COMPUTER ARCHITECTURE

(Textbook for Universities and Colleges)

VOLUME I

COMPUTER SYSTEMS

STRUCTURE AND FUNCTION

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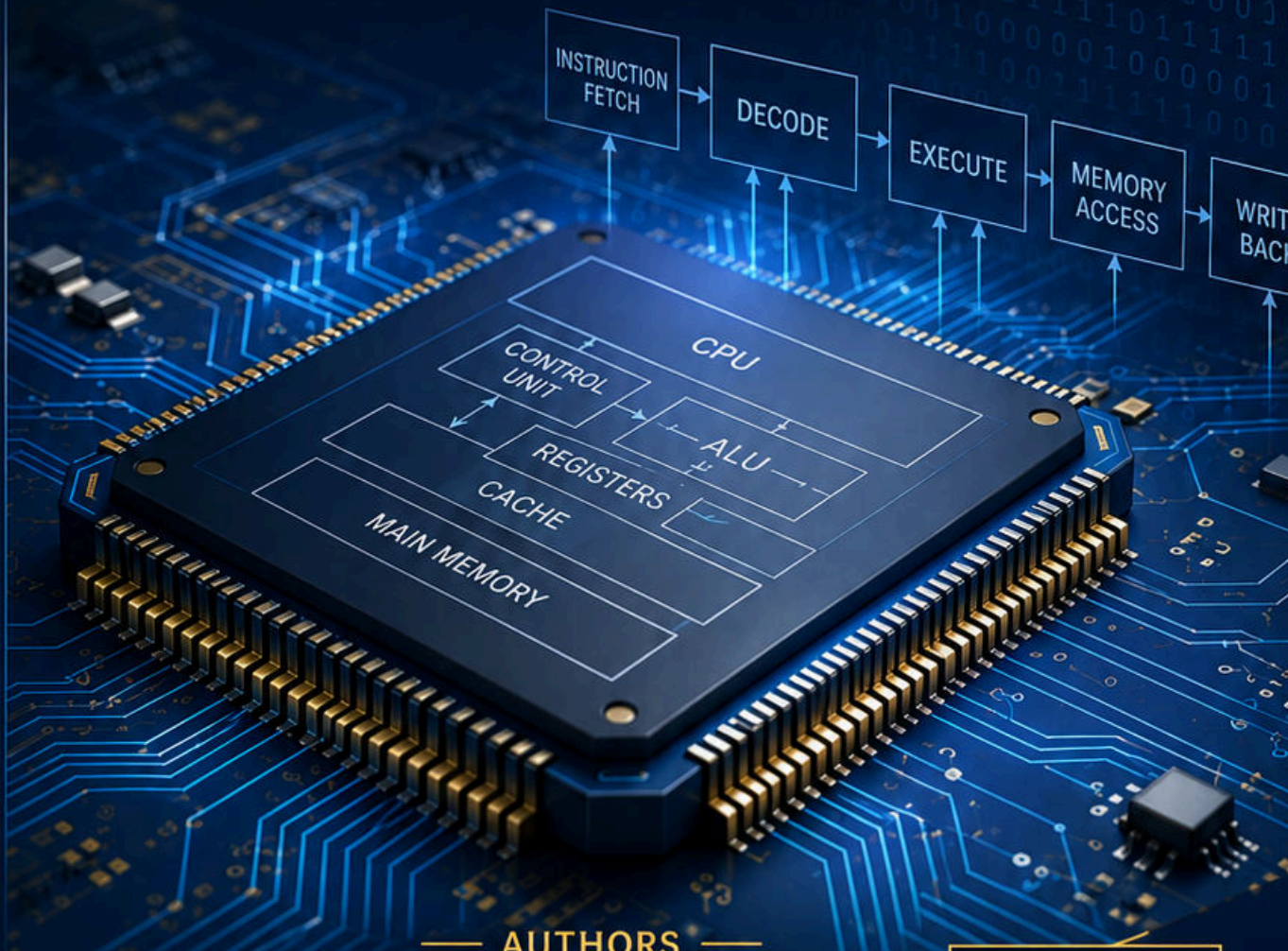

AUTHORS

Huseynov Zakir Nasib
Mammadov Mahil Isa
Masimov Afiq Qazanfar
Guliyev Anar Fikrat
Kazimova Elnara Kazim
Oqtaylı Shehla Rufat

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Authored By:

Huseynov Zakir Nasib
Candidate of Technical Sciences, Head of the Department of Information Technologies at the Azerbaijan State Agricultural University.

