9th International scientific conference
Technics and Informatics in Education – TIE 2022
16-18 September 2022

Session: *Enginering Education and Practice*
Review paper
DOI: 10.46793/TIE22.141V

New Challenges in Computer Architecture Education

Dejan Vujičić *, Siniša Ranđić
University of Kragujevac, Faculty of Technical Sciences, Čačak, Serbia
* dejan.vujicic@ftn.kg.ac.rs

Abstract: *This paper provides a brief overview of the development of computer architecture and its impact on approaches to the presentation of appropriate information and computer education. The relative constancy of the concepts that were applied in the architecture of the computer influenced that the classical approaches to the appropriate education are kept until today. The changes that occurred in architecture during the development of computer technology, in conjunction with technological development, required a corresponding adjustment in the sphere of education. The turning point was the advent of the microprocessor, which introduced the x86 architecture into education. The beginning of the new century was marked by the ARM architecture. And today, the RISC-V architecture is emerging more and more as a new design challenge.*

Keywords: *computer architecture, microprocessors, x86, ARM, RISC-V*

1. INTRODUCTION

With the development of computer science, computer architecture has somewhat gone out of the view of the wider population of those whose work is related to the computer. This was also reflected in the education of computer science engineers in terms of computer architecture. Instead of a generalized approach, students are mostly introduced to computer architecture through concrete examples of computer architecture. Today, these are mainly microprocessor architectures on which the development of modern computers is based.

The beginnings of computer development are related mainly to university environments, primarily in the United States of America, Great Britain, and Germany. Intensive research was started on the eve of World War II and continued immediately after its end. The largest number of experts were concentrated in the universities, so they were a natural environment for the development of the new science from which so much was expected. The hint of a new world conflict was enough justification for powerful countries to finance the development of computers.

New momentum in the development of computer technology was brought by the appearance of companies that offered the market computers based on their architecture. Until the end of the seventies of the last century and the advent of microcomputers, the computer market was dominated primarily by American companies, such as IBM, DEC, Honeywell, Burroughs, CDC, NCR, General Electric, RCA, and Sperry Rand. In addition to them, we should also mention the British companies Ferranti and ICL, the French Bull, and the Italian Olivetti. Computers were also developed in other countries, but they were placed on the world market on a smaller scale.

In principle, each company based its computers on its own development. First of all, that meant defining one's architecture on which the work of those computers was based. On the other hand, computers from that time were offered as complete units. In addition to complete computer hardware, companies also offered customers appropriate system software: operating systems and tools for program development. This meant primarily making compilers available to users. This was a logical consequence of the fact that operating systems and compilers depended directly on the architecture of the computer on which they were used.

Following the state of the computer market, universities began to try to link teaching in fundamental computer disciplines to the computers that dominated the market. In this respect, the architecture of the IBM computers from the 360 and 370 series [1], [2] is the most used computer architecture. In the 1970s, computer architecture education focused more on DEC computers and their PDP-11 [3] and VAX-11 [4] systems. Given that some companies had computers with a very specific architecture, they were used as an educational platform for pointing out advanced techniques in computing. In this respect, Burroughs computers were particularly characteristic.

Although the development of computers was dominantly linked to large computer companies, research at universities in the field of computing did not abate. Considering that computers were becoming more and more important for military needs, especially large countries gave great support to research at universities in the field of computing. On the other hand, many companies have also invested in university research intending to create ideas in those environments in which computing will rest in the future. It has proven particularly successful in areas such as programming languages and operating systems. From the MULTICS project [5], [6], which was realized at MIT University, the concept of a multiuser operating system was designed, on which all later known operating systems were more or less based. As far as programming languages are concerned, the example of the ADA programming language [7] whose development was financed by the United States Department of Defense can be mentioned.

As far as computer architecture is concerned, the universities mainly engaged in research in the field of advanced architectures. With a special emphasis on the development of parallel computer systems.

2. MICROPROCESSORS BRING CHANGE

The development of semiconductor technology and the emergence of microprocessors represented a turning point in the development of computing [8]. But also, education in terms of computer architecture. The emergence of 8-bit microprocessors is of particular importance for the development of computing. Table 1 provides an overview of the 8-bit microprocessors that were most commonly used. And thus influenced the changes in computer education in the following decades.

