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# THE DEFINITIVE GUIDE TO ARM® CORTEX®-M3 AND CORTEX®-M4 PROCESSORS

Third Edition

Joseph Yiu

# The Definitive Guide to ARM® Cortex®-M3 and Cortex-M4 Processors

Third Edition

**Joseph Yiu**

*ARM Ltd., Cambridge, UK*

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Newnes is an imprint of Elsevier

Newnes is an imprint of Elsevier
The Boulevard, Langford Lane, Kidlington, Oxford OX5 1GB, UK
225 Wyman Street, Waltham, MA 02451, USA



**British Library Cataloguing in Publication Data**
A catalogue record for this book is available from the British Library

**Library of Congress Cataloging-in-Publication Data**
A catalog record for this book is available from the Library of Congress

ISBN−13: 978-0-12-408082-9



Printed and bound in the United States

14 15 16 17 18 10 9 8 7 6 5 4 3 2 1

# Foreword

There is a revolution on the embedded market: Most new microcontrollers are nowadays based on the ARM architecture and specifically on the popular Cortex-M3 and Cortex-M4 processors. Recently we also saw the launch of several new ARM processors. At the low-end of the spectrum, the Cortex-M0+ processor has been introduced for applications that were previously dominated by 8-bit and 16-bit microcontrollers. The new 64-bit Cortex-A50 series processors address the high-end market such as servers. Along with the demand for standardized systems and energy efficient computing performance, the Internet-of-Things (IoT) is one driver for this revolution. In the year 2020, analysts are forecasting 50 billion devices that are connected to the IoT, and the ARM processors will span the whole application range from sensors to servers. Many devices will be based on Cortex-M3 and Cortex-M4 microcontrollers and may just use a small battery or even energy harvesting as power source.

Using ARM Cortex-M3 and Cortex-M4 processors based devices today is straightforward since a wide range of development tools, debug utilities, and many example projects are available. However, writing efficient applications could require in-depth knowledge about the hardware architecture and the software model. This book provides essential information for system architects and software engineers: It gives insight into popular software development tools along with extensive programming examples that are based on the Cortex Microcontroller Software Interface Standard (CMSIS). It also covers the Digital Signal Processing (DSP) features of the Cortex-M4 processor and the CMSIS-DSP library for interfacing with the analog world. And with many embedded applications becoming more complex and the wider availability of more capable microcontrollers, using of real-time operating systems is becoming common practice. All these topics are covered with easy-to-understand application examples.

I recommend this book to all type of users: From students that start with a small Cortex-M microcontroller project to system experts that need an in-depth understanding of processor features.

Reinhard Keil
Director of MCU Tools, ARM

# Preface

The last few years has seen the ARM® Cortex®-M3 processor continue to expand its market coverage and the adoption of the Cortex-M4 processor gaining momentum. At the same time the software development tools and various technologies surrounding the Cortex-M processors have also evolved. For example, the CMSIS-Core is now being used in almost all Cortex-M device driver libraries and the CMSIS project has expanded into areas such as the DSP library software.

In this edition, I have restructured my original book to enable beginners to quickly understand the M3 & M4 processor architecture, enabling them in the process to quickly develop software applications. I have also covered a number of advanced topics that numerous users have asked me to cover and which were missing from the previous editions – and were not covered in other books or in documentation created by ARM. In this edition I have also added a great deal of new information on the Cortex-M4 processor, for example, the detail uses of the floating point unit and the DSP instructions, and have extended the coverage of a number of topics. For example, this edition includes more microcontroller software development suites than previous editions, including a chapter on Real-Time Operating Systems (RTOS) based on the CMSIS-RTOS API, and additional information on a number of advanced topics.

Also included in this edition are two chapters on DSP written by Paul Beckmann, CEO of DSP Concepts, a company that has developed the CMSIS-DSP library for ARM. I am extremely pleased to have his contribution, since his in-depth knowledge of DSP applications and the CMSIS-DSP library make this book a worthwhile investment for any ARM-embedded software developer.

This book is for both embedded hardware system designers and software engineers. Because it has a wide range of chapters covering topics from "Getting Started" – to those detailing advanced information, it is suitable for a wide range of readers including programmers, embedded product designers, electronic enthusiasts, academic researchers, and even System-on-a-Chip (SoC) engineers. A chapter on software porting is also included to help readers who are porting software from other architectures or from ARM7TDMI™, a classic ARM processor, to Cortex-M microcontrollers.

Hopefully you will find this book useful and well worth reading.

Joseph Yiu

# Synopsis

This is the third edition of the Definitive Guide to the ARM® Cortex®-M3. The book name has been changed to reflect the addition of the details for the ARM Cortex-M4 processor. This third edition has been fully revised and updated, and now includes extensive information on the ARM Cortex-M4 processor, providing a complete up-to-date guide to both Cortex-M3 and Cortex-M4 processor but which also enables migration from various processor architectures to the exciting world of the Cortex-M3 and M4.

The book presents the background of the ARM architecture and outlines the features of the processors such as the instruction set and interrupt-handling and also demonstrates how to program and utilize various advanced features available such as the floating point unit.