Mammadov Mahil Isa
Associate Professor, PhD in Technical Sciences, Azerbaijan State Agricultural University, Department of Information Technologies.

Masimov Afiq Qazanfar
Associate Professor, PhD in Technical Sciences, Azerbaijan State Agricultural University, Department of Information Technologies.

Guliyev Anar Fikrat
Senior Lecturer, Department of Information Technologies, Azerbaijan State Agrarian University, Ganja, Azerbaijan

Kazimova Elnara Kazim
Senior Lecturer, Department of Information Technologies, Azerbaijan State Agrarian University, Ganja, Azerbaijan

Oqtaylı Shehla Rufat
Assistant, Department of Information Technologies, Azerbaijan State Agrarian University, Ganja, Azerbaijan

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REVIEWERS:

Bayram Ibrahimov — Professor of the Department of Defense Systems and Technology Integration, Faculty of Special Equipment and Technology, Azerbaijan Technical University; Doctor of Technical Sciences

Aida Mustafayeva — Head of the Department of Information Technologies, Mingachevir State University; Associate Professor
Azar Huseyn — Associate Professor of the Department of Information Technologies, Mingachevir State University

The textbook Computer Architecture is a fundamental educational publication prepared for undergraduate students studying in the specialties of "Computer Engineering" and "Information Technologies" at Azerbaijan State Agrarian University. The book explains the theoretical foundations of computer systems, digital logic, data encoding, processor organization, memory, and input-output subsystems according to a consistent instructional logic. The topics are not merely listed; their role in the general operating principle of a computer system is also shown. The textbook consists of two volumes: Volume I covers Sections I-IV, and Volume II covers Sections V-VIII. The publication is intended for students, master's students, doctoral students, instructors, and specialists.

zakir.huseynov@adau.edu.az
mahil.mammadov@adau.edu.az

Preface

In this textbook, we explain computer architecture in a different way. It is not merely naming the parts. How do the processor, memory, and input-output all work together? That is our central issue. The goal is not to list individual components, but to show the role of each one in the system. It is also to explain how each affects performance. For this reason, the topics proceed in sequence: first processor organization, then memory, parallel processing, and specialized architectures. They are all united under a single logic.

The quality of a computer is not only that a program runs correctly. Suppose two systems perform the same task. Where does the difference come from? Very often it comes from memory organization, the execution mechanism, and the organization of resources. Studying architecture does not mean memorizing terms. No; you must learn how these architectural choices affect speed, reliability, and resource use.

We moved beyond the classical processor and went further. Today, multicore execution, GPUs, artificial intelligence accelerators, and programmable platforms are not separate additions. They are full partners of architecture. In the book, we present computer architecture not only as CPU organization, but as a systems approach. That is, we bring different computing modes together in one place.

The sequence of topics was not chosen randomly. First, we show how data is represented in a computer. Then, how an instruction is executed. After that, how memory and input-output are involved in this execution. This sequence is used so that the student sees the concepts not as separate things, but as mechanisms that complement one another.

In this edition, we preserved accuracy and also tried to be clear. We selected terms correctly. We explained complex concepts in simple language. The purpose is not to accumulate information. The purpose is to show the logic behind every fact and definition, the technical choices, and the results of architectural decisions. This opens the way to a deeper understanding of architecture.

This book is not only for students. It is for undergraduate students, master's students, doctoral students, instructors, and even anyone with a professional interest in this field. Especially for those working in computer engineering, information technologies, and applied computing, the knowledge presented here builds a strong bridge between theory and practical thinking.

Knowing computer architecture well means understanding the modern digital world correctly. After all, the power of programs, the speed of systems, and the efficiency of technical solutions are all connected with architectural principles. Studying this field is not only professional preparation. It also develops analytical thinking and an engineering perspective.

We hope this textbook becomes a reliable source for you. We hope it deepens your knowledge, increases your interest in the topic, and perhaps opens new paths of research.

Respectfully,
The Authors

About the Book

The textbook Computer Architecture is intended as a fundamental instructional source for undergraduate students studying in the specialties of "Computer Engineering" and "Information Technologies" at Azerbaijan State Agrarian University. The book explains the theoretical foundations of computer systems, digital logic, data encoding, processor organization, memory, and input-output subsystems according to a consistent instructional logic. The topics are not merely listed; their role in the general operating principle of a computer system is also shown. Alongside classical architectural concepts, the textbook broadly explains issues related to the processor, memory, input-output system, parallel and multiprocessor computing environments, graphics and embedded systems, specialized architectures for artificial intelligence, as well as reliability, security, and energy management. Theoretical propositions are complemented by practical explanation; this approach enables students to understand how architectural decisions affect real system performance, memory use, and program execution. This approach helps students develop systems thinking, analytical analysis, and technical comparison skills. The textbook consists of two volumes.

