

Computer Systems

A Programmer's Perspective

Randal E. Bryant

Carnegie Mellon University

David R. O'Hallaron

Carnegie Mellon University and Intel Labs

Prentice Hall

Boston Columbus Indianapolis New York San Francisco Upper Saddle River
Amsterdam Cape Town Dubai London Madrid Milan Munich Paris Montreal Toronto
Delhi Mexico City Sao Paulo Sydney Hong Kong Seoul Singapore Taipei Tokyo

Contents

Preface xix

About the Authors xxxiii

1

A Tour 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 7
 - 1.4.2 Running the `hello` Program 10
- 1.5** Caches Matter 12
- 1.6** Storage Devices Form a Hierarchy 13
- 1.7** The Operating System Manages the Hardware 14
 - 1.7.1 Processes 16
 - 1.7.2 Threads 17
 - 1.7.3 Virtual Memory 17
 - 1.7.4 Files 19
- 1.8** Systems Communicate with Other Systems Using Networks 20
- 1.9** Important Themes 21
 - 1.9.1 Concurrency and Parallelism 21
 - 1.9.2 The Importance of Abstractions in Computer Systems 24
- 1.10** Summary 25
- Bibliographic Notes 26

Part I Program Structure and Execution

2

Representing and Manipulating Information 29

- 2.1** Information Storage 33
 - 2.1.1 Hexadecimal Notation 34
 - 2.1.2 Words 38
 - 2.1.3 Data Sizes 38

2.1.4	Addressing and Byte Ordering	39
2.1.5	Representing Strings	46
2.1.6	Representing Code	47
2.1.7	Introduction to Boolean Algebra	48
2.1.8	Bit-Level Operations in C	51
2.1.9	Logical Operations in C	54
2.1.10	Shift Operations in C	54
2.2	Integer Representations	56
2.2.1	Integral Data Types	57
2.2.2	Unsigned Encodings	58
2.2.3	Two's-Complement Encodings	60
2.2.4	Conversions Between Signed and Unsigned	65
2.2.5	Signed vs. Unsigned in C	69
2.2.6	Expanding the Bit Representation of a Number	71
2.2.7	Truncating Numbers	75
2.2.8	Advice on Signed vs. Unsigned	76
2.3	Integer Arithmetic	79
2.3.1	Unsigned Addition	79
2.3.2	Two's-Complement Addition	83
2.3.3	Two's-Complement Negation	87
2.3.4	Unsigned Multiplication	88
2.3.5	Two's-Complement Multiplication	89
2.3.6	Multiplying by Constants	92
2.3.7	Dividing by Powers of Two	95
2.3.8	Final Thoughts on Integer Arithmetic	98
2.4	Floating Point	99
2.4.1	Fractional Binary Numbers	100
2.4.2	IEEE Floating-Point Representation	103
2.4.3	Example Numbers	105
2.4.4	Rounding	110
2.4.5	Floating-Point Operations	113
2.4.6	Floating Point in C	114
2.5	Summary	118
	Bibliographic Notes	119
	Homework Problems	119
	Solutions to Practice Problems	134

