Computer Systems: An Integrated Approach to Architecture and Operating Systems

Table of Contents

Preface	i
Why a New Book on Computer Systems?	
The structure of the book	ii
Where Does This Textbook Fit into the Continuum of CS Curriculum?	iii
Supplementary Material for Teaching an Integrated Course in Systems	v
Example project ideas included in the supplementary material	vi
Chapter 1 Introduction	1-1
1.1 What is Inside a Box?	1-1
1.2 Levels of Abstraction in a Computer System	1-2
1.3 The Role of the Operating System	1-5
1.4 What is happening inside the box?	1-7
1.4.1 Launching an application on the computer	1-9
1.5 Evolution of Computer Hardware	1-9
1.6 Evolution of Operating Systems	1-11
1.7 Roadmap of the rest of the book	1-12
1.8 Review Questions	1-13
Chapter 2 Processor Architecture	2-1
2.1 What is involved in processor design?	2-2
2.2 How do we design an instruction set?	2-2
2.3 A Common High-Level Language Feature Set	2-3

2.4 Expressions and Assignment Statements	2-4
2.4.1 Where to keep the operands?	2-4
2.4.2 How do we specify a memory address in an instruction?	2-9
2.4.3 How wide should each operand be?	2-10
2.4.4 Endianness	2-12
2.4.5 Packing of operands and Alignment of word operands	2-15
2.5 High-level data abstractions	2-17
2.5.1 Structures	2-17
2.5.2 Arrays	2-18
2.6 Conditional statements and loops	2-20
2.6.1 If-then-else statement	2-20
2.6.2 Switch statement	2-22
2.6.3 Loop statement	2-23
2.7 Checkpoint	2-24
2.8 Compiling Function calls	2-24
2.8.1 State of the Caller	2-25
2.8.2 Remaining chores with procedure calling	2-28
2.8.3 Software Convention	2-29
2.8.4 Activation Record	2-36
2.8.5 Recursion	2-37
2.8.6 Frame Pointer	2-37
2.9 Instruction-Set Architecture Choices	2-40
2.9.1 Additional Instructions	2-40
2.9.2 Additional addressing modes	2-40
2.9.3 Architecture styles	2-41
2.9.4 Instruction Format	2-41
2.10 LC-2200 Instruction Set	2-45
2.10.1 Instruction Format	2-45
2.10.2 LC-2200 Register Set	2-48
2.11 Issues influencing processor design	2-48
2.11.1 Instruction-set	2-48
2.11.2 Influence of applications on instruction-set design	2-50

2.11.3 Other issues driving processor design	2-51
2.12 Summary	2-52
2.13 Review Questions	2-53
Chapter 3 Processor Implementation	3-1
3.1 Architecture versus Implementation	3-1
3.2 What is involved in Processor Implementation?	3-2
3.3 Key hardware concepts	3-3
3.3.1 Circuits	3-3
3.3.2 Hardware resources of the datapath	3-3
3.3.3 Edge Triggered Logic	3-5
3.3.4 Connecting the datapath elements	3-7
3.3.5 Towards bus-based Design	3-10
3.3.6 Finite State Machine (FSM)	3-13
3.4 Datapath Design	3-15
3.4.1 ISA and datapath width	3-17
3.4.2 Width of the Clock Pulse	3-18
3.4.3 Checkpoint	3-18
3.5 Control Unit Design	3-18
3.5.1 ROM plus state register	3-19
3.5.2 FETCH macro state	3-23
3.5.3 DECODE macro state	3-25
3.5.4 EXECUTE macro state: ADD instruction (part of R-Type)	3-26
3.5.5 EXECUTE macro state: NAND instruction (part of R-Type)	3-28
3.5.6 EXECUTE macro state: JALR instruction (part of J-Type)	3-28
3.5.7 EXECUTE macro state: LW instruction (part of I-Type)	3-29
3.5.8 EXECUTE macro state: SW and ADDI instructions (part of I-Type)	3-30
3.5.9 EXECUTE macro state: BEQ instruction (part of I-Type)	3-31
3.5.10 Engineering a conditional branch in the microprogram	3-32
3.5.11 DECODE macro state revisited	3-34
3.6 Alternative Style of Control Unit Design	3-35
3.6.1 Microprogrammed Control	3-35

