Contents

2.1.2 Data Sizes 39

	ι
Prefa	nce xix
Abou	at the Authors xxxv
1	,
1	r
A To	our of Computer Systems 1 ", ",
1.1	Information Is Bits + Context 3
1.2	Programs Are Translated by Other Programs into Different Forms 4
1.3	It Pays to Understand How Compilation Systems Work 6
1.4	Processors Read and Interpret Instructions Stored in Memory 7
	1.4.1 Hardware Organization of a System 8
	1.4.2 Running the hello Program 10
1.5	Caches Matter 11
1.6	Storage Devices Form a Hierarchy, 14
1.7	The Operating System Manages the Hardware 14
	1.7.1 Processes 15
	1.7.2 Threads 17
	1.7.3 Virtual Memory 18
_	1.7.4 Files 19
1.8	Systems Communicate with Other Systems Using Networks 19,
1.9	Important Themes 22
	1.9.1 Amdahl's Law 22, 30
	1.9.2 Concurrency and Parallelism 24
4 40	1.9.3 The Importance of Abstractions in Computer Systems 26
1.10	Summary 27
	Bibliographic Notes 28
	Solutions to Practice Problems 28
Part	Program Structure and Execution
2	
2_	
Rep	resenting and Manipulating Information 31
2.1	Information Storage 34
	2.1.1 Hexadecimal Notation 36

	2.1.3	Addressing and Byte Ordering 42
	2.1.4	Representing Strings 49
	2.1.5	Representing Code 49
	2.1.6	Introduction to Boolean Algebra 50
	2.1.7	Bit-Level Operations in C 54
	2.1.8	Logical Operations in C 56
	2.1.9	Shift Operations in C 57
2.2		r Representations 59
	2.2.1	Integral Data Types 60
	2.2.2	Unsigned Encodings 62
	2.2.3	Two's-Complement Encodings, 64
	2.2.4	Conversions between Signed and Unsigned 70
	2.2.5	Signed versus Unsigned in C 74
•	2.2.6	
	2.2.7	Truncating Numbers 81
	2.2.8	Advice on Signed versus Unsigned 83
2.3		er Arithmetic 84
	2.3.1	Unsigned Addition 84
	2.3.2	Two's-Complement Addition 90 Two's-Complement Negation 95
	2.3.3	1MO 2-Combiemone 1.08====
	2.3.4	Unsigned Multiplication 96 Two's Complement Multiplication 97
	2.3.5	IMO 2-Combient marchineases
	2.3.6	141dtdp13td 5) 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5
	2.3.7	Dividing of 2 of the Anishmentin 107
	2.3.8	
2.4		100
	2.4.1	112
	2.4.2 2.4.3	
		Rounding 120
	2.7.7	Floating-Point Operations 122
	2.4.6	
2.5		imary 126
210		iographic Notes 127
		nework Problems 128
		ations to Practice Problems 143

	· ·
3.2	Program Encodings 169
	3.2.1 Machine-Level Code 170
	3.2.2 Code Examples 172
	3.2.3 Notes on Formatting 175
3.3	Data Formats 177-
3.4	Accessing Information 179
	3.4.1 Operand Specifiers 180
	3.4.2 Data Movement Instructions 182
	3.4.3 Data Moyement Example '186
	3.4.4 Pushing and Popping Stack Data 189
3.5	Arithmetic and Logical Operations 191
	3.5.1 Load Effective Address 191
	3.5.2 Unary and Binary Operations, 194
	3.5.3 Shift Operations 104
	354 Discussion 106
	3.5.5 Special Arithmetic Operations 197
3.6	Control 200'
J.U	2.6.1 Co. div. C. 1 004
	260
	3.6.2 Tump Instructions 206
	3.6.4 Jump Instruction Encodings 207
	3.6.5 Implementing Conditional Branches with
	Conditional Control 209
	3.6.6 Implementing Conditional Branches with
	Conditional Moves 214
	3.6.7 Loops 220
-	3.6.8 Switch Statements 232
3.7	Procedures 238
	3.7.1 The Run-Time Stack 239
	3.7.2 Control Transfer 241
	3.7.3 Data Transfer 245
	3.7.4 Local Storage on the Stack 248
	3.7.5 Local Storage in Registers 251
	3.7.6 Recursive Procedures 253
3.8	Array Allocation and Access 255
	3.8.1 Basic Principles 255
	3.8.2 Pointer Arithmetic 257
	3.8.3 Nested Arrays 258
	3.8.4 Fixed-Size Arrays 260,
	3.8.5 Variable-Size Arrays 262

