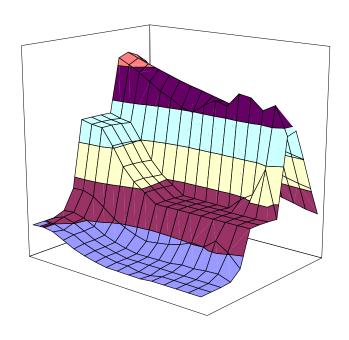
## Computer Systems A Programmer's Perspective 1



Randal E. Bryant David R. O'Hallaron

June 7, 2002

 $<sup>^{1}\</sup>text{Copyright}$  © 2002, R. E. Bryant, D. R. O'Hallaron. All rights reserved.

## **Contents**

Pr	eface			XV
1	A To	our of C	Computer Systems	1
	1.1	Inform	ation is Bits + Context	2
	1.2	Progra	ms Are Translated by Other Programs into Different Forms	3
	1.3	It Pays	to Understand How Compilation Systems Work	4
	1.4	Proces	sors Read and Interpret Instructions Stored in Memory	5
		1.4.1	Hardware Organization of a System	6
		1.4.2	Running the hello Program	8
	1.5	Caches	Matter	10
	1.6	Storage	e Devices Form a Hierarchy	11
	1.7	The O <sub>1</sub>	perating System Manages the Hardware	12
		1.7.1	Processes	13
		1.7.2	Threads	14
		1.7.3	Virtual Memory	14
		1.7.4	Files	16
	1.8	System	ns Communicate With Other Systems Using Networks	17
	1.9	The No	ext Step	18
	1.10	Summ	ary	18
Ι	Pro	gram S	tructure and Execution	21
2	Rep	resentin	g and Manipulating Information	25
	2.1	Inform	ation Storage	27
		2.1.1	Hexadecimal Notation	2.7

ii CONTENTS

	2.1.2	Words	31
	2.1.3	Data Sizes	31
	2.1.4	Addressing and Byte Ordering	32
	2.1.5	Representing Strings	39
	2.1.6	Representing Code	39
	2.1.7	Boolean Algebras and Rings	40
	2.1.8	Bit-Level Operations in C	44
	2.1.9	Logical Operations in C	46
	2.1.10	Shift Operations in C	47
2.2	Integer	Representations	48
	2.2.1	Integral Data Types	48
	2.2.2	Unsigned and Two's-Complement Encodings	48
	2.2.3	Conversions Between Signed and Unsigned	52
	2.2.4	Signed vs. Unsigned in C	54
	2.2.5	Expanding the Bit Representation of a Number	56
	2.2.6	Truncating Numbers	59
	2.2.7	Advice on Signed vs. Unsigned	60
2.3	Integer	Arithmetic	61
	2.3.1	Unsigned Addition	61
	2.3.2	Two's-Complement Addition	64
	2.3.3	Two's-Complement Negation	68
	2.3.4	Unsigned Multiplication	69
	2.3.5	Two's-Complement Multiplication	70
	2.3.6	Multiplying by Powers of Two	71
	2.3.7	Dividing by Powers of Two	72
2.4	Floatin	g Point	75
	2.4.1	Fractional Binary Numbers	75
	2.4.2	IEEE Floating-Point Representation	78
	2.4.3	Example Numbers	79
	2.4.4	Rounding	84
	2.4.5	Floating-Point Operations	85
	2.4.6	Floating Point in C	86
2.5	Summe	arv	91

CONTENTS

3	Mac	chine-L	evel Representation of Programs	115
	3.1	A Hist	torical Perspective	. 116
	3.2	Progra	m Encodings	. 119
		3.2.1	Machine-Level Code	. 119
		3.2.2	Code Examples	. 120
		3.2.3	A Note on Formatting	. 123
	3.3	Data F	Formats	. 125
	3.4	Acces	sing Information	. 126
		3.4.1	Operand Specifiers	. 127
		3.4.2	Data Movement Instructions	. 128
		3.4.3	Data Movement Example	. 131
	3.5	Arithn	netic and Logical Operations	. 133
		3.5.1	Load Effective Address	. 133
		3.5.2	Unary and Binary Operations	. 134
		3.5.3	Shift Operations	. 135
		3.5.4	Discussion	. 135
		3.5.5	Special Arithmetic Operations	. 136
	3.6	Contro	ol	. 138
		3.6.1	Condition Codes	. 138
		3.6.2	Accessing the Condition Codes	. 139
		3.6.3	Jump Instructions and their Encodings	. 141
		3.6.4	Translating Conditional Branches	. 146
		3.6.5	Loops	. 147
		3.6.6	Switch Statements	. 156
	3.7	Proced	lures	. 160
		3.7.1	Stack Frame Structure	. 160
		3.7.2	Transferring Control	. 162
		3.7.3	Register Usage Conventions	. 162
		3.7.4	Procedure Example	. 164
		3.7.5	Recursive Procedures	. 168
	3.8	Array	Allocation and Access	. 171
		3.8.1	Basic Principles	. 171
		3.8.2	Pointer Arithmetic	. 172

