Synthesis Lectures on
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Moinuddin K. Qureshi · Sudhanva Gurumurthi
Bipin Rajendran

Phase Change Memory

From Devices to Systems

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Phase Change Memory Moinuddin K. Qureshi,Sudhanva Gurumurthi,Bipin Rajendran,2011-11-11 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 **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 *Storage Systems* Alexander Thomasian,2021-10-13 Storage Systems Organization Performance Coding Reliability and Their Data Processing was motivated by the 1988 Redundant Array of Inexpensive Independent Disks proposal to replace large form factor mainframe disks with an array of commodity disks Disk loads are balanced by striping data into strips with one strip per disk and storage reliability is enhanced via replication or erasure coding which at best dedicates k strips per stripe to tolerate k disk failures Flash memories have resulted in a paradigm shift with Solid State Drives SSDs replacing Hard Disk Drives HDDs for high performance applications RAID and Flash have resulted in the emergence of new storage companies namely EMC NetApp SanDisk and Purestorage and a multibillion dollar storage market Key new conferences and publications are reviewed in this book The goal of the book is to expose students researchers and IT professionals to the more important developments in storage systems while covering the evolution of storage technologies traditional and novel databases and novel sources of

data We describe several prototypes FAWN at CMU RAMCloud at Stanford and Lightstore at MIT Oracle s Exadata AWS Aurora Alibaba s PolarDB Fungible Data Center and author s paper designs for cloud storage namely heterogeneous disk arrays and hierarchical RAID Surveys storage technologies and lists sources of data measurements text audio images and video Familiarizes with paradigms to improve performance caching prefetching log structured file systems and merge trees LSMs Describes RAID organizations and analyzes their performance and reliability Conserves storage via data compression deduplication compaction and secures data via encryption Specifies implications of storage technologies on performance and power consumption Exemplifies database parallelism for big data analytics deep learning via multicore CPUs GPUs FPGAs and ASICs e g Google s Tensor Processing Units *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 **Innovations in the Memory System** Rajeev Balasubramonian,2022-05-31 The memory system has the potential to 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 This book takes a tour through recent and prominent research works touching upon 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 *Architectural and Operating System Support for Virtual Memory* Abhishek Bhattacharjee,Daniel Lustig,2022-05-31 This book provides computer engineers academic researchers new graduate students and seasoned practitioners an end to end overview of virtual memory We begin with a recap of foundational concepts and discuss not only state of the art virtual memory hardware and software support available today but also emerging research trends in this space The span of topics covers processor microarchitecture memory systems operating system design and memory allocation We show how efficient virtual memory implementations hinge on careful hardware and software cooperation and we discuss new research directions aimed at addressing emerging problems in this space Virtual memory is a classic computer science abstraction and one of the pillars of the computing revolution It has long enabled hardware flexibility software portability and overall better security to name just a few of its powerful benefits Nearly all user level programs today take for granted that they will have been freed from the burden of physical memory management by the hardware the operating system device drivers and system libraries However despite its ubiquity in systems ranging from warehouse scale datacenters to embedded Internet of Things IoT devices the overheads of virtual memory are becoming a critical performance bottleneck today Virtual memory architectures designed for individual CPUs or even individual cores are in many cases struggling to scale up and scale out to today s systems which now increasingly include exotic hardware accelerators such as GPUs FPGAs or DSPs and emerging memory technologies such as non volatile memory and which run increasingly intensive workloads such as virtualized and or big data applications As such many of the fundamental abstractions and implementation approaches for virtual memory are being augmented extended or entirely rebuilt in order to ensure that virtual memory remains viable and performant in the years to come FPGA-Accelerated Simulation of Computer Systems Hari Angepat,Derek Chiou,Eric S. Chung,James C. Hoe,2022-05-31 To date the most common form of simulators of computer systems are software based running on standard computers One promising approach to improve simulation performance is to apply hardware specifically reconfigurable hardware in the form of field programmable gate arrays FPGAs This manuscript describes various approaches of using FPGAs to accelerate software implemented simulation of computer systems and selected simulators that incorporate those techniques More precisely we describe a simulation architecture taxonomy that incorporates a simulation architecture specifically designed for FPGA accelerated simulation survey the state of the art in FPGA accelerated simulation and describe in detail selected instances of the described techniques Table of Contents Preface Acknowledgments Introduction Simulator Background Accelerating Computer System

