Bruce Jacob

The Memory System

You Can't Avoid It,
You Can't Ignore It,
You Can't Fake It

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Memory Systems Bruce Jacob,David Wang,Spencer Ng,2010-07-28 Is your memory hierarchy stopping your microprocessor from performing at the high level it should be Memory Systems Cache DRAM Disk shows you how to resolve this problem The book tells you everything you need to know about the logical design and operation physical design and operation performance characteristics and resulting design trade offs and the energy consumption of modern memory hierarchies You learn how to to tackle the challenging optimization problems that result from the side effects that can appear at any point in the entire hierarchy As a result you will be able to design and emulate the entire memory hierarchy Understand all levels of the system hierarchy Xcache DRAM and disk Evaluate the system level effects of all design choices Model performance and energy consumption for each component in the memory hierarchy **The Memory System** Bruce Jacob,2009-07-08 Today computer system optimization at both the hardware and software levels must consider the details of the memory system in its analysis failing to do so yields systems that are increasingly inefficient as those systems become more complex This lecture seeks to introduce the reader to the most important details of the memory system it targets both computer scientists and computer engineers in industry and in academia Roughly speaking computer scientists are the users of the memory system and computer engineers are the designers of the memory system Both can benefit tremendously from a basic understanding of how the memory system really works the computer scientist will be better equipped to create algorithms that perform well and the computer engineer will be better equipped to design systems that approach the optimal given the resource limitations Currently there is consensus among architecture researchers that the memory system is the bottleneck and this consensus has held for over a decade Somewhat inexplicably most of the research in the field is still directed toward improving the CPU to better tolerate a slow memory system as opposed to addressing the weaknesses of the memory system directly This lecture should get the bulk of the computer science and computer engineering population up the steep part of the learning curve Not every CS CE researcher developer needs to do work in the memory system but just as a carpenter can do his job more efficiently if he knows a little of architecture and an architect can do his job more efficiently if he knows a little of carpentry giving the CS CE worlds better intuition about the memory system should help them build better systems both software and hardware Table of Contents Primers It Must Be Modeled Accurately and It Will Change Soon **The Memory System** Bruce Jacob,2009-06-19 Today computer system optimization at both the hardware and software levels must consider the details of the memory system in its analysis failing to do so yields systems that are increasingly inefficient as those systems become more complex This lecture seeks to introduce the reader to the most important details of the memory system it targets both computer scientists and computer engineers in industry and in academia Roughly speaking computer scientists are the users of the memory system and computer engineers are the designers of the memory system Both can benefit tremendously from a basic understanding of how the memory system really

works the computer scientist will be better equipped to create algorithms that perform well and the computer engineer will be better equipped to design systems that approach the optimal given the resource limitations Currently there is consensus among architecture researchers that the memory system is the bottleneck and this consensus has held for over a decade Somewhat inexplicably most of the research in the field is still directed toward improving the CPU to better tolerate a slow memory system as opposed to addressing the weaknesses of the memory system directly This lecture should get the bulk of the computer science and computer engineering population up the steep part of the learning curve Not every CS CE researcher developer needs to do work in the memory system but just as a carpenter can do his job more efficiently if he knows a little of architecture and an architect can do his job more efficiently if he knows a little of carpentry giving the CS CE worlds better intuition about the memory system should help them build better systems both software and hardware Table of Contents Primers It Must Be Modeled Accurately and It Will Change Soon   Innovations in the Memory System Rajeev Balasubramonian,2019-09-10 This is a tour through recent and prominent works regarding new DRAM chip designs and technologies near data processing approaches new memory channel architectures techniques to tolerate the overheads of refresh and fault tolerance security attacks and mitigations and memory scheduling The memory system will soon be a hub for future innovation While conventional memory systems focused primarily on high density other memory system metrics like energy security and reliability are grabbing modern research headlines With processor performance stagnating it is also time to consider new programming models that move some application computations into the memory system This in turn will lead to feature rich memory systems with new interfaces The past decade has seen a number of memory system innovations that point to this future where the memory system will be much more than dense rows of unintelligent bits