3

Machine-Level Representation of Programs 153

3.1	A Historical Perspective	156
3.2	Program Encodings	159

3.2.1	Machine-Level Code	160
3.2.2	Code Examples	162
3.2.3	Notes on Formatting	165
3.3	Data Formats	167
3.4	Accessing Information	168
3.4.1	Operand Specifiers	169
3.4.2	Data Movement Instructions	171
3.4.3	Data Movement Example	174
3.5	Arithmetic and Logical Operations	177
3.5.1	Load Effective Address	177
3.5.2	Unary and Binary Operations	178
3.5.3	Shift Operations	179
3.5.4	Discussion	180
3.5.5	Special Arithmetic Operations	182
3.6	Control	185
3.6.1	Condition Codes	185
3.6.2	Accessing the Condition Codes	187
3.6.3	Jump Instructions and Their Encodings	189
3.6.4	Translating Conditional Branches	193
3.6.5	Loops	197
3.6.6	Conditional Move Instructions	206
3.6.7	Switch Statements	213
3.7	Procedures	219
3.7.1	Stack Frame Structure	219
3.7.2	Transferring Control	221
3.7.3	Register Usage Conventions	223
3.7.4	Procedure Example	224
3.7.5	Recursive Procedures	229
3.8	Array Allocation and Access	232
3.8.1	Basic Principles	232
3.8.2	Pointer Arithmetic	233
3.8.3	Nested Arrays	235
3.8.4	Fixed-Size Arrays	237
3.8.5	Variable-Size Arrays	238
3.9	Heterogeneous Data Structures	241
3.9.1	Structures	241
3.9.2	Unions	244
3.9.3	Data Alignment	248
3.10	Putting It Together: Understanding Pointers	252
3.11	Life in the Real World: Using the GDB Debugger	254
3.12	Out-of-Bounds Memory References and Buffer Overflow	256
3.12.1	Thwarting Buffer Overflow Attacks	261

3.13	x86-64: Extending IA32 to 64 Bits	267
3.13.1	History and Motivation for x86-64	268
3.13.2	An Overview of x86-64	270
3.13.3	Accessing Information	273
3.13.4	Control	279
3.13.5	Data Structures	290
3.13.6	Concluding Observations about x86-64	291
3.14	Machine-Level Representations of Floating-Point Programs	292
3.15	Summary	293
	Bibliographic Notes	294
	Homework Problems	294
	Solutions to Practice Problems	308

4

Processor Architecture 333

4.1	The Y86 Instruction Set Architecture	336
4.1.1	Programmer-Visible State	336
4.1.2	Y86 Instructions	337
4.1.3	Instruction Encoding	339
4.1.4	Y86 Exceptions	344
4.1.5	Y86 Programs	345
4.1.6	Some Y86 Instruction Details	350
4.2	Logic Design and the Hardware Control Language HCL	352
4.2.1	Logic Gates	353
4.2.2	Combinational Circuits and HCL Boolean Expressions	354
4.2.3	Word-Level Combinational Circuits and HCL Integer Expressions	355
4.2.4	Set Membership	360
4.2.5	Memory and Clocking	361
4.3	Sequential Y86 Implementations	364
4.3.1	Organizing Processing into Stages	364
4.3.2	SEQ Hardware Structure	375
4.3.3	SEQ Timing	379
4.3.4	SEQ Stage Implementations	383
4.4	General Principles of Pipelining	391
4.4.1	Computational Pipelines	392
4.4.2	A Detailed Look at Pipeline Operation	393
4.4.3	Limitations of Pipelining	394
4.4.4	Pipelining a System with Feedback	398
4.5	Pipelined Y86 Implementations	400
4.5.1	SEQ+: Rearranging the Computation Stages	400

4.5.2	Inserting Pipeline Registers	401
4.5.3	Rearranging and Relabeling Signals	405
4.5.4	Next PC Prediction	406
4.5.5	Pipeline Hazards	408
4.5.6	Avoiding Data Hazards by Stalling	413
4.5.7	Avoiding Data Hazards by Forwarding	415
4.5.8	Load/Use Data Hazards	418
4.5.9	Exception Handling	420
4.5.10	PIPE Stage Implementations	423
4.5.11	Pipeline Control Logic	431
4.5.12	Performance Analysis	444
4.5.13	Unfinished Business	446
4.6	Summary	449
4.6.1	Y86 Simulators	450
	Bibliographic Notes	451
	Homework Problems	451
	Solutions to Practice Problems	457