Simulators with FPGAs Simulation Virtualization Categorizing FPGA based Simulators Conclusion Bibliography Authors Biographies *Quantum Computer Systems* Yongshan Ding,Frederic T. Chong,2022-05-31 This book targets computer scientists and engineers who are familiar with concepts in classical computer systems but are curious to learn the general architecture of quantum computing systems It gives a concise presentation of this new paradigm of computing from a computer systems point of view without assuming any background in quantum mechanics As such it is divided into two parts The first part of the book provides a gentle overview on the fundamental principles of the quantum theory and their implications for computing The second part is devoted to state of the art research in designing practical quantum programs building a scalable software systems stack and controlling quantum hardware components Most chapters end with a summary and an outlook for future directions This book celebrates the remarkable progress that scientists across disciplines have made in the past decades and reveals what roles computer scientists and engineers can play to enable practical scale quantum computing *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 *In-/Near-Memory Computing* Daichi Fujiki,Xiaowei Wang,Arun Subramaniyan,Reetuparna Das,2022-05-31 This book provides a structured introduction of the key concepts and techniques that enable in near memory computing For decades processing in memory or near memory computing has been attracting growing interest due to its potential to break the memory wall Near memory computing moves compute logic near the memory and thereby reduces data movement Recent work has also shown that certain memories can morph themselves into compute units by exploiting the physical properties of the memory cells enabling in situ

computing in the memory array While in and near memory computing can circumvent overheads related to data movement it comes at the cost of restricted flexibility of data representation and computation design challenges of compute capable memories and difficulty in system and software integration Therefore wide deployment of in near memory computing cannot be accomplished without techniques that enable efficient mapping of data intensive applications to such devices without sacrificing accuracy or increasing hardware costs excessively This book describes various memory substrates amenable to in and near memory computing architectural approaches for designing efficient and reliable computing devices and opportunities for in near memory acceleration of different classes of applications **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 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 **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 Datacenter Design and Management Benjamin C. Lee,2022-05-31 An era of big data demands datacenters which house the computing infrastructure that translates raw data into valuable information This book defines datacenters broadly as large distributed systems that perform parallel computation for diverse users These systems exist in multiple forms private and public and are built at multiple scales Datacenter design and management is multifaceted requiring the simultaneous pursuit of multiple objectives Performance efficiency and fairness are first order design and management objectives which can each be viewed from several perspectives This book surveys datacenter research from a computer architect s perspective addressing challenges in applications design management server simulation and system simulation This perspective complements the rich bodies of work in datacenters as a warehouse scale system which study the implications for infrastructure that encloses computing equipment and in datacenters as distributed systems which employ abstract details in processor and memory subsystems This book is written for first or second year graduate students in computer architecture and may be helpful for those in computer systems The goal of this book is to prepare computer architects for datacenter oriented research by describing prevalent perspectives and the state of the art *Optimization and Mathematical Modeling in Computer Architecture* Karthikeyan Sankaralingam,Michael Ferris,Tony Nowatzki,Cristian Estan,Nilay Vaish,David Wood,2022-05-31 In this book we give an overview of modeling techniques used to describe computer systems to mathematical optimization tools We give a brief introduction to various classes of mathematical optimization frameworks with special focus on mixed integer linear programming which provides a good balance between solver time and expressiveness We present four detailed case studies instruction set customization data center resource management spatial architecture scheduling and resource allocation in tiled architectures showing how MILP can be used

