Contents

1

2

Pref	<i>ace</i>		<i>page</i> xi	
Com	puting	and the Transformation of Society	1	
1.1	Comp	outing Transforms Society and Economy	1	
	1.1.1	Home	2	
	1.1.2	Automobiles and Transportation	2	
	1.1.3	Commerce	3	
1.2	Comp	outing Transforms Science and Discovery	5	
1.3	Extrac	ordinary Characteristics of Computing	6	
1.4	What	/hat is Computer Architecture?		
1.5	Four Pillars of Computer Performance: Miniaturization, Hidden			
	Parallelism, Dynamic Locality, and Explicit Parallelism			
1.6	Expec	ted Background	10	
1.7	Organ	ization of the Book	11	
1.8	Summ	hary	13	
1.9	Proble	ems	13	
Instr	uctions	Sets, Software, and Instruction Execution	16	
2.1	Comp	outer Instruction Sets	16	
2.2	Comp	uter Systems Architecture	17	
2.3	Instruction Set Architecture: RISC-V Example			
	2.3.1	Computation Instructions	19	
	2.3.2	Conditional Control and Procedure Linkage Instructions	20	
	2.3.3	Memory Instructions	22	
2.4	Machine Instructions and Basic Software Structures			
	2.4.1	Implementing Basic Expressions	23	
	2.4.2	Implementing Data Structures: Structs and Objects	23	
	2.4.3	Implementing One- and Multi-dimensional Arrays	26	
	2.4.4	Implementing Conditional Iterative Constructs: Loops	27	
	2.4.5	Implementing Procedure Call and Return and the Stack	30	
2.5	Basic Instruction Execution and Implementation			
	2.5.1	Sequential State and Instruction Execution	35	
	2.5.2	Hardware Implementation of Instruction Execution	35	
2.6	Speed	36		

2.7	Summary	37
2.8	Digging Deeper	38
2.9	Problems	39
Proc	essors and Scaling: Small is Fast!	48
3.1	Miniaturization and Information Processing	48
3.2	What Is the Natural Size of a Computer?	50
	3.2.1 Example: Bit Size and Speed	52
	3.2.2 Shrinking Computers	53
3.3	Computer Size and Speed	53
	3.3.1 Smaller Computers Are Faster	54
	3.3.2 Example: Applying the Size and Clock Period Model	56
	3.3.3 Size Scaling Computers from Room-Sized to a Single Chip	57
	3.3.4 Size Scaling Single-Chip Computers: The Power	
	Problem and Dennard's Solution	59
	3.3.5 The End of Dennard Scaling	62
3.4	Computer Size and Power Consumption	62
3.5	Size in Other Technologies	64
3.6	Tiny Computers Enable an Explosion of Applications	65
3.7	Summary	67
3.8	Digging Deeper	68
3.9	Problems	70
Sequ	uential Abstraction, But Parallel Implementation	76
4.1	Sequential Computation Abstraction	
	4.1.1 Sequential Programs	76
	4.1.2 Instruction-Level Parallelism: Pipelining and More	79
	4.1.3 Data Dependence and the Illusion of Sequence	80
4.2	The Illusion of Sequence: Renaming and Out-of-Order Execution	
	4.2.1 Variable and Register Renaming	85
	4.2.2 Implementing Register Renaming: The Reorder Buffer	88
	4.2.3 Limits of Out-of-Order Execution	89
4.3	Illusion of Causality: Speculative Execution	90
	4.3.1 Branch Prediction	91
	4.3.2 Speculative Execution	93
	4.3.3 Accurate Branch Predictors	97
	4.3.4 Security Risks of Speculation: Spectre and Meltdown	99
4.4	Summary	101
4.5	Digging Deeper	102
4.6	Problems	102
Men	nories: Exploiting Dynamic Locality	113
5.1	Memory Technologies, Miniaturization, and Growing Canacity	113
5.2	Software and Applications Demand Memory Capacity	118
		110