iv CONTENTS

		3.8.3	Arrays and Loops	. 173
		3.8.4	Nested Arrays	. 175
		3.8.5	Fixed Size Arrays	. 176
		3.8.6	Dynamically Allocated Arrays	. 179
	3.9	Hetero	geneous Data Structures	. 181
		3.9.1	Structures	. 181
		3.9.2	Unions	. 184
	3.10	Alignn	nent	. 188
	3.11	Putting	g it Together: Understanding Pointers	. 190
	3.12	Life in	the Real World: Using the GDB Debugger	. 194
	3.13	Out-of	-Bounds Memory References and Buffer Overflow	. 194
	3.14	*Floati	ng-Point Code	. 200
		3.14.1	Floating-Point Registers	. 201
		3.14.2	Stack Evaluation of Expressions	. 201
		3.14.3	Floating-Point Data Movement and Conversion Operations	. 204
		3.14.4	Floating-Point Arithmetic Instructions	. 206
		3.14.5	Using Floating Point in Procedures	. 209
		3.14.6	Testing and Comparing Floating-Point Values	. 211
	3.15	*Embe	edding Assembly Code in C Programs	. 213
		3.15.1	Basic Inline Assembly	. 214
		3.15.2	Extended Form of asm	. 216
	3.16	Summa	ary	. 219
	ъ			242
4			rchitecture	243
	4.1		86 Instruction Set Architecture	
	4.2		Design and the Hardware Control Language HCL	
		4.2.1	Logic Gates	
		4.2.2	Combinational Circuits and HCL Boolean Expressions	
		4.2.3	Word-Level Combinational Circuits and HCL Integer Expressions	
		4.2.4	Set Membership	
		4.2.5	Memory and Clocking	
	4.3	•	ntial Y86 Implementations	
		4.3.1	Organizing Processing into Stages	. 267

CONTENTS

		4.3.2	SEQ Hardware Structure
		4.3.3	SEQ Timing
		4.3.4	SEQ Stage Implementations
		4.3.5	SEQ+: Rearranging the Computation Stages
	4.4	Genera	l Principles of Pipelining
		4.4.1	Computational Pipelines
		4.4.2	A Detailed Look at Pipeline Operation
		4.4.3	Limitations of Pipelining
		4.4.4	Pipelining a System with Feedback
	4.5	Pipelin	ed Y86 Implementations
		4.5.1	Inserting Pipeline Registers
		4.5.2	Rearranging and Relabeling Signals
		4.5.3	Next PC Prediction
		4.5.4	Pipeline Hazards
		4.5.5	Avoiding Data Hazards by Stalling
		4.5.6	Avoiding Data Hazards by Forwarding
		4.5.7	Load/Use Data Hazards
		4.5.8	PIPE Stage Implementations
		4.5.9	Pipeline Control Logic
		4.5.10	Performance Analysis
		4.5.11	Unfinished Business
	4.6	Summa	ıry
		4.6.1	Y86 Simulators
5	Opti	imizing l	Program Performance 36.
	5.1	_	lities and Limitations of Optimizing Compilers
	5.2	•	sing Program Performance
	5.3	_	n Example
	5.4	•	ating Loop Inefficiencies
	5.5		ng Procedure Calls
	5.6		ating Unneeded Memory References
	5.7		tanding Modern Processors
			Overall Operation