Cache and Memory Hierarchy Design Steven A. Przybylski,1990 A widely read and authoritative book for hardware and software designers This innovative book exposes the characteristics of performance optimal single and multi level cache hierarchies by approaching the cache design process through the novel perspective of minimizing execution time   Digital Systems and Applications Vojin G. Oklobdzija,2017-12-19 New design architectures in computer systems have surpassed industry expectations Limits which were once thought of as fundamental have now been broken Digital Systems and Applications details these innovations in systems design as well as cutting edge applications that are emerging to take advantage of the fields increasingly sophisticated capabilities This book features new chapters on parallelizing iterative heuristics stream and wireless processors and lightweight embedded systems This fundamental text Provides a clear focus on computer systems architecture and applications Takes a top level view of system organization before moving on to architectural and organizational concepts such as superscalar and vector processor VLIW architecture as well as new trends in multithreading and multiprocessing includes an entire section dedicated to embedded systems and their applications Discusses topics such as digital signal processing applications circuit implementation aspects parallel I O algorithms and

operating systems Concludes with a look at new and future directions in computing Features articles that describe diverse aspects of computer usage and potentials for use Details implementation and performance enhancing techniques such as branch prediction register renaming and virtual memory Includes a section on new directions in computing and their penetration into many new fields and aspects of our daily lives **The Computer Engineering Handbook** Vojin G. Oklobdzija,2001-12-26 There is arguably no field in greater need of a comprehensive handbook than computer engineering The unparalleled rate of technological advancement the explosion of computer applications and the now in progress migration to a wireless world have made it difficult for engineers to keep up with all the developments in specialties outside their own References published only a few years ago are now sorely out of date The Computer Engineering Handbook changes all of that Under the leadership of Vojin Oklobdzija and a stellar editorial board some of the industry s foremost experts have joined forces to create what promises to be the definitive resource for computer design and engineering Instead of focusing on basic introductory material it forms a comprehensive state of the art review of the field s most recent achievements outstanding issues and future directions The world of computer engineering is vast and evolving so rapidly that what is cutting edge today may be obsolete in a few months While exploring the new developments trends and future directions of the field The Computer Engineering Handbook captures what is fundamental and of lasting value **Portable Electronics: World Class Designs** John Donovan,2009-03-12 All the design and development inspiration and direction an electronics engineer needs in one blockbuster book John Donovan Editor in Chief Portable Design has selected the very best electronic design material from the Newnes portfolio and has compiled it into this volume The result is a book covering the gamut of electronic design from design fundamentals to low power approaches with a strong pragmatic emphasis In addition to specific design techniques and practices this book also discusses various approaches to solving electronic design problems and how to successfully apply theory to actual design tasks The material has been selected for its timelessness as well as for its relevance to contemporary electronic design issues Contents Chapter 1 System Resource Partitioning and Code OptimizationChapter 2 Low Power Design Techniques Design Methodology and ToolsChapter 3 System Level Approach to Energy ConservationChapter 4 Radio Communication BasicsChapter 5 Applications and TechnologiesChapter 6 RF Design ToolsChapter 7 On Memory Systems and Their DesignChapter 8 Storage in Mobile Consumer Electronics DevicesChapter 9 Analog Low Pass FiltersChapter 10 Class A AmplifiersChapter 11 MPEG 4 and H 264Chapter 12 Liquid Crystal Displays Hand picked content selected by John Donovan Editor in Chief Portable Design Proven best design practices for low power storage and streamlined development Case histories and design examples get you off and running on your current project Phase Change Memory Naveen Muralimanohar,Moinuddin K. Qureshi,Sudhanva Gurumurthi,Bipin Rajendran,2022-05-31 As conventional memory technologies such as DRAM and Flash run into scaling challenges architects and system designers are forced to look at alternative technologies for building future computer systems This synthesis lecture begins by listing the