5

Optimizing Program Performance 473

5.1	Capabilities and Limitations of Optimizing Compilers	476
5.2	Expressing Program Performance	480
5.3	Program Example	482
5.4	Eliminating Loop Inefficiencies	486
5.5	Reducing Procedure Calls	490
5.6	Eliminating Unneeded Memory References	491
5.7	Understanding Modern Processors	496
5.7.1	Overall Operation	497
5.7.2	Functional Unit Performance	500
5.7.3	An Abstract Model of Processor Operation	502
5.8	Loop Unrolling	509
5.9	Enhancing Parallelism	513
5.9.1	Multiple Accumulators	514
5.9.2	Reassociation Transformation	518
5.10	Summary of Results for Optimizing Combining Code	524
5.11	Some Limiting Factors	525
5.11.1	Register Spilling	525
5.11.2	Branch Prediction and Misprediction Penalties	526
5.12	Understanding Memory Performance	531
5.12.1	Load Performance	531
5.12.2	Store Performance	532

5.13	Life in the Real World: Performance Improvement Techniques	539
5.14	Identifying and Eliminating Performance Bottlenecks	540
5.14.1	Program Profiling	540
5.14.2	Using a Profiler to Guide Optimization	542
5.14.3	Amdahl's Law	545
5.15	Summary	547
	Bibliographic Notes	548
	Homework Problems	549
	Solutions to Practice Problems	552

6

The Memory Hierarchy 559

6.1	Storage Technologies	561
6.1.1	Random-Access Memory	561
6.1.2	Disk Storage	570
6.1.3	Solid State Disks	581
6.1.4	Storage Technology Trends	583
6.2	Locality	586
6.2.1	Locality of References to Program Data	587
6.2.2	Locality of Instruction Fetches	588
6.2.3	Summary of Locality	589
6.3	The Memory Hierarchy	591
6.3.1	Caching in the Memory Hierarchy	592
6.3.2	Summary of Memory Hierarchy Concepts	595
6.4	Cache Memories	596
6.4.1	Generic Cache Memory Organization	597
6.4.2	Direct-Mapped Caches	599
6.4.3	Set Associative Caches	606
6.4.4	Fully Associative Caches	608
6.4.5	Issues with Writes	611
6.4.6	Anatomy of a Real Cache Hierarchy	612
6.4.7	Performance Impact of Cache Parameters	614
6.5	Writing Cache-friendly Code	615
6.6	Putting It Together: The Impact of Caches on Program Performance	620
6.6.1	The Memory Mountain	621
6.6.2	Rearranging Loops to Increase Spatial Locality	625
6.6.3	Exploiting Locality in Your Programs	629
6.7	Summary	629
	Bibliographic Notes	630
	Homework Problems	631
	Solutions to Practice Problems	642

Part II Running Programs on a System

7

Linking 653

- 7.1** Compiler Drivers 655
- 7.2** Static Linking 657
- 7.3** Object Files 657
- 7.4** Relocatable Object Files 658
- 7.5** Symbols and Symbol Tables 660
- 7.6** Symbol Resolution 663
 - 7.6.1 How Linkers Resolve Multiply Defined Global Symbols 664
 - 7.6.2 Linking with Static Libraries 667
 - 7.6.3 How Linkers Use Static Libraries to Resolve References 670
- 7.7** Relocation 672
 - 7.7.1 Relocation Entries 672
 - 7.7.2 Relocating Symbol References 673
- 7.8** Executable Object Files 678
- 7.9** Loading Executable Object Files 679
- 7.10** Dynamic Linking with Shared Libraries 681
- 7.11** Loading and Linking Shared Libraries from Applications 683
- 7.12** Position-Independent Code (PIC) 687
- 7.13** Tools for Manipulating Object Files 690
- 7.14** Summary 691
 - Bibliographic Notes 691
 - Homework Problems 692
 - Solutions to Practice Problems 698

8

Exceptional Control Flow 701

- 8.1** Exceptions 703
 - 8.1.1 Exception Handling 704
 - 8.1.2 Classes of Exceptions 706
 - 8.1.3 Exceptions in Linux/IA32 Systems 708
- 8.2** Processes 712
 - 8.2.1 Logical Control Flow 712
 - 8.2.2 Concurrent Flows 713
 - 8.2.3 Private Address Space 714
 - 8.2.4 User and Kernel Modes 714
 - 8.2.5 Context Switches 716