vi CONTENTS

		5.7.2	Functional Unit Performance	84
		5.7.3	A Closer Look at Processor Operation	85
	5.8	Reduci	ng Loop Overhead	93
	5.9	Conver	ting to Pointer Code	98
	5.10	Enhanc	cing Parallelism	00
		5.10.1	Loop Splitting	01
		5.10.2	Register Spilling	05
		5.10.3	Limits to Parallelism	07
	5.11	Putting	it Together: Summary of Results for Optimizing Combining Code	08
		5.11.1	Floating-Point Performance Anomaly	09
		5.11.2	Changing Platforms	10
	5.12	Branch	Prediction and Misprediction Penalties	10
	5.13	Unders	tanding Memory Performance	13
		5.13.1	Load Latency	14
		5.13.2	Store Latency	16
	5.14	Life in	the Real World: Performance Improvement Techniques	21
	5.15	Identify	ying and Eliminating Performance Bottlenecks	22
		5.15.1	Program Profiling	22
		5.15.2	Using a Profiler to Guide Optimization	24
		5.15.3	Amdahl's Law	27
	5.16	Summa	ary	28
5	The	Memor	y Hierarchy 4	39
,	6.1		e Technologies	
	0.1	6.1.1	Random-Access Memory	
			Disk Storage	
		6.1.3	Storage Technology Trends	
	6.2		y	
		6.2.1	Locality of References to Program Data	
		6.2.2	Locality of Instruction Fetches	
		6.2.3	Summary of Locality	
	6.3		emory Hierarchy	
		6.3.1	Caching in the Memory Hierarchy	
		-		

CONTENTS vii

		6.3.2 Sumn	mary of Memory Hierarchy Concepts	467
	6.4	Cache Memor	ries	468
		6.4.1 Gener	ric Cache Memory Organization	469
		6.4.2 Direct	t-Mapped Caches	471
		6.4.3 Set A	ssociative Caches	477
		6.4.4 Fully	Associative Caches	479
		6.4.5 Issues	s with Writes	482
		6.4.6 Instru	action Caches and Unified Caches	483
		6.4.7 Perfor	rmance Impact of Cache Parameters	484
	6.5	Writing Cache	e-friendly Code	486
	6.6	Putting it Tog	gether: The Impact of Caches on Program Performance	491
		6.6.1 The M	Memory Mountain	491
		6.6.2 Rearra	ranging Loops to Increase Spatial Locality	495
		6.6.3 Using	g Blocking to Increase Temporal Locality	499
	6.7	Putting It Tog	gether: Exploiting Locality in Your Programs	502
	6.8	Summary .		502
II	Ru	nning Progra	ams on a System	517
7	T : 1	•		501
7	Link	· ·		521
	7.1	•	vers	
	7.2	_	g	
	7.3	· ·	N	
	7.4		Object Files	
	7.5	Symbols and		526
		0 1 1 5 1	Symbol Tables	
	7.6	•	lution	529
	7.6	7.6.1 How	lution	529
	7.6	7.6.1 How 17.6.2 Linkin	lution	529
		7.6.1 How 1 7.6.2 Linkin 7.6.3 How 1	lution	529 530 533
	7.6	7.6.1 How 1 7.6.2 Linkin 7.6.3 How 1 Relocation .	lution	529 530 533 536
		7.6.1 How 1 7.6.2 Linkin 7.6.3 How 1 Relocation . 7.7.1 Reloc	lution	529 530 533 536 538
		7.6.1 How 1 7.6.2 Linkin 7.6.3 How 1 Relocation . 7.7.1 Reloc 7.7.2 Reloc	lution	529 530 533 536 538 539

viii CONTENTS

	7.9	Loadin	g Executable Object Files	544
	7.10	Dynam	ic Linking with Shared Libraries	546
	7.11	Loadin	g and Linking Shared Libraries from Applications	548
	7.12	*Positi	on-Independent Code (PIC)	551
	7.13	Tools f	or Manipulating Object Files	554
	7.14	Summa	ary	554
8	Exce	ptional	Control Flow	565
	8.1	Except	ions	566
		8.1.1	Exception Handling	567
		8.1.2	Classes of Exceptions	569
		8.1.3	Exceptions in Intel Processors	571
	8.2	Process	ses	572
		8.2.1	Logical Control Flow	573
		8.2.2	Private Address Space	574
		8.2.3	User and Kernel Modes	574
		8.2.4	Context Switches	575
	8.3	System	Calls and Error Handling	577
	8.4	Process	s Control	578
		8.4.1	Obtaining Process ID's	578
		8.4.2	Creating and Terminating Processes	579
		8.4.3	Reaping Child Processes	584
		8.4.4	Putting Processes to Sleep	589
		8.4.5	Loading and Running Programs	590
		8.4.6	Using fork and execve to Run Programs	593
	8.5	Signals		594
		8.5.1	Signal Terminology	594
		8.5.2	Sending Signals	598
		8.5.3	Receiving Signals	601
		8.5.4	Signal Handling Issues	604
		8.5.5	Portable Signal Handling	609
		8.5.6	Explicitly Blocking Signals	611
	8.6	Nonloc	eal Jumps	613