3.9	Heterogeneous Data Structures 265	
012	3.9.1 Structures 265	
	3.9.2 Unions 269	
	3 0.3 Data Alignment 273	
3.10	Combining Control and Data in Machine-Level Programs 270	
2125	2.10.1 Understanding Pointers 277	
	2.10.2 Life in the Real World: Using the GDB Debugger 2/9	
	3 10 3 Out-of-Bounds Memory References and Builer Overnow 277	
	3 10 4 Thwarting Buffer Overflow Attacks 284	
	3.10.5 Supporting Variable-Size Stack Frames 290	
3.11	Floating-Point Code 293	
	3.11.1 Floating-Point Movement and Conversion Operations 290	
	3 11 2 Floating-Point Code in Procedures 301	
	3.11.3 Floating-Point Arithmetic Operations 302	
	2 11 4 Defining and Using Floating-Point Constants 304	
	3 11 5 Using Bitwise Operations in Floating-Point Gode 303	
	3.11.6 Floating-Point Comparison Operations 306	
	3.11.7 Observations about Floating-Point Code 309	
3.12		
•	Bibliographic Notes 310	
	Homework Problems 311	
	Solutions to Practice Problems 325	
4		
<u> </u>		
Pro	ocessor Architecture 351	
4.1	The Y86-64 Instruction Set Architecture 355	
4.1	4.1.1 Programmer-Visible State 355	
	4.1.2 Y86-64 Instructions 356	
	4.1.3 Instruction Encoding 358	
	4.1.4 Y86-64 Exceptions 363	
	4 1.5 Y86-64 Programs 364	
	4.1.6 Some Y86-64 Instruction Details 370	
4.2	Logic Design and the Hardware Control Language HCL 372	
••-	421 Logic Gates 373	
	422 Combinational Circuits and HCL Boolean Expressions 3/4	
	4.2.3 Word-Level Combinational Circuits and HCL	
	Integer Expressions 376	
	4.2.4 Set Membership 380	
	4.2.5 Memory and Clocking 381	
4.3	Sequential Y86-64 Implementations 384	
-	4.3.1 Organizing Processing into Stages 384	

	4.3.2 SEQ Hardware Structure 396q A in Santa Santa Control of the Santa
	4.3.3 SEQ Timing 400
	4.3.4 SEQ Stage Implementations 404 years
4.4	General Principles of Pipelining 412 1 11
	4.4.1 Computational Pipelines 412 yr W
	4.4.2 A Detailed Look at Pipeline Operation, 414
	4.4.3 Limitations of Pipelining 416
	4.4.4 Pipelihing: System with Feedback 419
4.5	Pipelined Y86-64 Implementations '421 11 111
	4.5.1 SEQ+: Rearranging the Computation Stages # 421
	4.5.2 Inserting Pipeline Registers 422
	4.5.3 Rearranging and Relabeling Signals 426
	4.5.4 Next PC Prediction 427
	4.5.5 Pipeline Hazards 429
	4.5.6 Exception Handling 444
	4.5.7 PIPE Stage Implementations 447
	4.5.8 Pipeline Control Logic 455
	4.5.9 - Performance Analysis -464.
	4.5.10 Unfinished Business 468
4.6	Summary 470
4.0	4.6.1 Y86-64 Simulators 472
	Bibliographic Notes 473
	Homework Problems 473
	Solutions to Practice Problems 480
	Solutions to Fractice Problems 400
_	
5	T, D
Ont	imizing Program Performance 495
Opt	imizing Program Periormance 493
5.1	Capabilities and Limitations of Optimizing Compilers 498
5.2	Expressing Program Performance 502
5.3	Program Example 504
5.4	Eliminating Loop Inefficiencies 508
5.5	Reducing Procedure Calls 5126
5.6	Eliminating Unneeded Memory References 3514
5.7	Understanding Modern Processors 517,
	5.7.1 Overall Operation 518
	5.7.2 Functional Unit Performance 523
	5.7.3 An Abstract Model of Processor Operation 525
5.8	Lasa I Lasa Ilias - Fold
5.9	Enhancing Parallelism 536
J.J	5.9.1 Multiple Accumulators 536
	5.9.1 Multiple Accumulators 550 5.9.2 Reassociation Transformation 541
	J.7.2 ACASSOCIATION MAISTONNIAUON J41