Volume I covers Sections I-IV of the textbook. This volume includes Chapter 1. Theoretical Foundations of Computer Architecture; Chapter 2. Number Systems and Foundations of Digital Logic; Chapter 3. Internal Representation and Encoding of Data; Chapter 4. Instruction Set Architecture (ISA); Chapter 5. Internal Organization of the Processor; Chapter 6. Technology of Pipeline Execution of Instructions (Pipelining); Chapter 7. Instruction-Level Parallelism; Chapter 8. Memory Hierarchy and Organization; Chapter 9. Cache Memory Architecture; Chapter 10. Virtual Memory and Address Translation; Chapter 11. Fundamentals of the Input-Output System; Chapter 12. Bus-Based Interconnection Systems and Communication Protocols; and Chapter 13. Architecture of Mass Storage Devices. This volume systematizes the basic theory of computer architecture. The internal organization of the central processing unit, the structure of memory systems, and input-output architecture are explained within a broad scientific framework.

Volume II covers Sections V-VIII of the textbook. This volume includes Chapter 14. Architecture of Parallel Computing Systems; Chapter 15. Multicore Processor Architecture; Chapter 16. Vector Processors and SIMD Architecture; Chapter 17. Graphics Processor (GPU) Architecture; Chapter 18. Architecture of Embedded Systems; Chapter 19. Specialized

Architectures for Artificial Intelligence; Chapter 20. Programmable Architectures; Chapter 21. Architectural Foundations of Quantum Computing; Chapter 22. Neuromorphic and Biologically Inspired Architectures; Chapter 23. The Future of Architecture: Trends and Forecasts; Chapter 24. Reliability of Computer Systems; Chapter 25. Security at the Architectural Level; and Chapter 26. Performance Analysis and Energy Management. This volume presents the principles of parallel and multiprocessor systems together with modern architectural directions. Special-purpose and prospective architectures, as well as issues related to the reliability, security, and performance management of systems, are examined here in a broad scientific context.

Introduction

In modern society, socioeconomic development is closely connected with computing technologies. Scientific and technical progress is not separate from this connection either. The growth of the information and communication field increases the demand for computer systems. Public administration, industry, education, and health care widely use these systems. Scientific research and everyday life also rely on the same technological foundation. The digital environment is continuously expanding. The flow of information is accelerating. Intelligent services are spreading. The level of automation is rising. All of this creates new quality requirements for computing platforms. Therefore, it is not enough to study computer systems only at the user level. Their internal structure and operating logic must also be examined separately.

Computer architecture is the main scientific direction that arises from this need. This field explains the functional structure of computing systems. It studies the relationship between hardware and software. Instruction execution mechanisms also occupy a central place here. Data processing, memory organization, and system behavior are studied together. Computer architecture is not simply a description of devices. It shows the principles according to which a system is designed. It also clarifies the limitations within which the system operates. Increasing performance is explained on a scientific basis. Therefore, this field is considered one of the basic directions of computer science. It is also one of the main subjects in information technology education.

The external appearance of a computer does not fully show its internal operation. The user sees the computer as a tool that performs ready-made functions. In reality, a complex architectural structure stands behind these functions. Instructions are executed at the machine level. Data is encoded. Registers operate. Arithmetic and logical operations are performed. A memory hierarchy is built. Input-output channels are coordinated. Control mechanisms complement one another in a single system. Therefore, studying architecture is not memorizing the names of components. The main issue is to understand how they are connected. It is also important to know why the components are organized in this way. Their effect on system efficiency must be evaluated separately.

Today’s computing environment has moved away from the classical personal computer model. Computing resources are not located only in desktop systems. Mobile devices, industrial equipment, and embedded systems are also included in this category. Network infrastructures, cloud platforms, and edge computing environments have become widespread. Artificial intelligence-based devices are also part of this field. This change has expanded the subject of computer architecture. In the past, the main focus was on the structure of the processor. Now memory subsystems have also become a main topic. High-speed communication environments play a separate role. Energy efficiency, parallel computing, and heterogeneous computing are coming to the forefront. Domain-specific accelerators are also part of architecture.

