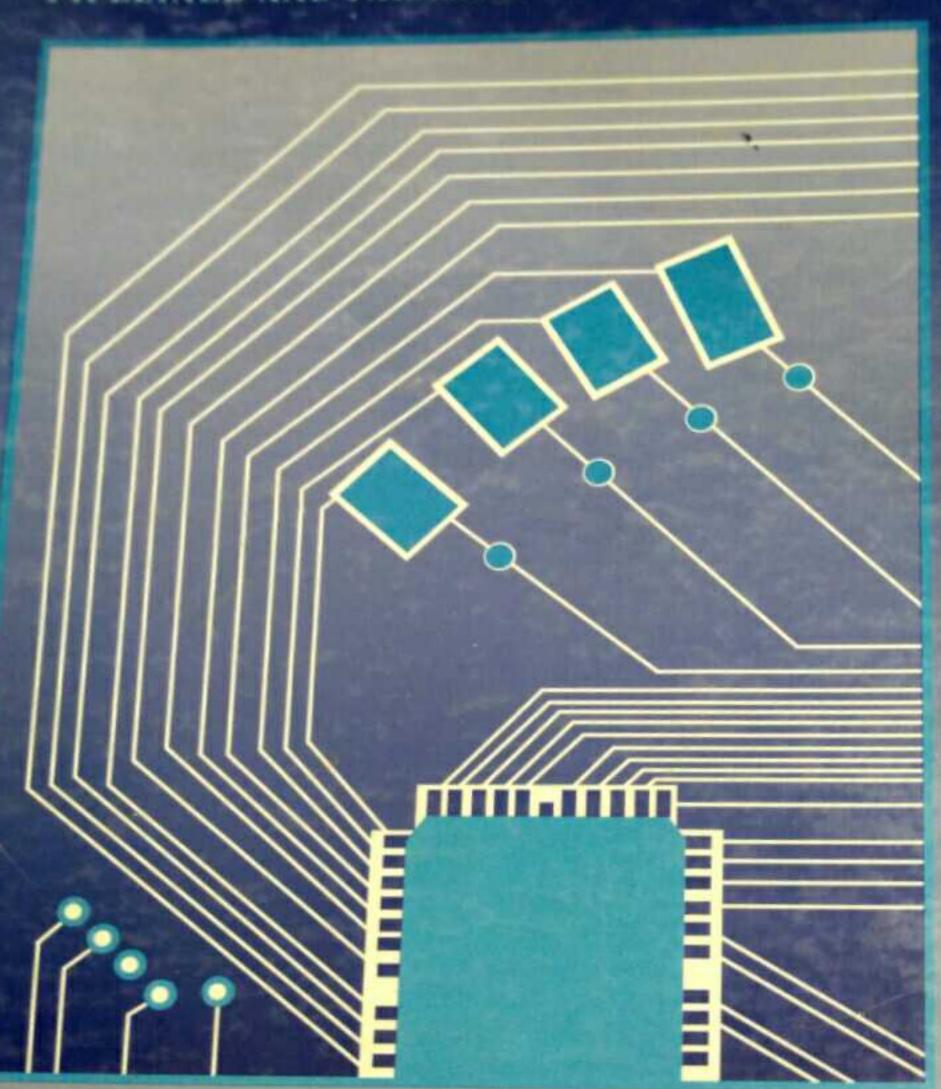
Michael J. Flynn Computer Architecture

PIPELINED AND PARALLEL PROCESSOR DESIGN



Contents

	xv
Preface	
Acknowledgments	xvii
1 Architecture and Machines	1
1.1 Some Definitions and Terms	3
1.2 Interpretation and Microprogramming	
1.3 The Instruction Set	
1.4 Basic Data Types	13
1.5 Instructions	21
1.5.1 Classes of Operations	
1.5.2 Instruction Mnemonics	
1.5.3 General Machine Conventions	
1.5.4 Branches	
1.5.5 Register Sets and Addressing Modes	32
1.5.6 Instruction Code Examples	
1.5.7 Other Instruction Set Issues	35
1.5.8 Program Size	37
1.6 Addressing and Memory	39
1.6.1 Process Addressing	
1.6.2 System Addresses and Segmentation	41
1.6.3 Memory Space	43
1.7 Virtual to Real Mapping	45
1.8 Basic Instruction Timing	47
1.8.1 Examples of Well-mapped Machine Instructi	ion Timing 49
1.8.2 Overlapped and Pipelined Processors	
.10 Historical Development of Computers	
.11 Annotated Bibliography	50
.12 Problem Set	5