8.3	System Call Error Handling	717
8.4	Process Control	718
8.4.1	Obtaining Process IDs	719
8.4.2	Creating and Terminating Processes	719
8.4.3	Reaping Child Processes	723
8.4.4	Putting Processes to Sleep	729
8.4.5	Loading and Running Programs	730
8.4.6	Using <code>fork</code> and <code>execve</code> to Run Programs	733
8.5	Signals	736
8.5.1	Signal Terminology	738
8.5.2	Sending Signals	739
8.5.3	Receiving Signals	742
8.5.4	Signal Handling Issues	745
8.5.5	Portable Signal Handling	752
8.5.6	Explicitly Blocking and Unblocking Signals	753
8.5.7	Synchronizing Flows to Avoid Nasty Concurrency Bugs	755
8.6	Nonlocal Jumps	759
8.7	Tools for Manipulating Processes	762
8.8	Summary	763
	Bibliographic Notes	763
	Homework Problems	764
	Solutions to Practice Problems	771

9

Virtual Memory 775

9.1	Physical and Virtual Addressing	777
9.2	Address Spaces	778
9.3	VM as a Tool for Caching	779
9.3.1	DRAM Cache Organization	780
9.3.2	Page Tables	780
9.3.3	Page Hits	782
9.3.4	Page Faults	782
9.3.5	Allocating Pages	783
9.3.6	Locality to the Rescue Again	784
9.4	VM as a Tool for Memory Management	785
9.5	VM as a Tool for Memory Protection	786
9.6	Address Translation	787
9.6.1	Integrating Caches and VM	791
9.6.2	Speeding up Address Translation with a TLB	791
9.6.3	Multi-Level Page Tables	792
9.6.4	Putting It Together: End-to-end Address Translation	794
9.7	Case Study: The Intel Core i7/Linux Memory System	799

9.7.1	Core i7 Address Translation	800
9.7.2	Linux Virtual Memory System	803
9.8	Memory Mapping	807
9.8.1	Shared Objects Revisited	807
9.8.2	The <code>fork</code> Function Revisited	809
9.8.3	The <code>execve</code> Function Revisited	810
9.8.4	User-level Memory Mapping with the <code>mmap</code> Function	810
9.9	Dynamic Memory Allocation	812
9.9.1	The <code>malloc</code> and <code>free</code> Functions	814
9.9.2	Why Dynamic Memory Allocation?	816
9.9.3	Allocator Requirements and Goals	817
9.9.4	Fragmentation	819
9.9.5	Implementation Issues	820
9.9.6	Implicit Free Lists	820
9.9.7	Placing Allocated Blocks	822
9.9.8	Splitting Free Blocks	823
9.9.9	Getting Additional Heap Memory	823
9.9.10	Coalescing Free Blocks	824
9.9.11	Coalescing with Boundary Tags	824
9.9.12	Putting It Together: Implementing a Simple Allocator	827
9.9.13	Explicit Free Lists	835
9.9.14	Segregated Free Lists	836
9.10	Garbage Collection	838
9.10.1	Garbage Collector Basics	839
9.10.2	Mark&Sweep Garbage Collectors	840
9.10.3	Conservative Mark&Sweep for C Programs	842
9.11	Common Memory-Related Bugs in C Programs	843
9.11.1	Dereferencing Bad Pointers	843
9.11.2	Reading Uninitialized Memory	843
9.11.3	Allowing Stack Buffer Overflows	844
9.11.4	Assuming that Pointers and the Objects They Point to Are the Same Size	844
9.11.5	Making Off-by-One Errors	845
9.11.6	Referencing a Pointer Instead of the Object It Points to	845
9.11.7	Misunderstanding Pointer Arithmetic	846
9.11.8	Referencing Nonexistent Variables	846
9.11.9	Referencing Data in Free Heap Blocks	847
9.11.10	Introducing Memory Leaks	847
9.12	Summary	848
	Bibliographic Notes	848
	Homework Problems	849
	Solutions to Practice Problems	853