Chapters on Getting Started with Keil™ MDK-ARM, IAR EWARM, gcc, and CooCox CoIDE tools are available to enable beginners to start developing program codes. The book then covers several important areas of software development such as input/output of information, using embedded OSs (CMSIS-RTOS), and mixed language projects with assembly and C.

Two chapters on DSP features and CMSIS-DSP libraries are contributed by Paul Beckmann, PhD, the founder and CEO of DSP Concepts. DSP Concepts is the company that developed the CMSIS-DSP library for ARM. These two chapters cover DSP fundamentals and how to write DSP software for the Cortex-M4 processor, including examples of using the CMSIS-DSP library, as well as useful information about the DSP capability of the Cortex-M4 processor.

Various debugging techniques are also covered in various chapters of the book, as well as topics on software porting from other architectures. This is the most comprehensive guide to the ARM Cortex-M3 and Cortex-M4 processors, written by an ARM engineer who helped to develop the core. It includes a full range of easy-to-understand examples, diagrams, quick reference appendices such as instruction sets, and CMSIS-Core APIs.

# About this Book

# Contributor Bio-Paul Beckmann

Paul Beckmann is the founder of DSP Concepts, an engineering services company that specializes in DSP algorithm development and supporting tools. He has many years of experience developing and implementing numerically intensive algorithms for audio, communications, and video. Paul has taught industry courses on digital signal processing, and holds a variety of patents in processing techniques. Prior to founding DSP Concepts, Paul spent 9 years at Bose Corporation and was involved in R&D and product development activities.

# Acknowledgments

I would like to thank the following people for providing me with help, advice and feedback for the 3rd edition of this book:

First of all, a big thank you to Paul Beckmann, PhD, for contributing two chapters on the DSP subject. The DSP capability is an important part of the Cortex-M4 processor and the CMSIS-DSP library is a significant stepping stone for allowing microcontroller users to develop DSP applications. This book would not be complete without these two chapters.

Secondly, I would like to thanks my colleagues at ARM for their support. I have received much useful feedback from Joey Ye, Stephen Theobald, Graham Cunningham, Edmund Player, Drew Barbier, Chris Shore, Simon Craske, and Robert Boys. Also many thanks for the support from the ARM Embedded marketing team: Richard York, Andrew Frame, Neil Werdmuller, and Ian Johnson.

I would also like to thank Reinhard Keil, Robert Rostohar, and Martin Günther of Keil for answering my many questions on CMSIS, Anders Lundgren of IAR Systems for reviewing the materials related to EWARM, and Magnus Unemyr for reviewing materials related to Atollic TrueStudio®.

I also want to thank the following people for their help in assisting with the writing of the first and second editions of this book: Dominic Pajak, Alan Tringham, Nick Sampays, Dan Brook, David Brash, Haydn Povey, Gary Campbell, Kevin McDermott, Richard Earnshaw, Shyam Sadasivan, Simon Axford, Takashi Ugajin, Wayne Lyons, Samin Ishtiaq, Dev Banerjee, Simon Smith, Ian Bell, Jamie Brettle, Carlos O'Donell, Brian Barrera, and Daniel Jacobowitz.

And of course, I must express my gratitude to all the readers of my previous books that have provided me with their very useful feedback.

Also, many thanks to the staff at Elsevier for their professional work, which has enabled this book to be published

And finally, a special thank you to all of my friends for their support and understanding whist I was writing this book.

Regards,
Joseph Yiu

# Terms and Abbreviations

| Abbreviation | Meaning |
|---|---|
| ADK | AMBA Design Kit |
| AHB | Advanced High-Performance Bus |
| AHB-AP | AHB Access Port |
| AMBA | Advanced Microcontroller Bus Architecture |
| APB | Advanced Peripheral Bus |
| API | Application Programming Interface |
| ARM ARM | ARM Architecture Reference Manual |
| ASIC | Application Specific Integrated Circuit |
| ATB | Advanced Trace Bus |
| BE8 | Byte Invariant Big Endian Mode |
| CMSIS | Cortex Microcontroller Software Interface Standard |
| CPI | Cycles Per Instruction |
| CPU | Central Processing Unit |
| DAP | Debug Access Port |
| DSP | Digital Signal Processor/Digital Signal Processing |
| DWT | Data WatchPoint and Trace |
| EABI/ABI | Embedded Application Binary Interface |
| ETM | Embedded Trace Macrocell |
| FPB | Flash Patch and Breakpoint |
| FPGA | Field Programmable Gate Array |
| FPU | Floating Point Unit |
| FSR | Fault Status Register |
| ICE | In-Circuit Emulator |
| IDE | Integrated Development Environment |
| IRQ | Interrupt Request (normally refers to external interrupts) |
| ISA | Instruction Set Architecture |
| ISR | Interrupt Service Routine |
| ITM | Instrumentation Trace Macrocell |
| JTAG | Joint Test Action Group (a standard of test/debug interfaces) |
| JTAG-DP | JTAG Debug Port |
| LR | Link Register |
| LSB | Least Significant Bit |
| LSU | Load/Store Unit |
| MAC | Multiply Accumulate |
| MCU | Microcontroller Unit |
| MMU | Memory Management Unit |

(*Continued*)