3

4

5

5.3	Memory System Challenges: The Memory Wall			
5.4	Memory Latency			
	5.4.1 Warping Space–Time (Caches)	123		
	5.4.2 Dynamic Locality in Programs	126		
	5.4.3 Address Filters (Caches)	128		
	5.4.4 The Effectiveness of Filters (Caches)	131		
	5.4.5 Implementing Caches (Warping and Filtering)	132		
	5.4.6 Recursive Filtering (Multi-level Caches)	133		
	5.4.7 Modeling Average Memory Hierarchy Performance	135		
5.5	Why Caches Work so Well and Programming for Locality	137		
5.6	Measuring Application Dynamic Locality and Modeling Performance	142		
	5.6.1 Measuring Dynamic Locality: Reuse Distance	142		
	5.6.2 Reuse Distance and Dynamic Locality	143		
	5.6.3 Modeling an Application's Memory Performance			
	Using Reuse Distance	145		
	5.6.4 Tuning a Program for Dynamic Locality	146		
5.7	Access Rate and Parallel Memory Systems	148		
5.8	Summary	150		
5.9	Digging Deeper	151		
5.10	Problems	152		
The	General Purpose Computer	161		
6.1	A Commercial Processor: Intel Skylake	161		
6.2	A Commercial Memory Hierarchy: Intel Skylake	164		
	6.2.1 Caches and Power	165		
6.3	CPUs Are General Purpose Computers	168		
6.4	Perspective: Mathematical Universality and Complexity	170		
6.5	Summary	171		
6.6	Digging Deeper	172		
6.7	Problems	173		
Bevo	and Sequential: Parallelism in MultiCore and the Cloud	176		
7.1	The End of Dennard Scaling and the Shift to Parallelism	176		
7.2	Parallel Single-Chip Computers: Multicore CPUs	179		
	7.2.1 Example: AMD Ryzen Multicore Chip and System	181		
7.3	Programming Multicore Computers: OpenMP and otherads	182		
	7.3.1 OpenMP: Pragma-Based Parallelism	183		
	7.3.2 pthreads: Explicit Thread-Parallelism	184		
	7.3.3 Challenging Parallelism in a Single Multicore CPU	185		
	7.3.4 Simpler Use of Multicore: Libraries and Servers	186		
7.4	Million-Way Parallelism: Supercomputers and the Cloud	187		
7.5	Efficient Parallelism: Computation Grain Size	189		
7.6	Programming Cloud Computers: Coarse-Grained Parallelism	192		
	7.6.1 Three-Tier Web: Scalable Web Services	192		

7

		7.6.2 Scale-Out Map–Reduce (Hadoop and Spark)	193
		7.6.3 Microservices: Modular Reliability and Evolution	194
		7.6.4 Serverless (Function-as-a-Service)	195
	7.7	Summary	196
	7.8	Digging Deeper	198
	7.9	Problems	198
8	Acce	elerators: Customized Architectures for Performance	205
	8.1	The Emergence of Accelerators	205
		8.1.1 Accelerator Hardware Opportunities	206
		8.1.2 Programming and Software Challenges	206
	8.2	Parallelism Accelerators	208
		8.2.1 The Architecture of GPUs	208
		8.2.2 Diverse GPUs and Performance	210
	8.3	Machine Learning Accelerators	212
		8.3.1 Google's Tensor Processing Unit	213
		8.3.2 Cerebras CS-2: A Wafer-Scale Machine Learning Accelerator	215
		8.3.3 Small Machine Learning Accelerators (Edge)	216
	8.4	Other Opportunities for Acceleration	217
	8.5	Limitations and Drawbacks of Accelerated Computing	217
	8.6	Summary	219
	8.7	Digging Deeper	219
	8.8	Problems	220
9	Com	puting Performance: Past, Present, and Future	226
	9.1	Historical Computer Performance	226
	9.2	Future Computer Performance: Opportunities for Performance Increase	228
		9.2.1 Hardware Scaling and Opportunities	228
		9.2.2 Resulting Programming and Software Challenges	230
	9.3	New Computing Models	231
		9.3.1 Higher-Level Architecture	232
		9.3.2 Quantum Computing	233
		9.3.3 Neuromorphic Computing	233
	9.4	Summary	234
	9.5	Digging Deeper	235
	9.6	Problems	235
Appendix	RISC	-V Instruction Set Reference Card	239
	Refe	rences	241
	Inde	x	247