	Onto.
Time, Area, and Instruction Sets	ments
area, and Inst	
2 Time, Area, and Instruction Sets 2 Time, Area, and Instruction 2.1 Introduction	. 63
2.1 International concept	
2.1 Time 2.2 Time 2.2 The Nature of a Cycle 2.2.1 Partitioning Instruction Execution into Cycle 2.2.1 Partitioning Into Cycle 2.2.1 Partitioning Instruction Into Cycle 2.2.1 Partitioning Instruction Into Cycle 2.2.1 Partitioning Into Cycle 2.2.1 Partitioning Instruction Into Cycle 2.2.1 Partitioning I	es 64
partitioning	
2.2.1 Partitioning Instruction 2.2.2 Partitioning Instruction 2.2.2 Clocking Overhead and Reliable Clocking	
2.2.2 Clocking Overhead to 2.2.3 Clocking Overhead to 2.2.4 Pipelined Processors	
2.2.4 Pipelined Processor 2.2.4 Optimum Pipelining	
2.2.6 Cycle Quantization 2.2.6 Wave Pipelining	77
2.3 Cost-Area	83
2 3.1	
2.3.2 Data Storage	93
Technology State of the Processor Project: A Study	99
2.4 Technology State of the Processor Project: A Study	103
2.5 The Economics of th	106
phase 2: Early Marie	10-
a All Good Hinigs Indeed	177.
Sets: Processor Lymna	10-
neagram Execution	110
- meetion Set Comparisons	110
temt Effects	112
2.6.3 Invariant Literature Stacks and Date	117
2.6.4 Code Density Evaluation Stacks, and Data	a Buffere
2.6.4 Code Delisters, Evaluation Stacks, and Data 2.6.5 Role of Registers, Evaluation Stacks, and Data	124
2.6.5 Role of Conclusions	132
Areas for Further Research	133
m Notes	1 134
2 10 Annotated Bibliography	* * * * * 134
2.11 Problem Set	136

Data: How Programs Behave 3.1 Introduction	141
3.1 Introduction	141
3.2 Instruction Usage	142
3.2.1 Data Categories	
3.2.2 Format Distribution	
3.2.3 Operation Set Distribution	
3.3 Process Management	150
3.3.1 Procedure Calls: User State	150
3.3.2 Calls to the System	153

	VII
Contents	

-		
3.	4 Break	ks in Machine Execution
	3.4.1	Instruction Run Length
	3.4.2	Branches
	3.4.3	Branch Target Distribution
	3.4.4	Condition Code Testing
	3.4.5	Move and Arithmetic Class Operations
	3.4.6	Register-Based Addressing
	3.4.7	Decimal and Character Operand Length
3.5	Conc	lusions
3.6	Some	Areas for Further Research
3.7	Data	Notes
3.8	Anno	otated Bibliography
3.9	Probl	lem Set
4 Pip	elined	Processor Design 181
4.1	Intro	duction
	4.1.1	Evolution of a Computer Processor Family
	4.1.2	Processor Design
	4.1.3	Organization of the Chapter
4.2	Appr	oaching Pipelined Processors
	4.2.1	Examples of Pipeline Implementations
4.3	Evalu	ating Pipelined Processor Performance
4.4	Desig	m of a Pipelined Processor
	4.4.1	Cache Access Controller
	4.4.2	Accounting for the Effect of Buffers in a Pipelined Sys-
		tem
	4.4.3	Buffer Design
	4.4.4	Designing a Buffer for a Mean Request Rate 216
	4.4.5	I-Buffers Designed for Maximum Request Rates 219
4.5	Branc	hes
310	4.5.1	Branch Elimination
	4.5.2	Branch Speedup
	4.5.3	Branch Prediction Strategies
	4.5.4	Branch Target Capture: Branch Target Buffers 236
40	Interl	ocks
4.6		Decoder and Interlocks
	4.6.1	Bypassing
	4.6.2	Address Generation Interlocks
	4.6.3	Address Generation interiocks
	4.6.4	Execution Interlocks and Interlock Tables
4.7	Run-O	on Delay

