

Contents

Foreword to the First Edition	xv
Preface to the First Edition	xvii
Preface to the Second Edition	xxi
Preface to the Third Edition	xxiii

CHAPTER 1 Embedded Computing	1
1.1 Introduction	1
1.2 Complex systems and microprocessors	1
1.2.1 Embedding computers	2
1.2.2 Characteristics of embedded computing applications	4
1.2.3 Why use microprocessors?	6
1.2.4 Cyber-physical systems	7
1.2.5 Challenges in embedded computing system design	8
1.2.6 Performance of embedded computing systems	9
1.3 The embedded system design process	10
1.3.1 Requirements	12
1.3.2 Specification	16
1.3.3 Architecture design	17
1.3.4 Designing hardware and software components	19
1.3.5 System integration	19
1.3.6 Formalisms for system design	20
1.3.7 Structural description	21
1.3.8 Behavioral description	25
1.4 Design example: Model train controller	28
1.4.1 Requirements	29
1.4.2 DCC	30
1.4.3 Conceptual specification	32
1.4.4 Detailed specification	35
1.4.5 Lessons learned	42
1.5 A guided tour of this book	42
1.5.1 Chapter 2: Instruction sets	43
1.5.2 Chapter 3: CPUs	43
1.5.3 Chapter 4: Computing platforms	44
1.5.4 Chapter 5: Program design and analysis	44
1.5.5 Chapter 6: Processes and operating systems	45
1.5.6 Chapter 7: System design techniques	46
1.5.7 Chapter 8: Networks and multiprocessors	47

1.6 Summary.....	47
What we learned.....	48
Further reading.....	48
Questions.....	48
Lab exercises.....	50
CHAPTER 2 Instruction Sets	51
2.1 Introduction	51
2.2 Preliminaries.....	51
2.2.1 Computer architecture taxonomy.....	52
2.2.2 Assembly languages.....	54
2.2.3 VLIW processors	56
2.3 ARM processor	57
2.3.1 Processor and memory organization.....	58
2.3.2 Data operations	59
2.3.3 Flow of control.....	66
2.3.4 Advanced ARM features.....	72
2.4 PICmicro mid-range family.....	73
2.4.1 Processor and memory organization.....	73
2.4.2 Data operations	73
2.4.3 Flow of control.....	76
2.5 TI C55x DSP.....	77
2.5.1 Processor and memory organization.....	78
2.5.2 Addressing modes	81
2.5.3 Data operations	83
2.5.4 Flow of control.....	84
2.5.5 C coding guidelines	86
2.6 TI C64x.....	87
2.7 Summary.....	90
What we learned.....	90
Further reading.....	91
Questions.....	91
Lab exercises.....	93
CHAPTER 3 CPUs.....	95
3.1 Introduction	95
3.2 Programming input and output.....	96
3.2.1 Input and output devices	96
3.2.2 Input and output primitives.....	98
3.2.3 Busy-wait I/O.....	99
3.2.4 Interrupts.....	101

3.3	Supervisor mode, exceptions, and traps	114
3.3.1	Supervisor mode	114
3.3.2	Exceptions.....	115
3.3.3	Traps.....	115
3.4	Co-processors	115
3.5	Memory system mechanisms.....	116
3.5.1	Caches.....	116
3.5.2	Memory management units and address translation...	123
3.6	CPU performance	128
3.6.1	Pipelining	128
3.6.2	Cache performance	132
3.7	CPU power consumption.....	133
3.8	Design example: Data compressor	137
3.8.1	Requirements and algorithm.....	137
3.8.2	Specification.....	140
3.8.3	Program design	141
3.8.4	Testing.....	148
3.9	Summary.....	149
	What we learned.....	149
	Further reading.....	150
	Questions.....	150
	Lab exercises.....	153
CHAPTER 4	Computing Platforms.....	155
4.1	Introduction	155
4.2	Basic computing platforms.....	155
4.2.1	Platform hardware components	156
4.2.2	Platform software components	158
4.3	The CPU bus.....	159
4.3.1	Bus organization and protocol	160
4.3.2	DMA	167
4.3.3	System bus configurations	170
4.4	Memory devices and systems.....	172
4.4.1	Memory system organization.....	174
4.5	Designing with computing platforms	176
4.5.1	Example platforms.....	176
4.5.2	Choosing a platform.....	176
4.5.3	Intellectual property.....	179
4.5.4	Development environments	180
4.5.5	Debugging techniques.....	181
4.5.6	Debugging challenges.....	183

- 4.6 Consumer electronics architecture..... 185
 - 4.6.1 Consumer electronics use cases and requirements... 185
 - 4.6.2 File systems 187
- 4.7 Platform-level performance analysis..... 188
- 4.8 Design example: Alarm clock..... 193
 - 4.8.1 Requirements..... 193
 - 4.8.2 Specification 194
 - 4.8.3 System architecture 197
 - 4.8.4 Component design and testing 200
 - 4.8.5 System integration and testing 200
- 4.9 Design example: Audio player 200
 - 4.9.1 Theory of operation and requirements 200
 - 4.9.2 Specification 202
 - 4.9.3 System architecture 204
 - 4.9.4 Component design and testing 206
 - 4.9.5 System integration and debugging 206
- 4.10 Summary 207
- What we learned..... 207
- Further reading..... 207
- Questions..... 207
- Lab exercises..... 210