requirements for a next generation memory technology and briefly surveys the landscape of novel non volatile memories Among these Phase Change Memory PCM is emerging as a leading contender and the authors discuss the material device and circuit advances underlying this exciting technology The lecture then describes architectural solutions to enable PCM for main memories Finally the authors explore the impact of such byte addressable non volatile memories on future storage and system designs Table of Contents Next Generation Memory Technologies Architecting PCM for Main Memories Tolerating Slow Writes in PCM Wear Leveling for Durability Wear Leveling Under Adversarial Settings Error Resilience in Phase Change Memories Storage and System Design With Emerging Non Volatile Memories **A Primer on Compression in the Memory Hierarchy** Somayeh Sardashti,Angelos Arelakis,Per Stenström,David A. Wood,2022-05-31 This synthesis lecture presents the current state of the art in applying low latency lossless hardware compression algorithms to cache memory and the memory cache link There are many non trivial challenges that must be addressed to make data compression work well in this context First since compressed data must be decompressed before it can be accessed decompression latency ends up on the critical memory access path This imposes a significant constraint on the choice of compression algorithms Second while conventional memory systems store fixed size entities like data types cache blocks and memory pages these entities will suddenly vary in size in a memory system that employs compression Dealing with variable size entities in a memory system using compression has a significant impact on the way caches are organized and how to manage the resources in main memory We systematically discuss solutions in the open literature to these problems Chapter 2 provides the foundations of data compression by first introducing the fundamental concept of value locality We then introduce a taxonomy of compression algorithms and show how previously proposed algorithms fit within that logical framework Chapter 3 discusses the different ways that cache memory systems can employ compression focusing on the trade offs between latency capacity and complexity of alternative ways to compact compressed cache blocks Chapter 4 discusses issues in applying data compression to main memory and Chapter 5 covers techniques for compressing data on the cache to memory links This book should help a skilled memory system designer understand the fundamental challenges in applying compression to the memory hierarchy and introduce him her to the state of the art techniques in addressing them *Deep Learning Systems* Andres Rodriguez,2022-05-31 This book describes deep learning systems the algorithms compilers and processor components to efficiently train and deploy deep learning models for commercial applications The exponential growth in computational power is slowing at a time when the amount of compute consumed by state of the art deep learning DL workloads is rapidly growing Model size serving latency and power constraints are a significant challenge in the deployment of DL models for many applications Therefore it is imperative to codesign algorithms compilers and hardware to accelerate advances in this field with holistic system level and algorithm solutions that improve performance power and efficiency Advancing DL systems generally involves three types of engineers 1 data scientists that utilize and develop DL algorithms in

partnership with domain experts such as medical economic or climate scientists 2 hardware designers that develop specialized hardware to accelerate the components in the DL models and 3 performance and compiler engineers that optimize software to run more efficiently on a given hardware Hardware engineers should be aware of the characteristics and components of production and academic models likely to be adopted by industry to guide design decisions impacting future hardware Data scientists should be aware of deployment platform constraints when designing models Performance engineers should support optimizations across diverse models libraries and hardware targets The purpose of this book is to provide a solid understanding of 1 the design training and applications of DL algorithms in industry 2 the compiler techniques to map deep learning code to hardware targets and 3 the critical hardware features that accelerate DL systems This book aims to facilitate co innovation for the advancement of DL systems It is written for engineers working in one or more of these areas who seek to understand the entire system stack in order to bettercollaborate with engineers working in other parts of the system stack The book details advancements and adoption of DL models in industry explains the training and deployment process describes the essential hardware architectural features needed for today s and future models and details advances in DL compilers to efficiently execute algorithms across various hardware targets Unique in this book is the holistic exposition of the entire DL system stack the emphasis on commercial applications and the practical techniques to design models and accelerate their performance The author is fortunate to work with hardware software data scientist and research teams across many high technology companies with hyperscale data centers These companies employ many of the examples and methods provided throughout the book   **Compiling Algorithms for Heterogeneous Systems** Steven Bell,Jing Pu,James Hegarty,Mark Horowitz,2022-05-31 Most emerging applications in imaging and machine learning must perform immense amounts of computation while holding to strict limits on energy and power To meet these goals architects are building increasingly specialized compute engines tailored for these specific tasks The resulting computer systems are heterogeneous containing multiple processing cores with wildly different execution models Unfortunately the cost of producing this specialized hardware and the software to control it is astronomical Moreover the task of porting algorithms to these heterogeneous machines typically requires that the algorithm be partitioned across the machine and rewritten for each specific architecture which is time consuming and prone to error Over the last several years the authors have approached this problem using domain specific languages DSLs high level programming languages customized for specific domains such as database manipulation machine learning or image processing By giving up generality these languages are able to provide high level abstractions to the developer while producing high performance output The purpose of this book is to spur the adoption and the creation of domain specific languages especially for the task of creating hardware designs In the first chapter a short historical journey explains the forces driving computer architecture today Chapter 2 describes the various methods for producing designs for accelerators outlining the push for more abstraction and the tools that enable designers to