5.10	Summary of Results for Optimizing Combining Code 347
5.11	Some Limiting Factors 548
	5.11.1 Register Spilling 548
	5.11.2 Branch Prediction and Misprediction Penalties 549
5.12	Understanding Memory Performance 553
	5.12.1 Load Performance 554ti 1
	5.12.2 Store Performance 555
5.13	Life in the Real World: Performance Improvement Techniques - 561
5.14	Identifying and Eliminating Performance Bottlenecks 562
	5.14.1 Program Profiling 562
	5.14.2 Using a Profiler to Guide Optimization 565
5.15	Summary 568
	Bibliographic Notes 569
	Homework Problems 570
	Solutions to Practice Problems 573
6	
The	Memory Hierarchy 579
6.1	Storage Technologies 581
	6.1.1 Random Access Memory 581
	6.1.2 Disk Storage 589
	6.1.3 Solid State Disks 600
	6.1.4 Storage Technology Trends 602
6.2	Locality 604
	6.2.1 Locality of References to Program Data 606
	6.2.2 Locality of Instruction Fetches, 607
	6.2.3 Summary of Locality 608
6.3	The Memory Hierarchy 609
	6.3.1 Caching in the Memory Hierarchy 610
	6.3.2 Summary of Memory Hierarchy Concepts 614
6.4	Cache Memories 614
	6.4.1 Generic Cache Memory Organization 615
	6.4.2 Direct-Mapped Caches 617
	6.4.3 Set Associative Caches 624 1
	6.4.4 Fully Associative Caches 626
	6.4.5 Issues with Writes 630
	6.4.6 Anatomy of a Real Cache Hierarchy 631
	6.4.7 Performance Impact of Cache Parameters 631
6.5	Writing Cache-Friendly Code 633
6.6	Putting It Together: The Impact of Caches on Program Performance 639

6.7	6.6.2 Rearranging Loops to Increase Spatial Locality 643 6.6.3 Exploiting Locality in Your Programs '647 Summary 648 Bibliographic Notes 648 Homework Problems 649 Solutions to Practice Problems 660		
Part	t II Running Programs on a System		
7_			
Link	king 669		
7.1	Compiler Drivers 671		
7.2	Static Linking 672		
7.3	Object Files 673		
7.4			
7.5	Symbols and Symbol Tables 675		
7.6	Symbol Resolution 679		
	7.6.1 How Linkers Resolve Duplicate Symbol Names 680		
	7.6.2 Linking with Static Libraries 6847.6.3 How Linkers Use Static Libraries to Resolve References 688		
7.7	7.6.3 How Linkers Use Static Libraries to Resolve References 688 Relocation 689		
, . <i>,</i>	7.7.1 Relocation Entries 690		
	7.7.2 Relocating Symbol References 691		
7.8 ∂.	Executable Object Files 695		
7.9	Loading Executable Object Files 697		
7.10	Dynamic Linking with Shared Libraries 698		
7.11	Loading and Linking Shared Libraries from Application's 701		
7.12	Position-Independent Code (PIC) 704		
7.13	Library Interpositioning 707		
	7.13.1 Compile-Time Interpositioning 708		
	7.13.2 Link-Time Interpositioning 708		
= 4 -	7.13.3 Run-Time Interpositioning 710		
7.14	Tools for Manipulating Object Files 713		
7.15	Summary 713		
	Bibliographic Notes 714		
	Homework Problems 714		
	Solutions to Practice Problems 717		