Behind the contents of Table 1 hides the important fact that, except for Motorola, the companies that offered microprocessors to the market were, so to speak, newly founded companies. Intel was founded in 1968, MOS Technology in 1969, and Zilog in 1974. Gordon Moor and Robert Noyce left Fairchild and founded Intel because in the previous company there was no sense in making highly integrated circuits.

Table 1. *The overview of 8-bit microprocessors*

Micro-processor	Manufacturer	Year	Technology
8080	Intel	1974	NMOS
8085	Intel	1976	HMOS
6800	Motorola	1974	NMOS
6809	Motorola	1978	NMOS
Z80	Zilog	1976	NMOS
6502	MOS Technology	1975	NMOS

Not neglecting other microprocessors, at the beginning of the new era in computing, microprocessors 8080/8085 from Intel [9] and 6800 from Motorola [10] had a dominant position.

The advent of the microprocessor brought a major change to the computer design process. Computers are now designed around microprocessors, as ready-made components, which could be bought, like any other electronic component. Accordingly, computer designers had to know the characteristics of microprocessors, first of all, their architecture and the way of connection with the environment. At the same time, this also meant the need for changes in the education of computer science engineers. Manufacturers of microprocessors had to provide all the necessary documentation to the designers of the new class of computers, which are called microcomputers due to the use of highly integrated components. Consequently, it was natural that the introduction to microprocessors and microcomputers should be based on the original literature.

On the other hand, knowledge of microprocessor architecture was important from the aspect of developing system software for computers, which were based on microprocessors. Given that the first computers based on microprocessors were not general purpose, the necessary system support for them was usually provided by microprocessor manufacturers. Classic examples are the PL/M programming language [11] and the CP/M operating system [12]. Considering that it was mainly about 8-bit microprocessors with limited resources, the operating systems developed for them did not contain elements of multiprogramming.

2.1 Personal computers - heralds of the new age

A new revolution in computing was brought by the so-called personal computers. The biggest contribution to this change was made by the IBM company with its microcomputer, which they gave the shortened name PC from Personal Computer [13]. Even before 1981, when the IBM PC appeared, there were similar computers on the market. However, the new computer brought for the users, and these were primarily people who already used computers, the way of usage they were used to. This largely explains the popularity that this type of computer will have in the future.

Thanks to the success of the IBM PC computer, Intel microprocessors from the 8086 series dominated the market. These were 16-bit processors that Intel offered to the market in 1985. They were the progenitors of a new family of computer architectures that is still known as the x86 architecture [14]. In the meantime, this architecture of 16-bit microprocessor realization was realized through 32-bit microprocessors, whose designations were 80386, 80486 and Pentium. The latest processors from the company

Intel carry the codes Core i3, i5, i7, i9 and Xeon [15].

The success and popularity of the x86 architecture caused many companies to "clone" it. The most successful "clone" of x86 architecture was made by AMD (Advanced Micro Devices). Thanks to this, personal computers compatible with IBM PCs are a serious competitor to corresponding computers based on Intel microprocessors. The current generation of AMD processors is codenamed Ryzen [16]. In addition to AMD, the company Cyrix also dealt with "cloning" of the x86 architecture [17].

The last quarter of the last century brought the appearance of a large number of new microprocessors. Many of them were more advanced in their architecture compared to the x86 family. However, Intel's dominance in the personal computer segment meant that most of them did not get full commercial satisfaction. To the greatest extent, they have found application in the design of the so-called graphic workstations. It was about computers intended for designing in various fields of technology. With such computers, extensive and fast calculations and graphical presentation of information were required. Also, computers with good graphics capabilities have found wide applications in the field of graphic design. In this regard, the company Apple particularly stood out with its family of Macintosh (MAC) computers, which were originally based on microprocessors from the Motorola 680x0 series [18]. Later, Apple, in cooperation with IBM and Motorola, will develop a new PowerPC microprocessor family, which will be incorporated into new versions of MAC computers. Interestingly, Intel and Motorola remained competitors in the domain of 32 microprocessors (80386 versus 68030). Although Motorola offered a more advanced architecture, commercial success was on Intel's side. Table 2 provides an overview of microprocessors developed during the last two decades of the 20th century. It was a time when 32-bits dominated, and 64-bit microprocessors were emerging. The latest 64-bit microprocessors were intended for very powerful computers. Servers, workstations, and supercomputers were developed on their basis.