*CONTENTS* ix

	8.7	Tools for Manipulating Processes	18
	8.8	Summary	18
9	Meas	suring Program Execution Time 6	29
	9.1	The Flow of Time on a Computer System	30
		9.1.1 Process Scheduling and Timer Interrupts	31
		9.1.2 Time from an Application Program's Perspective	32
	9.2	Measuring Time by Interval Counting	35
		9.2.1 Operation	35
		9.2.2 Reading the Process Timers	36
		9.2.3 Accuracy of Process Timers	37
	9.3	Cycle Counters	40
		9.3.1 IA32 Cycle Counters	40
	9.4	Measuring Program Execution Time with Cycle Counters	42
		9.4.1 The Effects of Context Switching	42
		9.4.2 Caching and Other Effects	43
		9.4.3 The <i>K</i> -Best Measurement Scheme	47
	9.5	Time-of-Day Measurements	56
	9.6	Putting it Together: An Experimental Protocol	59
	9.7	Looking into the Future	59
	9.8	Life in the Real World: An Implementation of the $K$ -Best Measurement Scheme 6	60
	9.9	Lessons Learned	60
	9.10	Summary	61
10	Virtu	ual Memory 6	667
	10.1	Physical and Virtual Addressing	68
	10.2	Address Spaces	69
	10.3	VM as a Tool for Caching	70
		10.3.1 DRAM Cache Organization	71
		10.3.2 Page Tables	
		10.3.3 Page Hits	
		10.3.4 Page Faults	
		10.3.5 Allocating Pages	

X CONTENTS

	10.3.6 Locality to the Rescue Again	5
10.4	VM as a Tool for Memory Management	5
	10.4.1 Simplifying Linking	6
	10.4.2 Simplifying Sharing	6
	10.4.3 Simplifying Memory Allocation	7
	10.4.4 Simplifying Loading	7
10.5	VM as a Tool for Memory Protection	8
10.6	Address Translation	9
	10.6.1 Integrating Caches and VM	2
	10.6.2 Speeding up Address Translation with a TLB	2
	10.6.3 Multi Level Page Tables	3
	10.6.4 Putting it Together: End-to-end Address Translation	6
10.7	Case Study: The Pentium/Linux Memory System	0
	10.7.1 Pentium Address Translation	0
	10.7.2 Linux Virtual Memory System	5
10.8	Memory Mapping	8
	10.8.1 Shared Objects Revisited	9
	10.8.2 The fork Function Revisited	1
	10.8.3 The execve Function Revisited	1
	10.8.4 User-level Memory Mapping with the mmap Function	2
10.9	Dynamic Memory Allocation	4
	10.9.1 The malloc and free Functions	5
	10.9.2 Why Dynamic Memory Allocation?	8
	10.9.3 Allocator Requirements and Goals	9
	10.9.4 Fragmentation	0
	10.9.5 Implementation Issues	1
	10.9.6 Implicit Free Lists	2
	10.9.7 Placing Allocated Blocks	3
	10.9.8 Splitting Free Blocks	4
	10.9.9 Getting Additional Heap Memory	4
	10.9.10 Coalescing Free Blocks	4
	10.9.11 Coalescing with Boundary Tags	5
	10.9.12 Putting it Together: Implementing a Simple Allocator	7

