

# Contents

	<b>Foreword</b>	<b>ix</b>
	<b>Preface</b>	<b>xv</b>
	<b>Acknowledgments</b>	<b>xxiii</b>
<b>Chapter 1</b>	<b>Fundamentals of Quantitative Design and Analysis</b>	
	1.1 Introduction	2
	1.2 Classes of Computers	5
	1.3 Defining Computer Architecture	11
	1.4 Trends in Technology	17
	1.5 Trends in Power and Energy in Integrated Circuits	21
	1.6 Trends in Cost	27
	1.7 Dependability	33
	1.8 Measuring, Reporting, and Summarizing Performance	36
	1.9 Quantitative Principles of Computer Design	44
	1.10 Putting It All Together: Performance, Price, and Power	52
	1.11 Fallacies and Pitfalls	55
	1.12 Concluding Remarks	59
	1.13 Historical Perspectives and References	61
	Case Studies and Exercises by Diana Franklin	61
<b>Chapter 2</b>	<b>Memory Hierarchy Design</b>	
	2.1 Introduction	72
	2.2 Ten Advanced Optimizations of Cache Performance	78
	2.3 Memory Technology and Optimizations	96
	2.4 Protection: Virtual Memory and Virtual Machines	105
	2.5 Crosscutting Issues: The Design of Memory Hierarchies	112
	2.6 Putting It All Together: Memory Hierarchies in the ARM Cortex-A8 and Intel Core i7	113
	2.7 Fallacies and Pitfalls	125

2.8	Concluding Remarks: Looking Ahead	129
2.9	Historical Perspective and References	131
	Case Studies and Exercises by Norman P. Jouppi, Naveen Muralimanohar, and Sheng Li	131
<b>Chapter 3 Instruction-Level Parallelism and Its Exploitation</b>		
3.1	Instruction-Level Parallelism: Concepts and Challenges	148
3.2	Basic Compiler Techniques for Exposing ILP	156
3.3	Reducing Branch Costs with Advanced Branch Prediction	162
3.4	Overcoming Data Hazards with Dynamic Scheduling	167
3.5	Dynamic Scheduling: Examples and the Algorithm	176
3.6	Hardware-Based Speculation	183
3.7	Exploiting ILP Using Multiple Issue and Static Scheduling	192
3.8	Exploiting ILP Using Dynamic Scheduling, Multiple Issue, and Speculation	197
3.9	Advanced Techniques for Instruction Delivery and Speculation	202
3.10	Studies of the Limitations of ILP	213
3.11	Cross-Cutting Issues: ILP Approaches and the Memory System	221
3.12	Multithreading: Exploiting Thread-Level Parallelism to Improve Uniprocessor Throughput	223
3.13	Putting It All Together: The Intel Core i7 and ARM Cortex-A8	233
3.14	Fallacies and Pitfalls	241
3.15	Concluding Remarks: What's Ahead?	245
3.16	Historical Perspective and References	247
	Case Studies and Exercises by Jason D. Bakos and Robert P. Colwell	247
<b>Chapter 4 Data-Level Parallelism in Vector, SIMD, and GPU Architectures</b>		
4.1	Introduction	262
4.2	Vector Architecture	264
4.3	SIMD Instruction Set Extensions for Multimedia	282
4.4	Graphics Processing Units	288
4.5	Detecting and Enhancing Loop-Level Parallelism	315
4.6	Crosscutting Issues	322
4.7	Putting It All Together: Mobile versus Server GPUs and Tesla versus Core i7	323
4.8	Fallacies and Pitfalls	330
4.9	Concluding Remarks	332
4.10	Historical Perspective and References	334
	Case Study and Exercises by Jason D. Bakos	334
<b>Chapter 5 Thread-Level Parallelism</b>		
5.1	Introduction	344
5.2	Centralized Shared-Memory Architectures	351
5.3	Performance of Symmetric Shared-Memory Multiprocessors	366