Exceptional Control Flow 721 Exceptions 723 8.1 Exception Handling 724 8.1.1 Classes of Exceptions 726 8.1.2 Exceptions in Linux/x86-64 Systems 729 8.1.3 Processes 732 8.2 Logical Control Flow 8.2.1 Concurrent Flows 733 8.2.2 Private Address Space 734 8.2.3 User and Kernel Modes 734 8.2.4 Context Switches 736 8.2.5 System Call Error Handling 737 8.3 11. Process Control 738 8.4 Obtaining Process IDs 739 8.4.1 Creating and Terminating Processes 8.4.2 Reaping Child Processes 743 8.4.3 Putting Processes to Sleep 749 8.4.4 Loading and Running Programs 750 8.4.5 Using fork and execve to Run Programs 753 8.4.6 Signals 756 8.5 Signal Terminology 758 8.5.1 8.5.2 Sending Signals 759 Receiving Signals 762 8.5.3 8.5.4 Blocking and Unblocking Signals 764 Writing Signal Handlers 766 8.5.5 Synchronizing Flows to Avoid Nasty Concurrency Bugs 776 8.5.6 Explicitly Waiting for Signals 778 8.5.7 Nonlocal Jumps 781 8.6 Tools for Manipulating Processes. 786 8.7 Summary 787 8.8 Bibliographic Notes 787 Homework Problems 788 Solutions to Practice Problems 795

9

Virtual Memory 801

- 9.1 Physical and Virtual Addressing 803
- 9.2 Address Spaces 804

9.3	VM as	a Tool for Caching 805		
	9.3.1	DRAM Cache Organization 806		
	9.3.2	Page Tables 806		
	9.3.3	Page Hits, 808		
	9.3.4	Page Faults 808,		
	9.3.5	Allocating Pages 810		
	9.3.6	Locality to the Rescue Again 810		
9.4		a Tool for Memory Management 811		
9.5	VM as	a Tool for Memory Protection ,812		
9.6	Addre	ss Translation 813 ,		
	9.6.1	Integrating Caches and VM 817		
	9.6.2	Speeding Up Address Translation with a TLB 817		
	9.6.3	Multi-Level Page Tables 819		
	9.6.4	Putting It Together: End-to-End Address Translation &	<u>3</u> 21	
9.7	Case S	Study: The Intel Core i7/Linux Memory System 825		
	9.7.1	Core i7 Address Translation 826		
	9.7.2	Linux Virtual Memory System 828		
9.8	Memo	ry Mapping 833		
	9.8.1	Shared Objects Revisited 833		
	9.8.2	The fork Function Revisited 836		
	9.8.3	The execve Function Revisited 836		
	9.8.4	User-Level Memory Mapping with the mmap Function	837	
9.9	Dynan	nic Memory Allocation 839		. 1
	9.9.1	The malloc and free Functions 840		
	9.9.2	Why Dynamic Memory Allocation? 843	1	
		Allocator Requirements and Goals 844		
	9.9.4	Fragmentation 846		
	9.9.5	Implementation Issues 846		13
	9.9.6	Implicit Free Lists 847		Ļi
	9.9.7	Placing Allocated Blocks 849	į	
	9.9.8	Splitting Free Blocks 849:		
	9.9.9	Getting Additional Heap Memory \$50	1)	
	9.9.10	Coalescing Free Blocks 850		
	9.9.11	Coalescing with Boundary Tags 851		
			854	
		Explicit Free Lists 862		
		Segregated Free Lists 863		
9.10		ge Collection 865°	ť	-
		Garbage Collector Basics 866		į
		Mark&Sweep Garbage Collectors 867 ' '		
	9.10.3	Conservative Mark & Sweep for C Programs 869	1	