*CONTENTS* xi

	10.9.13 Explicit Free Lists	. 725
	10.9.14 Segregated Free Lists	. 726
10.	10Garbage Collection	. 728
	10.10.1 Garbage Collector Basics	. 729
	10.10.2 Mark&Sweep Garbage Collectors	. 730
	10.10.3 Conservative Mark&Sweep for C Programs	. 731
10.	.11Common Memory-Related Bugs in C Programs	. 733
	10.11.1 Dereferencing Bad Pointers	. 733
	10.11.2 Reading Uninitialized Memory	. 733
	10.11.3 Allowing Stack Buffer Overflows	. 734
	10.11.4 Assuming that Pointers and the Objects they Point to Are the Same Size	. 734
	10.11.5 Making Off-by-one Errors	. 735
	10.11.6 Referencing a Pointer Instead of the Object it Points to	. 735
	10.11.7 Misunderstanding Pointer Arithmetic	. 736
	10.11.8 Referencing Nonexistent Variables	. 736
	10.11.9 Referencing Data in Free Heap Blocks	. 736
	10.11.10ntroducing Memory Leaks	. 737
10.	.12Recapping Some Key Ideas About Virtual Memory	. 737
10.	13Summary	. 738
III 1	Interaction and Communication Between Programs	749
11 Sy	stem-Level I/O	753
11.	.1 Unix I/O	. 754
11.	2 Opening and Closing Files	. 754
11.	3 Reading and Writing Files	. 756
11.	4 Robust Reading and Writing with the RIO Package	. 758
	11.4.1 RIO Unbuffered Input and Output Functions	. 758
	11.4.2 RIO Buffered Input Functions	. 759
11.	.5 Reading File Metadata	. 762
11.	6 Sharing Files	. 767
11.	7 I/O Redirection	. 770
11	8 Standard I/O	771

xii CONTENTS

	11.9	Putting It Together: Which I/O Functions Should I Use?	72
	11.10	OSummary	173
12	Netw	vork Programming	777
	12.1	The Client-Server Programming Model	177
	12.2	Networks	78
	12.3	The Global IP Internet	183
		12.3.1 IP Addresses	184
		12.3.2 Internet Domain Names	186
		12.3.3 Internet Connections	190
	12.4	The Sockets Interface	791
		12.4.1 Socket Address Structures	791
		12.4.2 The socket Function	192
		12.4.3 The connect Function	193
		12.4.4 The open_clientfdFunction	194
		12.4.5 The bind Function	195
		12.4.6 The listen Function	195
		12.4.7 The open_listenfdFunction	195
		12.4.8 The accept Function	
		12.4.9 Example Echo Client and Server	198
	12.5	Web Servers	
		12.5.1 Web Basics	301
		12.5.2 Web Content	
		12.5.3 HTTP Transactions	303
		12.5.4 Serving Dynamic Content	306
	12.6	Putting it Together: The TINY Web Server	307
	12.7	Summary	317
13	Conc	current Programming 8	323
		Concurrent Programming With Processes	324
		13.1.1 A Concurrent Server Based on Processes	
		13.1.2 Pros and Cons of Processes	
	13.2	Concurrent Programming With I/O Multiplexing	

xii

		13.2.1	A Concurrent Event-Driven Server Based on I/O Multiplexing 831
		13.2.2	Pros and Cons of I/O Multiplexing
	13.3	Concu	rrent Programming With Threads
		13.3.1	Thread Execution Model
		13.3.2	Posix Threads
		13.3.3	Creating Threads
		13.3.4	Terminating Threads
		13.3.5	Reaping Terminated Threads
		13.3.6	Detaching Threads
		13.3.7	Initializing Threads
		13.3.8	A Concurrent Server Based on Threads
	13.4	Shared	Variables in Threaded Programs
		13.4.1	Threads Memory Model
		13.4.2	Mapping Variables to Memory
		13.4.3	Shared Variables
	13.5	Synchr	conizing Threads with Semaphores
		13.5.1	Progress Graphs
		13.5.2	Using Semaphores to Access Shared Variables
		13.5.3	Posix Semaphores
		13.5.4	Using Semaphores to Schedule Shared Resources
	13.6	Putting	It Together: A Concurrent Server Based on Prethreading
	13.7	Other (	Concurrency Issues
		13.7.1	Thread Safety
		13.7.2	Reentrancy
		13.7.3	Using Existing Library Functions in Threaded Programs
		13.7.4	Races
		13.7.5	Deadlocks
	13.8	Summa	ary
A			aptions of Processor Control Logic 877
	A.1	HCL R	Reference Manual
		A.1.1	Signal Declarations
		A.1.2	Quoted Text

•	
X1V	CONTENTS
7 <b>.1</b> V	COLLECTS

		A.1.3 Expressions and Blocks	8				
		A.1.4 HCL Example	0				
	A.2	SEQ	2				
	A.3	SEQ+	5				
	A.4	PIPE	9				
В	Error Handling						
	B.1	Error Handling in Unix Systems	7				
	B.2	Error-Handling Wrappers	9				
	B.3	The csapp.h Header File	2				
	B.4	The csapp.c Source File	6				