and quantifying by how much it outperforms traditional design exploration techniques This book should help a skilled systems designer to learn techniques for using MILP in their problems and the skilled optimization expert to understand the types of computer systems problems that MILP can be applied to The Datacenter as a Computer Luis Andre Barroso,Jimmy Clidaras,2022-11-10 As computation continues to move into the cloud the computing platform of interest no longer resembles a pizza box or a refrigerator but a warehouse full of computers These new large datacenters are quite different from traditional hosting facilities of earlier times and cannot be viewed simply as a collection of co located servers Large portions of the hardware and software resources in these facilities must work in concert to efficiently deliver good levels of Internet service performance something that can only be achieved by a holistic approach to their design and deployment In other words we must treat the datacenter itself as one massive warehouse scale computer WSC We describe the architecture of WSCs the main factors influencing their design operation and cost structure and the characteristics of their software base We hope it will be useful to architects and programmers of today s WSCs as well as those of future many core platforms which may one day implement the equivalent of today s WSCs on a single board Notes for the Second Edition After nearly four years of substantial academic and industrial developments in warehouse scale computing we are delighted to present our first major update to this lecture The increased popularity of public clouds has made WSC software techniques relevant to a larger pool of programmers since our first edition Therefore we expanded Chapter 2 to reflect our better understanding of WSC software systems and the toolbox of software techniques for WSC programming In Chapter 3 we added to our coverage of the evolving landscape of wimpy vs brawny server trade offs and we now present an overview of WSC interconnects and storage systems that was promised but lacking in the original edition Thanks largely to the help of our new co author Google Distinguished Engineer Jimmy Clidaras the material on facility mechanical and power distribution design has been updated and greatly extended see Chapters 4 and 5 Chapters 6 and 7 have also been revamped significantly We hope this revised edition continues to meet the needs of educators and professionals in this area **iRODS Primer 2** Yu-Ting Chen,Jason Cong,Michael Gill,Glenn Reinman,Bingjun Xiao,Zhiyang Ong,2015-07-01 Since the end of Dennard scaling in the early 2000s improving the energy efficiency of computation has been the main concern of the research community and industry The large energy efficiency gap between general purpose processors and application specific integrated circuits ASICs motivates the exploration of customizable architectures where one can adapt the architecture to the workload In this Synthesis lecture we present an overview and introduction of the recent developments on energy efficient customizable architectures including customizable cores and accelerators on chip memory customization and interconnect optimization In addition to a discussion of the general techniques and classification of different approaches used in each area we also highlight and illustrate some of the most successful design examples in each category and discuss their impact on performance and energy efficiency We hope that this work captures the state of the art research and development

on customizable architectures and serves as a useful reference basis for further research design and implementation for large scale deployment in future computing systems *Security Basics for Computer Architects* Ruby B. Lee,2022-05-31 Design for security is an essential aspect of the design of future computers However security is not well understood by the computer architecture community Many important security aspects have evolved over the last several decades in the cryptography operating systems and networking communities This book attempts to introduce the computer architecture student researcher or practitioner to the basic concepts of security and threat based design Past work in different security communities can inform our thinking and provide a rich set of technologies for building architectural support for security into all future computers and embedded computing devices and appliances I have tried to keep the book short which means that many interesting topics and applications could not be included What the book focuses on are the fundamental security concepts across different security communities that should be understood by any computer architect trying to design or evaluate security aware computer architectures **On-Chip Networks, Second Edition** Natalie Enright Jerger,Tushar Krishna,Li-Shiuan Peh,2022-05-31 This book targets engineers and researchers familiar with basic computer architecture concepts who are interested in learning about on chip networks This work is designed to be a short synthesis of the most critical concepts in on chip network design It is a resource for both understanding on chip network basics and for providing an overview of state of the art research in on chip networks We believe that an overview that teaches both fundamental concepts and highlights state of the art designs will be of great value to both graduate students and industry engineers While not an exhaustive text we hope to illuminate fundamental concepts for the reader as well as identify trends and gaps in on chip network research With the rapid advances in this field we felt it was timely to update and review the state of the art in this second edition We introduce two new chapters at the end of the book We have updated the latest research of the past years throughout the book and also expanded our coverage of fundamental concepts to include several research ideas that have now made their way into products and in our opinion should be textbook concepts that all on chip network practitioners should know For example these fundamental concepts include message passing multicast routing and bubble flow control schemes

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