The importance of this subject is connected with the correct understanding of real performance. The power of a computer system is not measured only by clock frequency. Operating speed alone is also not sufficient. Latency, bandwidth, and cache memory efficiency must be considered. Memory access time also has a serious effect on the result. The organization of the input-output environment is evaluated separately. Energy consumption, reliability, and security indicators are also important. Sometimes two systems with the same function operate differently. This difference arises from their architectural organization. Thus, computer architecture does not explain performance only as speed. It shows a broader engineering balance. Speed, cost, energy consumption, and stability are evaluated together. Scalability and software compatibility are also included in this balance.

In higher education, computer architecture creates systems thinking in the student. The goal is not only to teach the functions of components. The student must also understand the place of that component in the system. Its relationship with other parts must also be properly understood. Cache memory is not simply an additional level of memory. It reduces the speed gap between the processor and main memory. The pipeline method is not considered only a staged execution scheme. This method serves to process instructions in a flow-like manner. Virtual memory is not only an address translation mechanism. It enables flexible management of memory resources. These examples clearly show the essence of the subject. Computer architecture is not a collection of terms. It is a complete scientific system based on cause-and-effect relationships.

The presented textbook is built according to this methodological line. The book first presents the theoretical foundations of computer architecture. Basic concepts and stages of historical development are explained. Then digital systems and logic circuits are examined. Number systems, internal

representation of data, and encoding are also presented. These sections create a theoretical foundation for the later chapters. This is because the topic cannot be fully opened without knowing how data is represented in the machine. Understanding the instruction set is also connected with this. The operating principle of memory and the internal organization of the processor are built on the same basis.

An important section of the textbook is devoted to the architecture of the central processing unit. The central processing unit is the main controlling part of the computer. Here the instruction set architecture is explained. Addressing modes and instruction formats are shown separately. The functional blocks of the processor are also presented in sequence. Control mechanisms and the staged execution of instructions are explained. Then modern microarchitectural approaches are discussed. These include pipelining, instruction-level parallelism, and dynamic scheduling. Out-of-order execution and speculative execution are also explained. The purpose is not only to list the parts of the processor. The textbook also shows the internal mechanisms that create its performance.

The architecture of memory systems directly affects overall efficiency. For this reason, the textbook presents this topic broadly and systematically. The memory hierarchy, main memory technologies, and the structure of cache memory are explained. Cache memory management is examined separately. Virtual memory and paging mechanisms are also presented. Address translation buffers and memory protection occupy a separate place. In modern systems, processor speed exceeds memory access time. This difference creates a serious technical problem. Therefore, it is important to know memory topics in depth. The textbook does not merely describe these issues. It connects them with performance and efficient use of resources.

A computing system needs an input-output subsystem in order to function completely. The communication environment is equally important. Communication with external devices determines system behavior. Data transfer, bus systems, and controllers are key topics here. Interrupt mechanisms also play an important role in the operation of a computer. Direct memory access methods are explained separately. Storage devices and modern interface standards form real operating conditions. The textbook does not present the input-output system as an auxiliary part. It explains it as a core element of overall architectural integrity.

At the current stage, computer architecture is distinguished by parallel and heterogeneous computing. Increasing single-core performance no longer provides broad opportunities as before. Therefore, multicore processors have

become widespread. The Single Instruction, Multiple Data principle and vector processing have come to the forefront. Graphics processing units are also widely used in computing processes. Artificial intelligence accelerators and programmable platforms are included in this category. This development has brought new directions to the content of architecture. Architecture no longer explains only general-purpose processors. It combines different computing modes in one system. Application areas are also studied within this scientific framework. Mastering modern architecture gives the student two directions. The student understands both classical principles and new technological trends.

The textbook also gives space to reliability, security, and energy efficiency. High speed is important for modern computer systems. But this is not the only evaluation criterion. System stability is of serious importance. Fault tolerance and secure operation are also important. Efficient use of resources must be evaluated separately. In critical applications, these factors appear more sharply. The same requirements also come to the forefront in large computing environments. Studying computer architecture is not only knowing the technical structure. This knowledge requires understanding the broader consequences of engineering decisions.

The presented textbook has been prepared for institutions of higher education. It may be used by undergraduate and master's students. It is also useful for doctoral students, instructors, and practicing specialists. The main purpose of the book is to create a consistent understanding in the reader. This understanding covers the internal structure of computer systems. Functional organization, modern development directions, and applied significance are also explained. The topics are presented with scientific precision. A clear method of explanation is also preserved. Special attention is given to connecting theoretical knowledge with practical thinking. Review questions, exercises, tables, and appendices serve the same purpose.

Computer architecture is one of the main theoretical foundations of the digital world. A person who studies it understands the essence of computer systems more deeply. The internal logic of technical decisions also becomes clear. The development trends of the modern computing environment are correctly evaluated. This textbook has been prepared to help learners master this knowledge in sequence. It serves as a systematic scientific and instructional source.