viii	Come
4.8 Miscellaneous Effects 4.8.1 Store in Instruction Stream Delay 4.8.1 Store in Instruction Stream Delay	
4.8.1 Store in Instruction 3.5.	
4.8.1 Store in History 4.9 Conclusions Comme Areas for Further Research	3
4.9 Conclusions 4.10 Some Areas for Further Research 4.10 Parta Notes	5
4.10 Some Areas for Full dies 4.11 Data Notes	5
4.11 Data Notes 4.12 Annotated Bibliography 4.12 Problem Set	5
4.12 Annotated Bibliography 4.13 Problem Set	9
The state of the s	
5 Cache Memory 5.1 Introduction	2
5.1 Introduction	2
5.2 Basic resignation	>
5.3 Cacine ora	34
5.4 Cacife Data for Cache Organization	25
5.5 Adjusting	25
5.6 Write Fond in Replacement at Miss Time	28
5.6 Write Policies 5.7 Strategies for Line Replacement at Miss Time 5.7 Leaching a Line	28
5.7.2 Line Replacement	- 28
5.9 Other Types of Caches	29
5.10 Spat P and D Caches	29
5.10.1 Palid D 5.10.2 Code Density Effects	29
5.11 On-Chip Caches	299
5.12 Two-Level Caches	- 303
5.12.1 Logical Inclusion	308
5.13 Write Assembly Cache	309
5.14 Cache References per Instruction	311
5.14.1 Instruction Traffic	- 311
5.14.2 Data Traffic	314
5.15 Technology-Dependent Cache Considerations	. 317
5.16 Virtual-to-Real Translation	. 322
5.16.1 Translation Lookaside Buffer (TLB)	. 323
5.17 Overlapping the T cycle in $V \rightarrow R$ Translation	. 325
	. 326
5.17.2 Virtual Caches	. 327
5.17.3 Real Caches Using Colored Pages	. 328
5.18 Studies	- 329
5.18.1 Actual Reference Traffic	. 331

Tim		Contract to the contract of th
	5.19.1	The state of the s
5.2		Cache/TLB Excess CPI Design Rules
5.2		e Areas for Further Research
5.2	2 Data	Notes
5.2		ography
5.2	4 Prot	olem Set
6 Me		ystem Design 345
6.1	Intro	fuction
6.2	The P	hysical Memory
	6.2.1	The Memory Module
	6.2.2	Error Detection and Correction
	6.2.3	Partitioning of the Address Space
	6.2.4	ls of Simple Processor-Memory Interaction
6.3		Memory Systems Design
	6.3.1	Multiple Simple Processors
	6.3.3	Hollerman's Model
	6.3.4	Strocker's Model
		Deute Model
	0.3.3	Modeling Using Queueing Theory
6.4		a Common Models of Processor Memory Interaction
	6.4.1	1 Patential
	6.4.2	- Distribution
	6.4.3	
	6.4.4	Queue Properties
	6.4.5	Queue Properties
6.5	Open	-, Closed-, and Mixed-Queue Models
	6.5.1	Owen Charles (Flores) Mellioly Model
	6.5.2	
	6.5.3	- c and siller size
6.6	Waiti	
	6.6.1	Pipelined Processors
	6.6.2	
	6.6.3	
6.7	Revie	w and see
6.8	e Processors with Cache	
		Fully and Partially Blocking Caches
	6.8.1	t reging a Line (Time access)
	6.8.2	Accessing a Line ($T_{\text{line access}}$)
	6.8.3	Contention Time (Ibusy) and Corr
	0.0.5	

	Conten
8 6.8.4 1/O Effects	10
6.8.4 1/O Effects	. 40
and Pelifornia La Chiefy and an analysis and a	E
The Color of the C	A-
c 9.7 Simple	de.
egs Wille	41
6.8.9 Shared Bus	. 41
6.8.10 Nonblocking Caches 6.8.11 Interleaved Caches	41
6.8.11 Interleaved Conclusions	41
6.9 Conclusions	41
6.10 Some Areas for Further 6.11 Data Notes	41
6.11 Data Notes	41
6.12 Annotated Bibliography 6.13 Problem Set	45
	72
Concurrent Processors	42
7.1 Introduction	42
7.1 Introduction	42
7.2.2 Vector Instruction 7.2.3 Vector Processor Implementation 7.2.3 Vector Processor Implementation 7.2.3 Vector Processor 7.2.3 Vector 9.2.3 Vector 9.	43
m to A A COMPLETE VILLIAM I LOCALISM	
an Master Mamory	
7.3.1 The Special Case of Vector Memory	. 43
7.3.1 The Special Care 7.3.2 Modeling Vector Memory Performance	44
7 2 2 Lamma (V)-Difformati Product	
7 2 A Runassing Delween rector manucions	
A Vactor Processor Speedup	
7.4.1 Basic issues	40.
7.4.Z Measures	40.
5 Multiple-Issue Machines	400
6 Out-of-Order and Multiple-Instruction Execution	
7.6.1 Data Dependencies	400
7.6.2 Representing Data Dependencies	4.00
7.6.3 Other Types of Dependencies	
7.6.4 When and How to Detect Instruction Concurrence.	11 0000
7.6.5 Two Scheduling Implementations	
7.6.6 An Improved Scoreboard	467
7.6.7 Dealing with Out-of-Order Execution	- 475
7.6.7 Dealing with Out-of-Order Execution	486
- Cacines	490
7.6.9 Branches and Speculative Execution	492