9.11	Common Memory-Related Bugs in C Programs 870.
	9.11.1 Dereferencing Bad Pointers 870
	9.11.2 Reading Uninitialized Memory 871
	9.11.3 Allowing Stack Buffer Overflows 871
	9.11.4 Assuming That Pointers and the Objects They Point to
	Are the Same Size 872
	9.11.5 Making Off-by-One Errors 872
	9.11.6 Referencing a Pointer Instead of the Object It Points To 873
	9.11.7 Misunderstanding Pointer Arithmetic 873
	9.11.8 Referencing Nonexistent Variables 874
	9.11.9 Referencing Data in Free Heap Blocks 874
0.44	9.11.10 Introducing Memory Leaks 875
9.12	Summary 875
	Bibliographic Notes 876
	Homework Problems 876
	Solutions to Practice Problems 880
Danie	III. Intersetion and Communication
Рап	III Interaction and Communication
	,
	between Programs
	,
10	,
10	between Programs
V	,
V	between Programs
Syst	between Programs em-Level I/O 889
Syst 10.1 10.2	between Programs em-Level I/O 889 Unix I/O 890
Syst 10.1 10.2	between Programs em-Level I/O 889 Unix I/O 890 Files 891
Syst 10.1 10.2 10.3	between Programs em-Level I/O 889 Unix I/O 890 Files 891 Opening and Closing Files 893
Syst 10.1 10.2 10.3 10.4	between Programs em-Level I/O 889 Unix I/O 890 Files 891 Opening and Closing Files 893 Reading and Writing Files 895
Syst 10.1 10.2 10.3 10.4	between Programs em-Level I/O 889 Unix I/O 890 Files 891 Opening and Closing Files 893 Reading and Writing Files 895 Robust Reading and Writing with the Rio Package 897,
Syst 10.1 10.2 10.3 10.4	between Programs em-Level I/O 889 Unix I/O 890 Files 891 Opening and Closing Files 893 Reading and Writing Files 895 Robust Reading and Writing with the Rio Package 897, 10.5.1 Rio Unbuffered Input and Output Functions 897
Syst 10.1 10.2 10.3 10.4 10.5	between Programs em-Level I/O 889 Unix I/O 890 Files 891 Opening and Closing Files 893 Reading and Writing Files 895 Robust Reading and Writing with the Rio Package 897, 10.5.1 Rio Unbuffered Input and Output Functions 897 10.5.2 Rio Buffered Input Functions 898
Syst 10.1 10.2 10.3 10.4 10.5	between Programs em-Level I/O 889 Unix I/O 890 Files 891 Opening and Closing Files 893 Reading and Writing Files 895 Robust Reading and Writing with the Rio Package 897, 10.5.1 Rio Unbuffered Input and Output Functions 897 10.5.2 Rio Buffered Input Functions 898 Reading File Metadata 903 Reading Directory Contents 905
Syst 10.1 10.2 10.3 10.4 10.5	between Programs em-Level I/O 889 Unix I/O 890 Files 891 Opening and Closing Files 893 Reading and Writing Files 895 Robust Reading and Writing with the Rio Package 897, 10.5.1 Rio Unbuffered Input and Output Functions 897 10.5.2 Rio Buffered Input Functions 898 Reading File Metadata 903 Reading Directory Contents 905
Syst 10.1 10.2 10.3 10.4 10.5 10.6 10.7 10.8 10.9 10.10	between Programs em-Level I/O 889 Unix I/O 890 Files 891 Opening and Closing Files 893 Reading and Writing Files 895 Robust Reading and Writing with the Rio Package 897, 10.5.1 Rio Unbuffered Input and Output Functions 897 10.5.2 Rio Buffered Input Functions 898 Reading File Metadata 903 Reading Directory Contents 905 Sharing Files 906 I/O Redirection 909 Standard I/O 911
Syst 10.1 10.2 10.3 10.4 10.5 10.6 10.7 10.8 10.9 10.10 10.11	between Programs em-Level I/O 889 Unix I/O 890 Files 891 Opening and Closing Files 893 Reading and Writing Files 895 Robust Reading and Writing with the Rio Package 897, 10.5.1 Rio Unbuffered Input and Output Functions 897 10.5.2 Rio Buffered Input Functions 898 Reading File Metadata 903 Reading Directory Contents 905 Sharing Files 906 I/O Redirection 909 Standard I/O 911 Putting It Together: Which I/O Functions Should I Use? 911
Syst 10.1 10.2 10.3 10.4 10.5 10.6 10.7 10.8 10.9 10.10 10.11	between Programs em-Level I/O 889 Unix I/O 890 Files 891 Opening and Closing Files 893 Reading and Writing Files 895 Robust Reading and Writing with the Rio Package 897, 10.5.1 Rio Unbuffered Input and Output Functions 897 10.5.2 Rio Buffered Input Functions 898 Reading File Metadata 903 Reading Directory Contents 905 Sharing Files 906 I/O Redirection 909 Standard I/O 911