3.6.2 Hardwired control	3-36
3.6.3 Choosing between the two control design styles	3-37
3.7 Historical Perspective	3-38
3.8 Review Questions	3-41
Chapter 4 Interrupts, Traps and Exceptions	4-1
4.1 Discontinuities in program execution	4-2
4.2 Dealing with program discontinuities	4-4
4.3 Architectural enhancements to handle program discontinuities	4-7
4.3.1 Modifications to FSM	4-8
4.3.2 A simple interrupt handler	4-9
4.3.3 Handling cascaded interrupts	4-10
4.3.4 Returning from the handler	4-13
4.3.5 Checkpoint	4-14
4.4 Hardware details for handling program discontinuities	4-14
4.4.1 Datapath details for interrupts	4-14
4.4.2 Details of receiving the address of the handler	4-16
4.4.3 Stack for saving/restoring	4-18
4.5 Putting it all together	4-20
4.5.1 Summary of Architectural/hardware enhancements	4-20
4.5.2 Interrupt mechanism at work	4-20
4.6 Summary	4-23
4.7 Review Questions	4-25
Chapter 5 Processor Performance and Rudiments	of
Pipelined Processor Design	5-1
5.1 Space and Time Metrics	5-1
5.2 Instruction Frequency	5-4
5.3 Benchmarks	5-5
5.4 Increasing the Processor Performance	5-9
5.5 Speedup	5-10
5.6 Increasing the Throughput of the Processor	5-14
5.7 Introduction to Pipelining	5-14

5.8 Towards an instruction processing assembly line	5-15
5.9 Problems with a simple-minded instruction pipeline	5-17
5.10 Fixing the problems with the instruction pipeline	5-18
5.11 Datapath elements for the instruction pipeline	5-20
5.12 Pipeline-conscious architecture and implementation	5-23
5.12.1 Anatomy of an instruction passage through the pipeline	5-23
5.12.2 Design of the Pipeline Registers	5-26
5.12.3 Implementation of the stages	5-27
5.13 Hazards	5-27
5.13.1 Structural hazard	5-28
5.13.2 Data Hazard	5-31
5.13.3 Control Hazard	5-41
5.13.4 Summary of Hazards	5-51
5.14 Dealing with program discontinuities in a pipelined processor	5-52
5.15 Advanced topics in processor design	5-55
5.15.1 Instruction Level Parallelism	5-55
5.15.2 Deeper pipelines	5-56
5.15.3 Revisiting program discontinuities in the presence of out-of-order	processing5-60
5.15.4 Managing shared resources	5-60
5.15.5 Power Consumption	5-62
5.15.6 Multi-core Processor Design	5-63
5.15.7 Intel Core Microarchitecture: An example pipeline	5-64
5.16 Historical Perspective	5-67
5.17 Review Questions	5-68
Chapter 6 Processor Scheduling	6-1
6.1 Introduction	6-1
6.2 Programs and Processes	6-2
6.3 Scheduling Environments	6-7
6.4 Scheduling Basics	6-8
6.5 Performance Metrics	6-12
6.6 Non-preemptive Scheduling Algorithms	6-15