work at a higher conceptual level From there Chapter 3 provides a brief introduction to image processing algorithms and hardware design patterns for implementing them Chapters 4 and 5 describe and compare Darkroom and Halide two domain specific languages created for image processing that produce high performance designs for both FPGAs and CPUs from the same source code enabling rapid design cycles and quick porting of algorithms The final section describes how the DSL approach also simplifies the problem of interfacing between application code and the accelerator by generating the driver stack in addition to the accelerator configuration This book should serve as a useful introduction to domain specialized computing for computer architecture students and as a primer on domain specific languages and image processing hardware for those with more experience in the field *High-Performance Embedded Computing* Marilyn Wolf,2014-03-17 High Performance Embedded Computing Second Edition combines leading edge research with practical guidance in a variety of embedded computing topics including real time systems computer architecture and low power design Author Marilyn Wolf presents a comprehensive survey of the state of the art and guides you to achieve high levels of performance from the embedded systems that bring these technologies together The book covers CPU design operating systems multiprocessor programs and architectures and much more Embedded computing is a key component of cyber physical systems which combine physical devices with computational resources for control and communication This revised edition adds new content and examples of cyber physical systems throughout the book including design methodologies scheduling and wide area CPS to illustrate the possibilities of these new systems Revised and updated with coverage of recently developed consumer electronics architectures and models of computing Includes new VLIW processors such as the TI Da Vinci and CPU simulation Learn model based verification and middleware for embedded systems Supplemental material includes lecture slides labs and additional resources *PROCEEDINGS OF THE 22ND CONFERENCE ON FORMAL METHODS IN COMPUTER-AIDED DESIGN – FMCAD 2022* Alberto Griggio,Neha Rungta,Georg Weissenbacher,Warren A. Hunt, Jr.,2022-10-12 The Conference on Formal Methods in Computer Aided Design FMCAD is an annual conference on the theory and applications of formal methods in hardware and system in academia and industry for presenting and discussing groundbreaking methods technologies theoretical results and tools for reasoning formally about computing systems FMCAD covers formal aspects of computer aided system testing A Primer on Memory Persistency Vaibhav Gogte,Aasheesh Kolli,Thomas F. Wenisch,2022-02-09 This book introduces readers to emerging persistent memory PM technologies that promise the performance of dynamic random access memory DRAM with the durability of traditional storage media such as hard disks and solid state drives SSDs Persistent memories PMs such as Intel s Optane DC persistent memories are commercially available today Unlike traditional storage devices PMs can be accessed over a byte addressable load store interface with access latency that is comparable to DRAM Unfortunately existing hardware and software systems are ill equipped to fully avail the potential of these byte addressable memory technologies as they have been designed to access