CHAPTER 5 Program Design and Analysis 213

- 5.1 Introduction 213
- 5.2 Components for embedded programs..... 214
 - 5.2.1 State machines..... 214
 - 5.2.2 Circular buffers and stream-oriented programming.. 216
 - 5.2.3 Queues and producer/consumer systems..... 221
- 5.3 Models of programs..... 223
 - 5.3.1 Data flow graphs..... 224
 - 5.3.2 Control/data flow graphs 226
- 5.4 Assembly, linking, and loading..... 228
 - 5.4.1 Assemblers 229
 - 5.4.2 Linking 233
 - 5.4.3 Object code design 235
- 5.5 Compilation techniques..... 236
 - 5.5.1 The compilation process..... 236
 - 5.5.2 Basic compilation methods 237
 - 5.5.3 Compiler optimizations 245
- 5.6 Program-level performance analysis 254
 - 5.6.1 Elements of program performance 256
 - 5.6.2 Measurement-driven performance analysis..... 259

5.7	Software performance optimization	262
5.7.1	Loop optimizations.....	262
5.7.2	Cache optimizations	264
5.7.3	Performance optimization strategies	265
5.8	Program-level energy and power analysis and optimization.....	266
5.9	Analysis and optimization of program size	270
5.10	Program validation and testing.....	271
5.10.1	Clear-box testing	271
5.10.2	Black-box testing	278
5.10.3	Evaluating functional tests	279
5.11	Design example: Software modem.....	280
5.11.1	Theory of operation and requirements	280
5.11.2	Specification.....	283
5.11.3	System architecture	283
5.11.4	Component design and testing	284
5.11.5	System integration and testing	285
5.12	Design example: Digital still camera	285
5.12.1	Theory of operation and requirements	285
5.12.2	Specification.....	290
5.12.3	System architecture	293
5.12.4	Component design and testing	296
5.12.5	System integration and testing	296
5.13	Summary	296
	What we learned.....	296
	Further reading	297
	Questions.....	297
	Lab exercises.....	305
CHAPTER 6	Processes and Operating Systems	307
6.1	Introduction	307
6.2	Multiple tasks and multiple processes	308
6.2.1	Tasks and processes.....	308
6.3	Multirate systems.....	310
6.3.1	Timing requirements on processes	311
6.3.2	CPU usage metrics	316
6.3.3	Process state and scheduling	316
6.3.4	Running periodic processes.....	317
6.4	Preemptive real-time operating systems.....	319
6.4.1	Two basic concepts.....	320
6.4.2	Processes and context.....	321
6.4.3	Processes and object-oriented design.....	324

6.5	Priority-based scheduling	325
6.5.1	Rate-monotonic scheduling.....	326
6.5.2	Shared resources.....	330
6.5.3	Priority inversion.....	332
6.5.4	Earliest-deadline-first scheduling	333
6.5.5	RMS versus EDF.....	337
6.5.6	A closer look at our modeling assumptions.....	337
6.6	Interprocess communication mechanisms.....	340
6.6.1	Shared memory communication.....	340
6.6.2	Message passing.....	341
6.6.3	Signals	342
6.6.4	Mailboxes	343
6.7	Evaluating operating system performance	344
6.8	Power optimization strategies for processes.....	349
6.9	Example real-time operating systems.....	352
6.9.1	POSIX	352
6.9.2	Windows CE.....	357
6.10	Design example: Telephone answering machine	361
6.10.1	Theory of operation and requirements	361
6.10.2	Specification.....	364
6.10.3	System architecture	366
6.10.4	Component design and testing	368
6.10.5	System integration and testing	368
6.11	Design example: Engine control unit.....	369
6.11.1	Theory of operation and requirements	369
6.11.2	Specification.....	370
6.11.3	System architecture.....	371
6.11.4	Component design and testing	373
6.11.5	System integration and testing	374
6.12	Summary	374
	What we learned.....	374
	Further reading	374
	Questions.....	375
	Lab exercises.....	380
CHAPTER 7	System Design Techniques	381
7.1	Introduction	381
7.2	Design methodologies	381
7.2.1	Why design methodologies?	381
7.2.2	Design flows.....	383

7.3	Requirements analysis	389
7.4	Specifications.....	390
7.4.1	Control-oriented specification languages.....	391
7.4.2	Advanced specifications.....	394
7.5	System analysis and architecture design	396
7.5.1	CRC cards	396
7.6	Quality assurance.....	400
7.6.1	Quality assurance techniques.....	402
7.6.2	Verifying the specification	404
7.6.3	Design reviews.....	406
7.7	Summary.....	407
	What we learned.....	407
	Further reading.....	408
	Questions.....	408
	Lab exercises.....	408
CHAPTER 8	Networks and Multiprocessors	409
8.1	Introduction	409
8.2	Why networks and multiprocessors?.....	409
8.3	Categories of multiprocessors	412
8.4	Distributed embedded systems	414
8.4.1	Network abstractions	414
8.4.2	CAN bus	416
8.4.3	Distributed computing in cars and airplanes.....	419
8.4.4	I ² C bus.....	422
8.4.5	Ethernet.....	426
8.4.6	Internet.....	429
8.5	MPSoCs and shared memory multiprocessors	431
8.5.1	Heterogeneous shared memory multiprocessors	431
8.5.2	Accelerators	432
8.5.3	Accelerator performance analysis.....	434
8.5.4	Scheduling and allocation.....	438
8.6	Design example: Video accelerator	441
8.6.1	Video compression.....	441
8.6.2	Algorithm and requirements	443
8.6.3	Specification.....	445
8.6.4	Architecture.....	446
8.6.5	Component design	449
8.6.6	System testing	449
8.7	Application example: Compact disc.....	449

8.8 Summary.....	454
What we learned.....	454
Further reading	454
Questions.....	455
Lab exercises.....	456
Glossary	459
References.....	477
Index.....	487