About the Authors

Huseynov Zakir Nasib — PhD in Engineering, Associate Professor. Was born 02 July 1955. In 1980 graduated from Kirovabad state pedagogical institute after named h. Zardabi, mathematic faculty. By the decree of the president of the republic of Azerbaijan dated 03.10.2006, he was awarded the honorary title "honored teacher of the republic". In 2012 he defended his dissertation on "research of performance indicators of priority service telecommunication networks" and received the degree of doctor of philosophy in technique. From November 2020 he is the head of the information Technologies Department of Azerbaijan State Agricultural University.

Mammadov Mahil Isa — PhD in Engineering, Associate Professor. Born on May 1, 1966, in Agdam village, Tovuz district. In 1990, he graduated from the Azerbaijan Polytechnic Institute (now Azerbaijan Technical University) with a degree in Electronic Computing Machines. On September 20, 2013, he defended his dissertation on “Improvement of the technology for preparing information-software-based feed pellets” and was awarded the degree of Doctor of Philosophy in Engineering in the specialty 3102.01 – Agroengineering. In 2017, he received the academic title of Associate Professor in the Department of Information Technologies. 1990–1994: Engineer-programmer at the Azerbaijan Agricultural Institute. 1994–2009: Leading specialist-programmer at the Ganja branch of the Azerbaijan Joint-Stock Commercial Bank. 2009–2017: Lecturer and Senior Lecturer at the Department of Information Technologies, Azerbaijan State Agrarian University. 2017–present: Associate Professor at the same department.

Masimov Afiq Qazanfar was born on May 18, 1963. He graduated from the Faculty of Applied Mathematics of Baku State University in 1985. From 1985 to 1990, he worked at the "MARS" Research Institute in Ulyanovsk, Russian Federation. Between 1990 and 2000, he served as a shop supervisor at the "Wine-1" production association in Ganja. From 2000 to 2017, he was a senior teacher at the Department of Information Technologies of Azerbaijan State Agricultural University. In 2013, he defended his PhD dissertation in Technical Sciences on "Energetic Assessment of the Technology and Mechanisation Means for Primary and Pre-sowing Soil Cultivation". In 2017, he received the academic title of Associate Professor in Information Technologies. Since 2017, he has been working as an Associate Professor at the same department.

Guliyev Anar Fikrat — Senior Lecturer. Born on November 10, 1974. In 1996, he graduated from the Faculty of Economics at the Azerbaijan State Agrarian University. Since 2010, he has been working at the Department of Information Technologies of the Azerbaijan State Agrarian University. He currently serves as a Senior Lecturer in the same department.

Kazimova Elnara Kazim — Senior Lecturer. Born on May 20, 1985, in the Russian Federation. From 2004 to 2008, she studied at Baku State University, earning a higher education degree in Mechanics and Mathematics. Between 2009 and 2011, she completed her master's studies in Informatics at Ganja State Agrarian University. From 2017 to 2025, she worked as an Assistant at the Azerbaijan State Agrarian University. Since 2025, she has been serving as a Senior Lecturer at the same university.

Oqtayli Shehla Rufat— Assistant. Born on February 7, 1996, in Ganja city. From 2014 to 2018, she studied at the Azerbaijan State Agrarian University, earning a higher education degree in Information Technologies and Systems Engineering. Between 2018 and 2020, she completed her master's studies in Applied Software at the same university. 2021–2022: Laboratory Assistant at Ganja State University. 2022–2023: Assistant at Azerbaijan Technological University. 2023–present: Assistant at the Department of Information Technologies, Azerbaijan State Agrarian University.

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ABOUT THE AUTHORS :

Huseynov Zakir Nasib
Head of Department,
Information Technologies, Azerbaijan State Agricultural University

Mammadov Mahil İsa
Associate Professor, PhD in Technical Sciences, Azerbaijan State Agricultural University, Department of Information Technologies.

Masimov Afiq Qazanfar
Associate Professor,
Department of Information Technologies, Azerbaijan State Agricultural University

Guliyev Anar Fikrat
Senior Lecturer, Department of Information Technologies, Azerbaijan State Agrarian University, Ganja, Azerbaijan

Kazimova Elnara Kazim
Senior Lecturer, Department of Information Technologies, Azerbaijan State Agrarian University, Ganja, Azerbaijan

Oqtaylı Shehla Rufat
Assistant, Department of Information Technologies, Azerbaijan State Agrarian University, Ganja, Azerbaijan

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