Homework Problems 914

Solutions to Practice Problems 915

Net	work Programming	917	
11.1	The Client-Server Program	ming Model	918
11.2	Networks 919		

11.3 The Global IP Internet 924

11.3.1 IP Addresses 925

11.3.2 Internet Domain Names 927

11.3.3 Internet Connections 929

11.4 The Sockets Interface 932

11.4.1 Socket Address Structures 933

11.4.2 The socket Function 934

11.4.3 The connect Function 934

11.4.4 The bind Function, 935

11.4.5 The listen Function 935

11.4.6 The accept Function 936

11.4.7 Host and Service Conversion 937

11.4.8 Helper Functions for the Sockets Interface 942

11.4.9 Example Echo Client and Server '944

11.5 Web Servers 948

11.5.1 Web Basics 948

11.5.2 Web Content 949

11.5.3 HTTP Transactions 950

11.5.4 Serving Dynamic Content 953

11.6 Putting It Together: The Tiny Web Server 956

11.7 Summary 964

Bibliographic Notes 965

Homework Problems 965

Solutions to Practice Problems 966

12

Concurrent Programming 971

- 12.1 Concurrent Programming with Processes 973
 - 12.1.1 A Concurrent Server Based on Processes 974
 - 12.1.2 Pros and Cons of Processes 975
- 12.2 Concurrent Programming with I/O Multiplexing 977
 - 12.2.1 A Concurrent Event-Driven Server Based on I/O Multiplexing 980
 - 12.2.2 Pros and Cons of I/O Multiplexing 985
- 12.3 Concurrent Programming with Threads 985
 - 12.3.1 Thread Execution Model 986

	12.3.2 Posix Threads 987
	12.3.3 Creating Threads 988
	12.3.4 Terminating Threads 988
	12.3.5 Reaping Terminated Threads 989
	12.3.6 Detaching Threads 989
	12.3.7 Initializing Threads 990
	12.3.8 A Concurrent Server Based on Threads 991
12.4	Shared Variables in Threaded Programs 992
	12.4.1 Threads Memory Model 993
	12.4.2 Mapping Variables to Memory 994
	12.4.3 Shared Variables 995
12.5	Synchronizing Threads with Semaphores 995
	12.5.1 Progress Graphs 999
	12.5.2 Semaphores 1001
	12.5.3 Using Semaphores for Mutual Exclusion 1002
	12.5.4 Using Semaphores to Schedule Shared Resources, 1004
	12.5.5 Putting It Together: A Concurrent Server Based on
	Prethreading 1008
	Using Threads for Parallelism 1013
12.7	•
	12.7.1 Thread Safety 1020
	12.7.2 Reentrancy 1023
	12.7.3 Using Existing Library Functions in Threaded Programs 1024
	12.7.4 Races 1025
	12.7.5 Deadlocks 1027
12.8	Summary 1030
	Bibliographic Notes 1030
	Homework Problems 1031
	Solutions to Practice Problems 1036
Α	

Error Handling 1041

A.1 Error Handling in Unix Systems 1042

A.2 Error-Handling Wrappers 1043

References 1047

Index 1053