In 1995, DEC (Digital Equipment Corporation) developed the Alpha 21164 microprocessor, which implemented the Alpha RISC architecture [19]. The idea was for the microprocessor to be a replacement for the 32-bit VAX architecture. As well this RISC (Reduced Instruction Set Computers) enabled DEC to be competitive in the field of UNIX workstations. In a way, DEC wanted to make up for not accepting personal computers during the 1980s.

Table 2. *The overview of 32/64 – bit microprocessors*

Micro-processor	Manu-facturer	Word length	Usage
68040	Motorola	32	Workstation
PowerPC 601,750	Motorola, IBM, Apple	32	RISC processor, Notebook
PowerPC 620	Motorola, IBM, Apple	64	Workstation
Alpha 21164 21264	DEC	64	RISC processor
ULTRA SPARC	SUN	64	RISC processor
MIPS	MIPS	64	RISC processor, workstation
PA 8500	Hewlett Packard	64	Workstation, servers

2.2 CISC and RISC architectures

The beginning of the eighties of the last century brought the RISC (Reduced Instruction Set Computers) concept [20], [21], [22] to be strongly opposed to the previous CISC (Complex Instruction Set Computers). Although it seems that CISC, thanks to the commercial success of the x86 architecture, is still dominant, the architectures of practically all new microprocessors are based on the RISC concept [23]. It can also be seen in Table 2.

The dominance of microprocessors as components for computer development has influenced computer education to be increasingly turning to familiar with specific microprocessor architectures. In the beginning, the x86 architecture dominated, and later other microprocessor architectures found their place in the educational process. First of all, MIPS. This orientation, as well as all recent approaches in education regarding computer architecture, followed the trail of the RISC concept. The importance of familiarizing future experts in the field of computer hardware can best be seen in the books by David Patterson and John Hennessy [24], [25].

Until the eighties of the last century, the development of microprocessors was tied to companies that were simultaneously the carriers of the development of semiconductor technology. A typical example was Intel and AMD. However, with the development of HDL (Hardware Description Languages) [26] and other VLSI (Very Large-Scale Integration) design tools [27], there have been major changes in this area. Thanks to this, many companies declared themselves as microprocessor manufacturers, even though they were essentially just their designers. While manufacturing was serviced by companies that exclusively specialized in that business.

3. ARM TAKES PRECEDENCE

The company whose family of computer architectures will mark the transition between centuries was created under the auspices of the British computer manufacturer Acorn Computers. This company entered the world of VLSI at a time when, in addition to the microprocessors themselves, the development of various coprocessor components began massively. Most often, it was about mathematical and graphic coprocessors. It was while looking for the best option for the graphics subsystem of the BBC Micro family [28] of computers that Acorn came up with the idea of developing a processor with its own architecture for these needs. As a result of cooperation with integrated circuit manufacturer VLSI Technology, the first ARM processor, ARM1, appeared in 1985. Already the following year, a serial processor was available, which bore the name ARM2.

At the beginning of the nineties of the last century, Acorn formed a new company, Acorn RISC Machine, from the processor design team, which will later change its name to Advanced RISC Machines, known by the abbreviation ARM. During the subsequent development of new architectures in ARM, they tried to make the processors based on them to have fewer transistors than typical microprocessors. The goal was to reduce energy consumption, reduce heating, and of course obtain a price-competitive product. The stated goals of ARM coincided with the requirements set by mobile devices oriented towards battery power at the beginning of the 21st century. The relative simplicity of its ARM processors is also due to the absence of microprogram memory.

The importance and possibilities of the philosophy applied by ARM in the specification of architectures have been noticed by many companies. One of the companies that has the longest cooperation with ARM is Apple. In addition to Apple, ARM-based systems are also implemented by nVidia, Qualcomm, Samsung, and Texas Instruments. It is almost difficult to list all the companies that have developed their processors around one of the ARM cores. Suffice it to say that ARM cores are dominant in processor solutions for smartphones and laptops. In the case of mobile phones, over 90% of them use processors based on the ARM architecture. However, we should not forget the multi-core processors based on ARM architectures, which are intended for the implementation of servers and supercomputers. Also, ARM architectures have become dominant in the development of microcontrollers.

