance at which the need for the task or interrupt from an event arises). The different operations may take place at

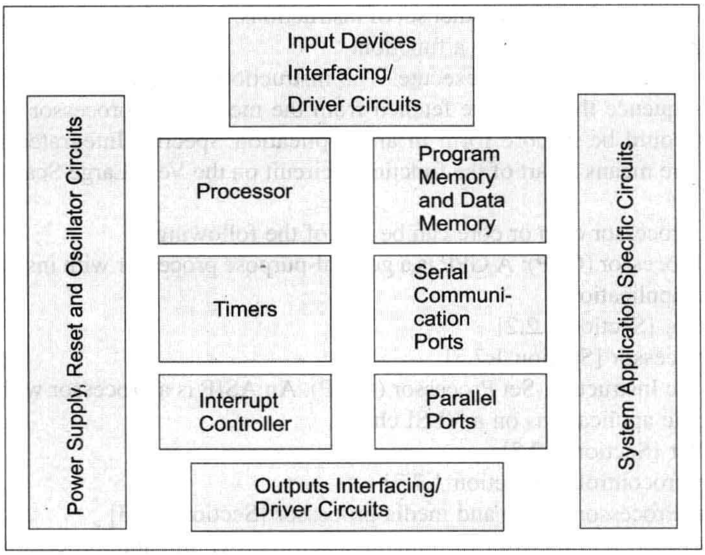
Input Devices Interfacing/ Driver Circuits
Power Supply, Reset and Oscillator Circuits
Processor
Program Memory and Data Memory
Timers
Serial Communication Ports
Interrupt Controller
Parallel Ports
Outputs Interfacing/ Driver Circuits
System Application Specific Circuits

Fig. 1.1 The components of embedded system hardware

distinct rates. For example, audio, video, data, network stream and events have different rates and time constraints. (2) Complex algorithms. (3) Complex graphic user interfaces (GUIs) and other user interfaces. (4) Dedicated functions.

Constraints An embedded system is designed keeping in view three constraints: (1) available system-memory, (2) available processor speed, (3) the need to limit power dissipation when running the system continuously in cycles of 'wait for events', 'run', 'stop', 'wake-up' and 'sleep'.

The system design or an embedded system has constraints with regard to performance, power, size and design and manufacturing costs.

1.2 PROCESSOR EMBEDDED INTO A SYSTEM

A processor is an important unit in the embedded system hardware. It is the heart of the embedded system. Knowledge of basic concept of microprocessors and microcontrollers is must for an embedded system designer. A reader may refer to a standard text or the texts listed in the 'References' at the end of this book for an in-depth understanding of microprocessors, microcontrollers and DSPs that are incorporated in embedded system design. Chapter 2 will explain 8051 and a few processors.

1.2.1 Embedded Processors in a System

A processor has two essential units: Program Flow Control Unit (CU) and Execution Unit (EU). The CU includes a fetch unit for fetching instructions from the memory. The EU has circuits that implement the instructions pertaining to data transfer operations and data conversion from one form to another. The EU includes the Arithmetic and Logical Unit (ALU) and also the circuits that execute instructions for a program