	5.4	Distributed Shared-Memory and Directory-Based Coherence	378
	5.5	Synchronization: The Basics	386
	5.6	Models of Memory Consistency: An Introduction	392
	5.7	Crosscutting Issues	395
	5.8	Putting It All Together: Multicore Processors and Their Performance	400
	5.9	Fallacies and Pitfalls	405
	5.10	Concluding Remarks	409
	5.11	Historical Perspectives and References	412
		Case Studies and Exercises by Amr Zaky and David A. Wood	412
<b>Chapter 6</b>		<b>Warehouse-Scale Computers to Exploit Request-Level and Data-Level Parallelism</b>	
	6.1	Introduction	432
	6.2	Programming Models and Workloads for Warehouse-Scale Computers	436
	6.3	Computer Architecture of Warehouse-Scale Computers	441
	6.4	Physical Infrastructure and Costs of Warehouse-Scale Computers	446
	6.5	Cloud Computing: The Return of Utility Computing	455
	6.6	Crosscutting Issues	461
	6.7	Putting It All Together: A Google Warehouse-Scale Computer	464
	6.8	Fallacies and Pitfalls	471
	6.9	Concluding Remarks	475
	6.10	Historical Perspectives and References	476
		Case Studies and Exercises by Parthasarathy Ranganathan	476
<b>Appendix A</b>		<b>Instruction Set Principles</b>	
	A.1	Introduction	A-2
	A.2	Classifying Instruction Set Architectures	A-3
	A.3	Memory Addressing	A-7
	A.4	Type and Size of Operands	A-13
	A.5	Operations in the Instruction Set	A-14
	A.6	Instructions for Control Flow	A-16
	A.7	Encoding an Instruction Set	A-21
	A.8	Crosscutting Issues: The Role of Compilers	A-24
	A.9	Putting It All Together: The MIPS Architecture	A-32
	A.10	Fallacies and Pitfalls	A-39
	A.11	Concluding Remarks	A-45
	A.12	Historical Perspective and References	A-47
		Exercises by Gregory D. Peterson	A-47
<b>Appendix B</b>		<b>Review of Memory Hierarchy</b>	
	B.1	Introduction	B-2
	B.2	Cache Performance	B-16
	B.3	Six Basic Cache Optimizations	B-22

B.4	Virtual Memory	B-40
B.5	Protection and Examples of Virtual Memory	B-49
B.6	Fallacies and Pitfalls	B-57
B.7	Concluding Remarks	B-59
B.8	Historical Perspective and References	B-59
	Exercises by Amr Zaky	B-60

**Appendix C    **Pipelining: Basic and Intermediate Concepts****

C.1	Introduction	C-2
C.2	The Major Hurdle of Pipelining—Pipeline Hazards	C-11
C.3	How Is Pipelining Implemented?	C-30
C.4	What Makes Pipelining Hard to Implement?	C-43
C.5	Extending the MIPS Pipeline to Handle Multicycle Operations	C-51
C.6	Putting It All Together: The MIPS R4000 Pipeline	C-61
C.7	Crosscutting Issues	C-70
C.8	Fallacies and Pitfalls	C-80
C.9	Concluding Remarks	C-81
C.10	Historical Perspective and References	C-81
	Updated Exercises by Diana Franklin	C-82

***Online Appendices***

Appendix D

**Storage Systems**

Appendix E

**Embedded Systems**

*By Thomas M. Conte*

Appendix F

**Interconnection Networks**

*Revised by Timothy M. Pinkston and José Duato*

Appendix G

**Vector Processors in More Depth**

*Revised by Krste Asanovic*

Appendix H

**Hardware and Software for VLIW and EPIC**

Appendix I

**Large-Scale Multiprocessors and Scientific Applications**

Appendix J

**Computer Arithmetic**

*by David Goldberg*

Appendix K

**Survey of Instruction Set Architectures**

Appendix L

**Historical Perspectives and References**

**References**

**R-1**

**Index**

**I-1**