Contents

		7.6.10 Adaptive Speculation
		7.6.11 Results
	7.7	Comparing Vector and Multiple-Issue Processors 499
		7.7.1 Cost Comparison
		7.7.2 Performance Comparison
		7.7.3 Alternative Organizations
	7.8	Conclusions
	7.10	Some Areas for Further Research
	7.11	
		The state of the s
	****	Problem Set
8	Shar	red Memory Multiprocessors 511
	8.1	Basic Issues
	8.2	Partitioning
	8.3	Scheduling
		8.3.1 Run-Time Scheduling Techniques 520
	8.4	Synchronization and Coherency
	8.5	The Effects of Partitioning and Scheduling Overhead 526
		8.5.1 Grain Size and Overhead
	8.6	Types of Shared Memory Multiprocessors
	8.7	Multithreaded or Shared Resource Multiprocessing 533
	8.8	Memory Coherence in Shared Memory Multiprocessors 538
	8.9	Shared-Bus Multiprocessors
		8.9.1 Snoopy Protocols
		8.9.2 Bus-Based Models
	8.10	
	8.11	AND A SECOND SEC
		8.11.1 Directory Structure
		8.11.2 Invalidate Protocols
		8.11.3 Update Protocols
	8.12	
	8.13	
	8.14	Static Networks
		8.14.1 Links and Nodes
	8.15	Dynamic Networks
	8.16	
		8.16.1 Direct Static vs. Indirect Dynamic 578
		8.16.2 Network Dimensionality and Link-Limited Network . 583
	8.17	

onte
wans of Multiprocessors
xii characterizations of
8.18 Other Characterizations of Multiprocessors
8.19 Concession for Further
8.20 Some Areas 8.21 Annotated Bibliography 8.21 Problem Set
8.21 Annotation Set
8.22 Problem Set 8.22 Problem Set 9
9 1/0 and the Storage Hierarchy 9 1/0 and the Role of I/O
9 1/O and the Storage Hierarchy 9 1/O and the Storage Hierarchy 9.1 The Role of I/O
- regulations // hannels
and I be a set for Muniper
0.2.2 I/O System
9.2.2 I/O System Support 103 9.2.2 I/O System Support 103 9.3 Design of Storage Systems 60 9.3 Disk Technology 60
03.1 DISK 100
9.3.1 Disk Technology 9.3.2 The Disk Device
9.3.2 The Disk Device
9.4 Simple I/O Transactions 9.4 Simple I/O Transactions 9.4.1 Multiple Servers
cingle Server Low Population 61:
Jaling
models and mire servers
1/O Response and Capacity
on and Virtual Memory Effects
n-sic 1/O Request Rate
1 Mamory I/O Traffic
- 1 Cache Buffers
9.5.3 Disk Cache Burrers
9.5.4 Concurrent Disks
9.5.4 Clusters of Independent Disks
9.5.6 Striping
9.5.7 Disk Arrays
9 5 8 Composite Configurations
9.6 Some Practical Considerations
I James in Diele Arrays
9.8 Conclusions
9.9 Some Areas for Further Research
9.10 Data Notes
9.11 Annotated Bibliography
0.12 Problem Cet
5.12 Problem Set
10 Processor Studies 663
10.1 The Baseline Mark II
10.1.1 Design Assumptions

Contents		xiii
10.1.2	Design Alternations	
10.1.3	- angle Attenditives	. 665
10.1.4	Pipeline Timing Analysis Pipeline Penalty Analysis	665
10.1.5	Pipeline Penalty Analysis	671
10.1.6	Cache and Memory Analysis Cost-Performance Analysis	676
10.2 Area	Performance Analysis of Processors	677
10.2.1	The Problem	683
10.2.2	Specifications	083
10.2.3	Assumptions	685
10.2.4	The Design	000
10.2.5	Analysis	704
10.3 Stud	ly Results	704
10.4 Con	clusions	717
	DTMR Cache Miss Rates	719
	DTMR	719
A.2 Assoc	ciativity Adjustments	710
A.3 User	+ System	719
A.4 Trans	saction-Based Systems	721
A.5 Multi	programmed (Warm Cache) Environment	722
	SPECmark vs. DTMR Cache Performance	
		741
Appendix C	Modeling System Effects in Caches	6.47.3
C.1 Cold	Start Cache	743
C.2 Cache	e Misses in Multiprogramming Environment	744
Appendix D	New DRAM Technologies	747
D.1 Typic	al Performance Enhancements	747
D.2 Enhan	nced DRAM	749
D.3 Synch	ronous DRAM	740
D.4 Cache	e DRAM	/48
D.5 Ramb	USE FIR AM	748
D.S. Ramio	ous DRAM	748
D.6 Ramli	ink DRAM	749
D.7 Chip	Level Summary	749
Appendix E	M/G/1 Queues	751
Appendix F	Some Details on Bus-Based Protocols	755
Bibliography		765
ndex		783