traditional storage media over a block based interface Several mechanisms have been explored in the research literature over the past decade to design hardware and software systems that provide high performance access to PMs Because PMs are durable they can retain data across failures such as power failures and program crashes Upon a failure recovery mechanisms may inspect PM data reconstruct state and resume program execution Correct recovery of data requires that operations to the PM are properly ordered during normal program execution Memory persistency models define the order in which memory operations are performed at the PM Much like memory consistency models memory persistency models may be relaxed to improve application performance Several proposals have emerged recently to design memory persistency models for hardware and software systems and for high level programming languages These proposals differ in several key aspects they relax PM ordering constraints introduce varying programmability burden and introduce differing granularity of failure atomicity for PM operations This primer provides a detailed overview of the various classes of the memory persistency models their implementations in hardware programming languages and software systems proposed in the recent research literature and the PM ordering techniques employed by modern processors **Transactional Memory** Tim Harris,James R. Larus,Ravi Rajwar,2010 The advent of multicore processors has renewed interest in the idea of incorporating transactions into the programming model used to write parallel programs This approach known as transactional memory offers an alternative and hopefully better way to coordinate concurrent threads The ACI atomicity consistency isolation properties of transactions provide a foundation to ensure that concurrent reads and writes of shared data do not produce inconsistent or incorrect results At a higher level a computation wrapped in a transaction executes atomically either it completes successfully and commits its result in its entirety or it aborts In addition isolation ensures the transaction produces the same result as if no other transactions were executing concurrently Although transactions are not a parallel programming panacea they shift much of the burden of synchronizing and coordinating parallel computations from a programmer to a compiler to a language runtime system or to hardware The challenge for the system implementers is to build an efficient transactional memory infrastructure This book presents an overview of the state of the art in the design and implementation of transactional memory systems as of early spring 2010 *A Primer on Memory Consistency and Cache Coherence, Second Edition* Vijay Nagarajan,Daniel J. Sorin,Mark D. Hill,David A. Wood,2022-05-31 Many modern computer systems including homogeneous and heterogeneous architectures support shared memory in hardware In a shared memory system each of the processor cores may read and write to a single shared address space For a shared memory machine the memory consistency model defines the architecturally visible behavior of its memory system Consistency definitions provide rules about loads and stores or memory reads and writes and how they act upon memory As part of supporting a memory consistency model many machines also provide cache coherence protocols that ensure that multiple cached copies of data are kept up to date The goal of this primer is to provide readers with a basic understanding of consistency and coherence This understanding

includes both the issues that must be solved as well as a variety of solutions We present both high level concepts as well as specific concrete examples from real world systems This second edition reflects a decade of advancements since the first edition and includes among other more modest changes two new chapters one on consistency and coherence for non CPU accelerators with a focus on GPUs and one that points to formal work and tools on consistency and coherence **A Primer on Memory Consistency and Cache Coherence** Daniel Sorin,Mark Hill,David Wood,2022-11-10 Many modern computer systems and most multicore chips chip multiprocessors support shared memory in hardware In a shared memory system each of the processor cores may read and write to a single shared address space For a shared memory machine the memory consistency model defines the architecturally visible behavior of its memory system Consistency definitions provide rules about loads and stores or memory reads and writes and how they act upon memory As part of supporting a memory consistency model many machines also provide cache coherence protocols that ensure that multiple cached copies of data are kept up to date The goal of this primer is to provide readers with a basic understanding of consistency and coherence This understanding includes both the issues that must be solved as well as a variety of solutions We present both highlevel concepts as well as specific concrete examples from real world systems Table of Contents Preface Introduction to Consistency and Coherence Coherence Basics Memory Consistency Motivation and Sequential Consistency Total Store Order and the x86 Memory Model Relaxed Memory Consistency Coherence Protocols Snooping Coherence Protocols Directory Coherence Protocols Advanced Topics in Coherence Author Biographies **Shared-Memory Synchronization** Michael L. Scott,2022-05-31 This book offers a comprehensive survey of shared memory synchronization with an emphasis on systems level issues It includes sufficient coverage of architectural details to understand correctness and performance on modern multicore machines and sufficient coverage of higher level issues to understand how synchronization is embedded in modern programming languages The primary intended audience for this book is systems programmers the authors of operating systems library packages language run time systems concurrent data structures and server and utility programs Much of the discussion should also be of interest to application programmers who want to make good use of the synchronization mechanisms available to them and to computer architects who want to understand the ramifications of their design decisions on systems level code *Advances in Computer Systems Architecture* Amos Omondi,2003-09-16 This book constitutes the refereed proceedings of the 8th Asia Pacific Computer Systems Architecture Conference ACSAC 2003 held in Aizu Wakamatsu Japan in September 2003 The 23 revised full papers presented together with 8 invited papers were carefully reviewed and selected from 30 submissions The papers are organized in topical sections on processor architectures and innovative microarchitectures parallel computer architectures and computation models reconfigurable architectures computer arithmetic cache and memory architectures and interconnection networks and network interfaces

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