ARM is one of the world's largest companies that deals with the specification of computer architectures. However, it does not manufacture processors as integrated circuits itself. Instead, ARM sells its architecture and integrated circuit design solutions to other firms. Based on them, these companies develop their products. First of all, it is about processors, but also about the so-called SoC (System on Chip). On them, memory, communication interfaces, and even radio components are integrated around the processor with ARM architecture. In addition to a complete description of the hardware cores, ARM provides its partners with translators, debuggers, and development tools.

Despite the dominant position of ARM processors in mobile devices, most computers in use are based on CISC processors. However, there is a growing trend to use ARM processors for these computers as well. In 2017, Microsoft and Qualcomm announced the symbiosis of the Windows 10 operating system and devices based on ARM processors. At the same time, Hewlett-Packard, Asus, and Lenovo produced laptops based on the Snapdragon 835 processor.

Thanks to the wide application of ARM architectures, they have also found their place in educational activities. More and more courses in which ARM architectures are studied are found in the curricula of world universities. Accordingly, chapters in many textbooks, even entire textbooks, are dedicated to familiarizing readers with ARM architectures, [29], [30], [31], [32].

The main advantages of ARM architectures are:

- Accessibility and low cost in terms of processor development;
- Low power consumption;
- Since operations are performed in one cycle, processors work faster;
- They are suitable for the realization of multi-process systems;
- Operations are performed on the contents of registers, which reduces interaction with memory.
- ARM processors are very simple so due to their compactness they can be used for small devices.

In addition to all the good features that have imposed themselves as a good basis for the development of modern processors, the ARM concept also has its drawbacks:

- Due to incompatibility with the x86 architecture, they have not been used in the Windows environment until recently;
- Some ARM processors have speed limitations;
- Correct execution of instructions depends on the programmer, which can affect the overall performance of the processor. This means that programming ARM processors requires highly skilled programmers;
- Finally, the ARM architecture is based on a closed concept.

4. RISC–V – SOMETHING NEW IS COMING

Microprocessor architectures arose and developed on the wave of changes brought to computing by semiconductor technology. The University of Berkeley pioneered the semiconductor realization of the RISC concept. At the University of Berkeley, the first integrated processor based on the RISC concept, RISC I, was realized in 1981 [33]. Under the direction of Professor David Patterson, the integrated processor was designed and implemented by students. The project was implemented to check the possibilities of reducing the hardware for decoding and managing instructions, a large set of registers, and the realization of 32-bit address space. Also, the idea was to check the possibility of executing instructions with overlapping phases (pipelining). The realization of RISC I was motivated by the ideas presented by Andrew Tanenbaum in his 1978 paper [34]. In doing so, he showed how a complex program written in a high-level programming language can be represented using a simple instruction architecture. RISC I had a little over 44 thousand transistors, it was made in 5-micron NMOS technology on a 77mm^2 board. It worked with a clock of 1MHz. Already in the next year, a new version of the RISC II processor was created. It had about 40 thousand transistors, it was made in 3-micron NMOS technology on a 60mm^2 board. Its operating clock speed was 3MHz [35].

After almost three decades of continuous research in this field and four generations of RISC processors, in 2010, work on the project of a new computer architecture called RISC-V was started in the Parallel Computing Laboratory (Par Lab) of the University of Berkeley. The research team consisted of Krste Asanović and Ph.D. students Yunsup Lee and Andrew Waterman. The development took place as part of a project whose goal was to improve parallel computing, and which was financed by Intel and Microsoft. It should be emphasized that the projects carried out in Par Lab were in "open source" mode. Their results are distributed under the Berkeley Software Distribution (BSD) license. At the same time, Par Lab developed Chisel, a new HDL (Hardware Description Language) that was intended for hardware implementation within the RISC-V project [36].

As a rule, previous instructional architectures (ISA) entailed the possession of a license for their use. Instead, RISC-V is available under an "open source" license. Although it has no technological implications, the appearance of RISC-V represented a real small revolution in computing. The architecture specification can be obtained for free; the desired measurements can be made; the hardware and software can be developed and finally, the corresponding processors can be realized. To popularize this concept, the RISC-V Foundation was formed in 2015, bringing together more than 20 companies. The foundation was renamed RISC-V International in 2020 and today gathers more than 2000 members in over 70 countries. Some of the founders of RISC-V International are Google, Qualcomm, Western Digital, Hitachi, Samsung, and others.