	6.6.1 First-Come First-Served (FCFS)	6-15
	6.6.2 Shortest Job First (SJF)	6-19
	6.6.3 Priority	6-22
	6.7 Preemptive Scheduling Algorithms	6-23
	6.7.1 Round Robin Scheduler	6-26
	6.8 Combining Priority and Preemption	6-31
	6.9 Meta Schedulers	6-31
	6.10 Evaluation	6-32
	6.11 Summary and a Look ahead	6-35
	6.12 Linux Scheduler – A case study	6-35
	6.13 Historical Perspective	6-38
	6.14 Review Questions	6-41
(Chapter 7 Memory Management Techniques	7-1
	7.1 Functionalities provided by a memory manager	7-1
	7.2 Simple Schemes for Memory Management	7-4
	7.3 Memory Allocation Schemes	7-8
	7.3.1 Fixed Size Partitions	7-9
	7.3.2 Variable Size Partitions	7-10
	7.3.3 Compaction	7-13
	7.4 Paged Virtual Memory	7-14
	7.4.1 Page Table	7-17
	7.4.2 Hardware for Paging	7-19
	7.4.3 Page Table Set up	7-20
	7.4.4 Relative sizes of virtual and physical memories	7-20
	7.5 Segmented Virtual Memory	7-21
	7.5.1 Hardware for Segmentation	7-26
	7.6 Paging versus Segmentation	7-27
	7.6.1 Interpreting the CPU generated address	7-29
	7.7 Summary	7-30
	7.8 Historical Perspective	7-32
	7.8.1 MULTICS	7-33

7.8.2 Intel's Memory Architecture	7-35
7.9 Review Questions	7-36
Chapter 8 Details of Page-based Memory Management	8-1
8.1 Demand Paging	8-1
8.1.1 Hardware for demand paging	8-1
8.1.2 Page fault handler	8-2
8.1.3 Data structures for Demand-paged Memory Management	8-3
8.1.4 Anatomy of a Page Fault	8-5
8.2 Interaction between the Process Scheduler and Memory Manager	8-8
8.3 Page Replacement Policies	8-9
8.3.1 Belady's Min	8-10
8.3.2 Random Replacement	8-10
8.3.3 First In First Out (FIFO)	8-11
8.3.4 Least Recently Used (LRU)	8-13
8.3.5 Second chance page replacement algorithm	8-17
8.3.6 Review of page replacement algorithms	8-20
8.4 Optimizing Memory Management	8-22
8.4.1 Pool of free page frames	8-22
8.4.2 Thrashing	8-23
8.4.3 Working set	8-25
8.4.4 Controlling thrashing	8-26
8.5 Other considerations	8-28
8.6 Translation Lookaside Buffer (TLB)	8-28
8.6.1 Address Translation with TLB	8-29
8.7 Advanced topics in memory management	8-31
8.7.1 Multi-level page tables	8-31
8.7.2 Access rights as part of the page table entry	8-34
8.7.3 Inverted page tables	8-34
8.8 Summary	8-34
8.9 Review Questions	8-35
Chapter 9 Memory Hierarchy	9-1

9.1 The Concept of a Cache	9-2
9.2 Principle of Locality	9-3
9.3 Basic terminologies	9-4
9.4 Multilevel Memory Hierarchy	9-5
9.5 Cache organization	9-8
9.6 Direct-mapped cache organization	9-9
9.6.1 Cache Lookup	9-11
9.6.2 Fields of a Cache Entry	9-13
9.6.3 Hardware for direct mapped cache	9-14
9.7 Repercussion on pipelined processor design	9-16
9.8 Cache read/write algorithms	9-17
9.8.1 Read access to the cache from the CPU	9-18
9.8.2 Write access to the cache from the CPU	9-19
9.9 Dealing with cache misses in the processor pipeline	9-22
9.9.1 Effect of memory stalls due to cache misses on pipeline performance	9-23
9.10 Exploiting spatial locality to improve cache performance	9-25
9.10.1 Performance implications of increased blocksize	9-30
9.11 Flexible placement	9-31
9.11.1 Fully associative cache	9-32
9.11.2 Set associative cache	9-34
9.11.3 Extremes of set associativity	9-37
9.12 Instruction and Data caches	9-39
9.13 Reducing miss penalty	9-40
9.14 Cache replacement policy	9-41
9.15 Recapping Types of Misses	9-43
9.16 Integrating TLB and Caches	9-46
9.17 Cache controller	9-48
9.18 Virtually indexed physically tagged cache	9-49
9.19 Recap of Cache Design Considerations	9-52
9.20 Main memory design considerations	9-52
9.20.1 Simple main memory	9-53
9.20.2 Main memory and bus to match cache block size	9-54