Part III Interaction and Communication Between Programs

10

System-Level I/O 861

- 10.1** Unix I/O 862
- 10.2** Opening and Closing Files 863
- 10.3** Reading and Writing Files 865
- 10.4** Robust Reading and Writing with the Rio Package 867
 - 10.4.1 Rio Unbuffered Input and Output Functions 867
 - 10.4.2 Rio Buffered Input Functions 868
- 10.5** Reading File Metadata 873
- 10.6** Sharing Files 875
- 10.7** I/O Redirection 877
- 10.8** Standard I/O 879
- 10.9** Putting It Together: Which I/O Functions Should I Use? 880
- 10.10** Summary 881
 - Bibliographic Notes 882
 - Homework Problems 882
 - Solutions to Practice Problems 883

11

Network Programming 885

- 11.1** The Client-Server Programming Model 886
- 11.2** Networks 887
- 11.3** The Global IP Internet 891
 - 11.3.1 IP Addresses 893
 - 11.3.2 Internet Domain Names 895
 - 11.3.3 Internet Connections 899
- 11.4** The Sockets Interface 900
 - 11.4.1 Socket Address Structures 901
 - 11.4.2 The `socket` Function 902
 - 11.4.3 The `connect` Function 903
 - 11.4.4 The `open_clientfd` Function 903
 - 11.4.5 The `bind` Function 904
 - 11.4.6 The `listen` Function 905
 - 11.4.7 The `open_listenfd` Function 905
 - 11.4.8 The `accept` Function 907
 - 11.4.9 Example Echo Client and Server 908

- 11.5** Web Servers 911
 - 11.5.1 Web Basics 911
 - 11.5.2 Web Content 912
 - 11.5.3 HTTP Transactions 914
 - 11.5.4 Serving Dynamic Content 916
- 11.6** Putting It Together: The TINY Web Server 919
- 11.7** Summary 927
 - Bibliographic Notes 928
 - Homework Problems 928
 - Solutions to Practice Problems 929

12

Concurrent Programming 933

- 12.1** Concurrent Programming with Processes 935
 - 12.1.1 A Concurrent Server Based on Processes 936
 - 12.1.2 Pros and Cons of Processes 937
- 12.2** Concurrent Programming with I/O Multiplexing 939
 - 12.2.1 A Concurrent Event-Driven Server Based on I/O Multiplexing 942
 - 12.2.2 Pros and Cons of I/O Multiplexing 946
- 12.3** Concurrent Programming with Threads 947
 - 12.3.1 Thread Execution Model 948
 - 12.3.2 Posix Threads 948
 - 12.3.3 Creating Threads 950
 - 12.3.4 Terminating Threads 950
 - 12.3.5 Reaping Terminated Threads 951
 - 12.3.6 Detaching Threads 951
 - 12.3.7 Initializing Threads 952
 - 12.3.8 A Concurrent Server Based on Threads 952
- 12.4** Shared Variables in Threaded Programs 954
 - 12.4.1 Threads Memory Model 955
 - 12.4.2 Mapping Variables to Memory 956
 - 12.4.3 Shared Variables 956
- 12.5** Synchronizing Threads with Semaphores 957
 - 12.5.1 Progress Graphs 960
 - 12.5.2 Semaphores 963
 - 12.5.3 Using Semaphores for Mutual Exclusion 964
 - 12.5.4 Using Semaphores to Schedule Shared Resources 966
 - 12.5.5 Putting It Together: A Concurrent Server Based on Prethreading 970
- 12.6** Using Threads for Parallelism 974

12.7	Other Concurrency Issues	979
12.7.1	Thread Safety	979
12.7.2	Reentrancy	980
12.7.3	Using Existing Library Functions in Threaded Programs	982
12.7.4	Races	983
12.7.5	Deadlocks	985
12.8	Summary	988
	Bibliographic Notes	989
	Homework Problems	989
	Solutions to Practice Problems	994

A

Error Handling	999
----------------	-----

A.1	Error Handling in Unix Systems	1000
A.2	Error-Handling Wrappers	1001

References	1005
------------	------

Index	1011
-------	------