The main features of the RISC-V architecture are:

- The specified ISA follows RISC design principles;
- Instructions are executed in one cycle;
- Execution of operations is based on the load/store principle;
- The project is software oriented;
- The architecture is modular and scalable, which means that it can be used for a wide range of applications, from microcontrollers to personal computers to supercomputers;
- It has 32-bit and 64-bit variants and plugins for working in floating-point;
- It is supported by different compilers and Linux operating system;
- Offers hardware support for the development of microcontrollers, SoM and SoC circuits, as well as FPGA circuits;
- Through cooperation within the RISC-V community and the possibility of reusing ready-made IP (Intellectual Property) solutions, the time needed to get from the project to the market is shortened.

The novelties offered by the RISC-V concept to the expert computing public have received a lot of attention. And not only companies that have been on the computer market for a long time, but also new companies that have based their solutions on the RISC-V architecture. All those interested have extensive literature available based on which they can get involved in the realization of processors and systems based on the RISC-V architecture [37 - 40].

The growing popularity of the RISC-V concept among computer hardware manufacturers has also found its response in the educational community. An increasing number of universities in the United States of America, but also around the world, are supplementing their programs in the field of computer architecture with topics related to RISC-V architecture.

5. CONCLUSION

Using a computer, primarily from the point of view of system software development, is practically impossible without detailed knowledge of computer architecture and organization. This was particularly evident with the advent of the microprocessor. It would be practically impossible, without detailed knowledge of the architecture and organization of the microprocessor, to develop a computer around it as a central component.

On the other hand, computer architecture represents one of the pillars of computer science. This implies that education in this segment of computer science is impossible without adequate literature. At first glance, the basic postulates of computer architecture have not changed much since the very beginnings of computer technology. However, the changes that took place, in conjunction with technological development, required adequate adaptation to computer education. Through this work, an attempt was made to draw a parallel between the changes in computer architecture and the approach to the presentation of appropriate information concerning the requirements of education in this area. The emergence of new architectures, such as RISC-V, presents a new challenge in this regard.

ACKNOWLEDGEMENTS

This study was supported by the Ministry of Education, Science and Technological Development of the Republic of Serbia, and these results are parts of Grant No. 451-03-68/2022-14/200132 with the University of Kragujevac - Faculty of Technical Sciences Čačak.

REFERENCES

[1] Amdahl, G. M., Blaaw, G. A., Brooks, J., F. P. (1964). Architecture of the IBM System/360. *IBM Journal of Research and Development*, 8 (*2*), 87-101

[2] Gifford, D., Spector, A. (1987). Case Study: IBM's System/360 – 370 Architecture. *Communications of the ACM*, 30(*4*), 281-307

[3] Bell, G., Wulf, W., et al. (1970). A New Architecture for Mini – computer – The DEC PDP-11. *Spring Joint Computer Conference*, 657-675

[4] Leonard, T. E. (1987*). VAX Architecture Reference Manual*. DEC Books, Burlington

[5] Corbato, F. J., Vyssotsky, V. A. (1965). Introduction and Overview of the Multics System. *Proceedings – Fall Joint Computer Conference*, 185 – 196

[6] Saltzer, J. H., Gintell, J. W. (1969). The Instrumentation of Multics. *Second ACM Symposium on Operating System Principles*, Princeton, New Jersey

[7] Sward, R. E. (2010). The Rise, Fall and Persistence of the ADA. *ACM SIGAda Ada Letters*, 30(*3*), 71–74

[8] Betker, M. R., Fernando, J. S., Whalen, S. (1997). The History of the Microprocessor. Bell Labs Technical Journal, 29 – 56

[9] Mazor, S. (2007). Intel 8080 CPU Chip Development. *IEEE Annals of the History of Computing*, 70 – 73

[10] M6800 Microcomputer: System Design Data. Motorola, Inc., 1976

[11] McCracken, D. D. (1978). *A Guide to PL/M Programming for Microcomputer Applications*. Addison – Wesley

[12] CP/M Operating System Manual. Digital Research, 1976

[13] Mazidi, M. A., Mazidi, J. G. (2003). *The 80x86 IBM PC and Compatible Computers: Assembly Language, Design, and Interfacing*. Volumes I & II, 4th Edition, Pearson Education

[14] Shanley, T. (2009). *x86 Instruction Set Architecture: Comprehensive 32/64 – bit Coverage*. 1st Edition, MindShare, Inc.