9.20.3 Interleaved memory	9-55
9.21 Elements of a modern main memory systems	9-56
9.21.1 Page mode DRAM	9-61
9.22 Performance implications of memory hierarchy	9-62
9.23 Summary	9-63
9.24 Memory hierarchy of modern processors – An example	9-65
9.25 Review Questions	9-66
Chapter 10 Input/Output and Stable Storage	10-1
10.1 Communication between the CPU and the I/O devices	10-1
10.1.1 Device controller	10-2
10.1.2 Memory Mapped I/O	10-3
10.2 Programmed I/O	10-5
10.3 DMA	10-6
10.4 Buses	10-9
10.5 I/O Processor	10-10
10.6 Device Driver	10-11
10.6.1 An Example	10-12
10.7 Peripheral Devices	10-15
10.8 Disk Storage	10-17
10.8.1 Saga of Disk Technology	10-24
10.9 Disk Scheduling Algorithms	10-27
10.9.1 First-Come First Served	10-30
10.9.2 Shortest Seek Time First	10-30
10.9.3 Scan (elevator algorithm)	10-31
10.9.4 C-Scan (Circular Scan)	10-32
10.9.5 Look and C-Look	10-33
10.9.6 Disk Scheduling Summary	10-33
10.9.7 Comparison of the Algorithms	10-34
10.10 Solid State Drive	10-36
10.11 Evolution of I/O Buses and Device Drivers	10-38
10.11.1 Dynamic Loading of Device Drivers	10-39

10.11.2 Putting it all Together	10-39
10.12 Summary	10-42
10.13 Review Questions	10-42
Chapter 11 File System	11-1
11.1 Attributes	11-2
11.2 Design Choices in implementing a File System on a Disk Subsystem	11-8
11.2.1 Contiguous Allocation	11-9
11.2.2 Contiguous Allocation with Overflow Area	11-12
11.2.3 Linked Allocation	11-12
11.2.4 File Allocation Table (FAT)	11-13
11.2.5 Indexed Allocation	11-15
11.2.6 Multilevel Indexed Allocation	11-17
11.2.7 Hybrid Indexed Allocation	11-18
11.2.8 Comparison of the allocation strategies	11-21
11.3 Putting it all together	11-22
11.3.1 i-node	11-28
11.4 Components of the File System	11-29
11.4.1 Anatomy of creating and writing files	11-30
11.5 Interaction among the various subsystems	11-31
11.6 Layout of the file system on the physical media	11-34
11.6.1 In memory data structures	11-37
11.7 Dealing with System Crashes	11-38
11.8 File systems for other physical media	11-39
11.9 A summary of modern file systems	11-39
11.9.1 Linux	11-39
11.9.2 Microsoft Windows	11-45
11.10 Summary	11-47
11.11 Review Questions	11-48
Chapter 12 Multithreaded Programming and	
Multiprocessors	12_1
•	
12.1 Why Multithreading?	12-1

12.2 Programming support for threads	12-3
12.2.1 Thread creation and termination	12-3
12.2.2 Communication among threads	12-6
12.2.3 Data race and Non-determinism	12-7
12.2.4 Synchronization among threads	12-12
12.2.5 Internal representation of data types provided by the threads library	12-19
12.2.6 Simple programming examples	12-20
12.2.7 Deadlocks and livelocks	12-25
12.2.8 Condition variables	12-26
12.2.9 A complete solution for the video processing example	12-30
12.2.10 Rechecking the predicate	12-33
12.3 Summary of thread function calls and threaded programming concepts	12-36
12.4 Points to remember in programming with threads	12-38
12.5 Using threads as software structuring abstraction	12-39
12.6 POSIX pthreads library calls summary	12-40
12.7 OS support for threads	12-42
12.7.1 User level threads	12-45
12.7.2 Kernel level threads	12-47
12.7.3 Solaris threads: An example of kernel level threads	12-49
12.7.4 Threads and libraries	12-50
12.8 Hardware support for multithreading in a uniprocessor	12-51
12.8.1 Thread creation, termination, and communication among threads	12-51
12.8.2 Inter-thread synchronization	12-51
12.8.3 An atomic test-and-set instruction	12-52
12.8.4 Lock algorithm with test-and-set instruction	12-54
12.9 Multiprocessors	12-55
12.9.1 Page tables	12-56
12.9.2 Memory hierarchy	12-56
12.9.3 Ensuring atomicity	12-59
12.10 Advanced Topics	
12.10.1 OS topics	
12.10.2 Architecture topics	