[15] 8th and 9th Generation Intel Core Processor Families and Intel Xeon E Processor Families. Volume 1, Revision 006, Intel, July 2020

[16] AMD64 Architecture Programmer's Manual – Volume 1: Application Programming. Revision 3.23, Advanced Micro Devices, 2020

[17] 5x86 Microprocessor – Superpipelined x86 Compatible CPU. Cyrix Corporation, July 1995

[18] Motorola M68000 Family: Programmer's Reference Manual. Motorola, Inc., 1992

[19] Alpha 21164 Microprocessor – Hardware Reference Manual. Compaq Computer Corporation, December 1998

[20] Muskan, S., et al. (2018). The Survey of Concepts of Architecture in RISC and CISC Computers. *International Journal of Advance Research, Ideas and Innovations in Technology*, 4(*6*), 146 – 151

[21] Patterson, D. A., Seguin, C. A. (1982). VLSI RISC. *Computer*, 15(9), 8 – 21

[22] Patterson, D. A. (1985). Reduced Instruction Set Computers. *Communications of the ACM*, 28(1), pp. 8 – 21

[23] Dandamudi, S. P. ed. (2005). *Guide to RISC Processors*. Springer

[24] Hennessy, J. L., Patterson, D. A. (2017). *Computer Architecture: A Quantitative Approach*. Morgan Kaufmann, 6th Edition

[25] Patterson, D. A., Hennessy, J. L. (2020). *Computer Organization and Design MIPS Edition: The Hardware/Software Interface*. Morgan Kaufmann, 6th Edition

[26] Botros, N. (2015). *HDL with Digital Design: VHDL and Verilog*. Mercury Learning and Information

[27] Brunvald, E. (2009). *Digital VLSI Chip Design with Cadence and Synopsys CAD Tools*. 1st Edition, Pearson

[28] Coll, J., Allen, D. (2020). *The BBC Microcomputer – User Guide*. British Broadcasting Corporation, Fourth Revision

[29] Ledin, J. (2020). Modern Computer Architecture and Organization. Packt Publishing

[30] Harris, S. L., Harris, D. (2015). *Digital Design and Computer Architecture: ARM Edition*. 1st Edition, Morgan Kaufmann

[31] Mazdi, M. A., Naimi, Sa., Naimi, Se., Chen, S. (2016). *ARM Assembly Language Programming & Architecture*. 2nd Edition, MicroDigital

[32] Greaves, D. (2021). *Modern System–on–Chip Design on Arm*. Arm Education media

[33] Patterson, D. A., Seguin, C. H. (1998). RISC I: Reduced Instruction Set VLSI Computer.

ISCA'98, 25 years of the international symposium on Computer architecture, 24 – 26

[34]Tanenbaum, A. S. (1978). Implications of Structured Programming for Machine Architecture. Communications of the ACM, 21(3)

[35]Peek, J. B. (1983). *The VLSI Circuitry of RISC I*. Technical Report No. UCB/CSD-83-135, Berkeley University

[36]Schoeberl, M. (2019). *Digital Design with Chisel*. 3rd Edition, Copyright Martin Schoeberl

[37]Waterman, A., Asanović, K. ed. (2019). *The RISC-V Instruction Set Manual, Volume I: User-Level ISA.* Document Version 20191213, RISC-V Foundation

[38]Waterman, A., Asanović, K., Hauser, J. ed. (2021). *The RISC-V Instruction Set Manual, Volume II: Privileged Instructions*. Document Version 20211203, RISC-V Foundation

[39]Patterson, D. A., Hennessy, J. L. (2017). *Computer Organization and Design RISC-V Edition: The Hardware Software Interface*. 1st Edition, Morgan Kaufmann

[40]Patterson, D. A., Waterman, A. (2017). *The RISC-V Reader: An Open Architecture Atlas*. 1st Edition, Strawberry Canyon