12.10.3 The Road Ahead: Multi- and Many-core Architectures	12-86
12.11 Summary	12-88
12.12 Historical Perspective	12-89
12.13 Review Questions	12-91
Chapter 13 Fundamentals of Networking and N	Network
Protocols	
13.1 Preliminaries	13-1
13.2 Basic Terminologies	
13.3 Networking Software	
13.4 Protocol Stack	
13.4.1 Internet Protocol Stack	13-9
13.4.2 OSI Model	13-12
13.4.3 Practical issues with layering	13-13
13.5 Application Layer	13-14
13.6 Transport Layer	13-15
13.6.1 Stop and wait protocols	13-17
13.6.2 Pipelined protocols	13-20
13.6.3 Reliable Pipelined Protocol	13-22
13.6.4 Dealing with transmission errors	13-28
13.6.5 Transport protocols on the Internet	13-28
13.6.6 Transport Layer Summary	13-32
13.7 Network Layer	13-32
13.7.1 Routing Algorithms	13-33
13.7.2 Internet Addressing	13-40
13.7.3 Network Service Model	13-43
13.7.4 Network Routing Vs. Forwarding	13-47
13.7.5 Network Layer Summary	13-48
13.8 Link Layer and Local Area Networks	13-50
13.8.1 Ethernet	13-50
13.8.2 CSMA/CD	13-51
13.8.3 IEEE 802.3	13-53

13.8.4 Wireless LAN and IEEE 802.11	13-54
13.8.5 Token Ring	13-55
13.8.6 Other link layer protocols	13-57
13.9 Networking Hardware	13-58
13.10 Relationship between the Layers of the Protocol Stack	13-63
13.11 Data structures for packet transmission	13-63
13.11.1 TCP/IP Header	13-65
13.12 Message transmission time	13-66
13.13 Summary of Protocol Layer Functionalities	13-72
13.14 Networking Software and the Operating System	13-73
13.14.1 Socket Library	13-73
13.14.2 Implementation of the Protocol Stack in the Operating System	13-75
13.14.3 Network Device Driver	13-76
13.15 Network Programming using Unix Sockets	13-77
13.16 Network Services and Higher Level Protocols	13-85
13.17 Summary	13-86
13.18 Historical Perspective	13-87
13.18.1 From Telephony to Computer Networking	13-87
13.18.2 Evolution of the Internet	13-90
13.18.3 PC and the arrival of LAN	13-91
13.18.4 Evolution of LAN	13-91
13.19 Review Questions	13-94
Chapter 14 Epilogue: A Look Back at the Jou	urney14-1
14.1 Processor Design	14-1
14.2 Process	14-1
14.3 Virtual Memory System and Memory Management	14-2
14.4 Memory Hierarchy	14-2
14.5 Parallel System	14-3
14.6 Input/Output Systems	14-3
14.7 Persistent Storage	14-3
14.8 Network	14-4

14.9 Concluding Remarks	14-4
Appendix A Network Programming with	Unix Sockets A-1
A.1 The problem	A-1
A.2 Source files provided	A-1
A.3 Makefile	A-1
A.4 Common header file	A-3
A.5 Client source code	A-3
A.6 Server source code	A-7
A.7 Instantiating the client/server programs	A-12